SUGARCANE EVAPOTRANSPIRATION ESTIMATES IN THE LOWVELD OF ZIMBABWE

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Abstract

In order to benchmark and improve estimates of sugarcane evapotranspiration (ET) and thereby facilitate increased irrigation water use efficiencies, a study was undertaken to compare, for the south east lowveld of Zimbabwe:

- the world standard, Food and Agricultural Organisation (FAO) Penman Monteith reference evaporation (E_{FAOpm}), with
- evaporation from United States Weather Bureau, Class A evaporation pans (E_{apan}), and
- evaporation from a relatively simple commercially available atmometer device, called an ETgage, which has been designed to mimic many of the evaporation characteristics of a plant (E_{etg}).

In addition, ET estimates for sugarcane, derived using state-of-the-art procedures presented in the FAO publication No.56 were used to derive refined monthly pan and ETgage factors in order to relate data from these instruments to benchmark FAO-based estimates of sugarcane ET.

The comparisons between evaporation estimates showed that there were large differences between E_{apan} and E_{FAOpm}, especially when E_{apan} was above 8 mm. At these high E_{apan} values, E_{apan} was shown to exceed the equivalent E_{FAOpm} by more than 30%. Nevertheless, the relationship between E_{apan} and the E_{FAOpm} estimates was very consistent, especially when averaged over a period of five days or longer. Accurate estimates of E_{FAOpm} could be predicted from E_{apan} data using a linear regression relationship. When compared with the A-pan, it is easier to install and operate the ETgage according to standard recommendations. The ETgage is also simpler and significantly cheaper than an automatic weather station and was shown to have potential to provide a good practical reference evaporation estimate. The study revealed that, for the data analysed, both sets of derived pan and ETgage factors showed seasonal trends, with values relatively lower in winter months than in summer months. The derived pan factors ranged from 0.85 in June to 1.01 in January. These pan factor values tally with the results of irrigation trials. The derived ETgage factors were slightly lower than corresponding FAO-based sugarcane crop coefficients. The greatest benefit of using data from an automatic weather station for the calculation of E_{FAOpm} is likely to be in situations when the crop is irrigated daily, as with drip irrigation.

Introduction

In Zimbabwe, estimates of sugarcane water requirements which are vital for irrigation planning, development, day-to-day water management, and crop yield forecasting, have usually been determined with reference to the evaporation from United States Weather Bureau, Class A evaporation pans (A-pan). While it has been routinely accepted that water loss from an A-pan is very closely related to water loss from a sugarcane crop (Thompson and Boyce, 1972; Cackett, 1984; Clowes and Breakwell, 1998), the suitability of the A-pan as a reference evaporation estimate for crops, has also been questioned (de Jager and van Zyl, 1989; Jensen *et al*., 1990; Schulze and Kunz, 1995).

In a number of comprehensive comparative evapotranspiration (ET) studies, the often erratic and poor performance of A-pans has been contrasted with the superior performance of the Penman Monteith (PM) approach (Jensen *et al*., 1990; Choisnel *et al*., 1992, cited by Allen *et al*., 1998). A panel of experts from the International Commission of Irrigation and Drainage, the World Meteorological Organization and the Food and Agricultural Organisation (FAO) have, therefore, recommended the adoption of the PM combination method as a new, globally valid standard for crop water requirement calculations (Allen *et al*., 1998).

The FAO PM approach accounts for differences in crop canopies and aerodynamic resistances, relative to a defined reference crop, within a 'crop coefficient' (K_c). K_c can be split into two factors which separately describe the evaporation from the soil surface, K_e, and the transpiration, K_{cb}, components. Under conditions of low relative humidity and/or high windspeeds, the aerodynamic differences between tall crops like sugarcane and the defined reference crop can be significant. In order to account for these differences, K_cs can be further adjusted for the influences of climatic conditions using an equation that contains crop height, wind speed and minimum relative humidity as variables (Allen *et al*., 1998).

An alternative methodology to using K_cs, is to use the PM equation in a one-step procedure for the direct calculation of ET because the surface and aerodynamic resistances in the PM equation are crop specific. This approach is being researched for sugarcane, for example, by McGlinchey and Inman-Bamber (1996). The one-step approach for sugarcane is, however, proving challenging and problems have been reported ([1] personal communication). It is pertinent to note that Pereira and Allen (1999) state that, due mainly to difficulties in describing changes in resistance and net radiation,

'the research community is probably some 10 to 15 years away from producing one-step procedures that are consistent, predictable and reliable'.

With this background and evidence that there is potential for deriving improved estimates of sugarcane ET, thereby benefiting irrigation water use efficiencies, a study was initiated to compare, for the south east lowveld of Zimbabwe, relationships between:

- the FAO PM reference evaporation estimates (E_{FAOpm})
- evaporation from A-pans (E_{apan}), and
- evaporation from a relatively simple commercially available atmometer device, called an ETgage which has been designed to mimic many of the evaporation characteristics of a plant (E_{etg}) (Asbell, 1999).

The ETgage was included in the study because literature (e.g. Broner and Law, 1980; Asbell,1999) had indicated that it has potential to give reference evaporation estimates comparable to those from a full automatic weather station (AWS), at a substantial reduction in cost and complexity.

In addition, ET estimates for sugarcane, derived using the state-of-the-art procedures presented in the FAO publication No.56 were used to derive monthly pan and ETgage factors. These factors can be used to relate data from these instruments to benchmark FAO-based estimates of sugarcane ET. This will help facilitate objective comparisons to be made between the water requirements of sugarcane and other, sometimes competing, crops.

The evaporation comparisons were based on 20 years of daily weather data collected at a manual weather station, three years of data from an automatic weather station and one years data from the ETgage atmometer device, all at the Zimbabwe Sugar Association Experiment Station (ZSAES). Data from pan factor irrigation trials were used in order to assess the pan factor values derived using the FAO-based ET estimates. The research methodology, results of the comparative studies and implications for irrigation water management are discussed in this paper.

Methodology

Weather data were recorded at the ZSAES which is located at latitude 21° 2.5' south and longitude 31° 57' east and altitude 420 m.a.s.l. The manual weather station (MWS) measurements which included radiation data were for the period from 1970 to 1990. Thereafter radiation data were not collected from the MWS because the Bellani pyranometer which had been used for the purpose broke and was not be replaced. The automatic weather station (AWS) was commissioned in April 1998, and the ETgage in February 2000.

Instrumentation and reference evaporation calculations

A Fortran 90 computer programme was written to calculate E_{FAOPM} according to procedures described by Allen *et al.* (1998). The options selected for the calculation of vapour pressures, the type of radiation instruments and the apparatus used for recording E_{apan} and E_{etg} are described as follows.

Manual Weather Station, E_{FAOpm}

For the weather data recorded manually, vapour pressures from wet and dry bulb readings recorded at 08:00h and 14:00h were averaged to estimate the average daily vapour pressure for the E_{FAOPM} calculations. Radiation was measured using a Bellani pyranometer. All instruments were installed according to standard recommendations (Doorenbos, 1976).

Manual Weather Station, E_{apan}

Two adjacent A-pans painted black inside (not standard according to FAO recommendations) and silver outside and covered with wire screens with a mesh size of 25 mm were read daily at 08:00h using a hook gauge, and the values averaged. No adjustment for the screening or black paint were made.

Manual Weather Station, E_{etg}

A single ETgage was read daily at 08h00 by recording the water level in a sight tube. A green canvas #30 vapor diffusion cover was used on the Etgage, which was installed according to standard recommendations (Asbell, 1999).

Automatic Weather Station, E_{FAOpm}

For data recorded using the AWS, average daily vapour pressure and saturated vapour pressure, based on relative humidity measurements recorded at ten second intervals using a Vaisala CS 500 air temperature and relative humidity sensor, were used for the daily E_{FAOPM} calculation. A LI-COR LI200X silicon pyranometer was used to measure solar radiation. The AWS was installed according to standard recommendations (Savage, 1998).

Evapotranspiration, pan factor and ETgage factor calculations

For the ET comparisons, the FAO methodology (Allen *et al.*,1998), which is also considered to be the most accurate estimate of sugarcane ET, was used as a benchmark (Equation 1).

$$ET_{FAOd} = E_{FAOpm}\, Kc_{(u2,RH)d} \qquad \text{Eq 1}$$

where ET_{FAOd} = FAO-based benchmark evapo-transpiration estimate for a 3 m tall full canopy sugarcane crop (mm/d)

$Kc_{(u2,RH)d}$ = FAO recommended sugarcane crop coefficient adjusted on a daily basis for influences of relative humidity and windspeed

$$= 1.25 + (0.04(u_2-2) - 0.004(RH_{min}-45))(h/3)^{0.3}$$

where u_2 = windspeed measured at a height of 2 m (m/s)

RH_{min} = minimum daily relative humidity (%)

h = crop height, taken as 3 m for sugarcane (m)

In order to:

- investigate the potential for refining pan and ETgage factors so that these instruments could be used to give ET estimates similar to benchmark ET_{FAOd} estimates

- observe whether there were any apparent seasonal trends in the pan and ETgage factors
- assess the derived pan factors in relation to existing pan factor recommendations and irrigation trial data, weather data recorded by the AWS during the period 1998 to 2001 were used to derive refined monthly pan factors. These were taken as the median monthly values of daily factors calculated according to Equation 2, *viz*.

$K_{pr} = ET_{FAOd} / E_{apan}$ Eq 2

where K_{pr} = refined pan factor to relate evaporation from an A-pan to sugarcane ET as estimated using the FAO methodology (Allen *et al.*, 1998)

E_{apan} = evaporation from a Class A evaporation pan (mm/d)

Similar calculations were used to derive refined monthly ETgage factors using data recorded during the period February 2000 to March 2001. The monthly ETgage factors were taken as the median monthly values of daily factors calculated according to Equation 3, *viz*.

$K_{etgr} = ET_{FAOd} / E_{etg}$ Eq 3

where K_{etgr} = refined ETgage factor to relate evapora tion from an ETgage to sugarcane ET as estimated using the FAO methodology (Allen *et al.*, 1998)

E_{etg} = evaporation from the ETgage (mm/d)

Results

A scatter plot showing comparisons between daily E_{apan} and E_{FAOpm} calculated using data recorded manually from 1970 to 1990 is shown in Figure 1. A second scatter plot showing the same data smoothed with a five day moving average is shown in Figure 2. The use of a moving average encapsulates all possible five day average values and is relevant as an appropriate representation of typical minimal irrigation application intervals, for most systems except drip. Similar scatter plots with E_{FAOpm} calculated using data recorded with the AWS from April 1998 to March 2001 are shown in Figures 3 and 4 respectively.

Both sets of data show similar trends, *viz*. the differences between E_{apan} and the E_{FAOpm} increase as the magnitude of the evaporation increases. For the months April to August (winter when evaporation is relatively low), the differences are small but during September to March (summer, when evaporation is higher), the differences can exceed 30%, (cf. Figure 4). From an irrigation management perspective, it is pertinent to note that the relationship between five day averaged values is much better than the relationship between daily values.

Using data from the AWS and the MWS resulted in two different linear regression relationships between five day average E_{apan} data and five day average E_{FAOpm} estimates, as shown in Table 1. Investigation of the Bellani pyranometer apparatus, which was used for the MWS radiation measurements, revealed that:

- the reading is temperature dependent, therefore

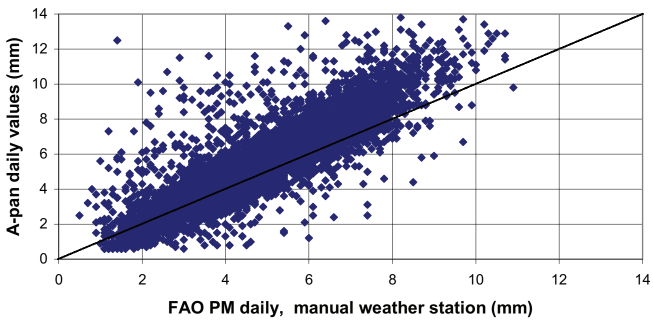

Figure 1. Scatter plot showing Eapan vs EFAOpm daily values, data were recorded at the manual weather station.

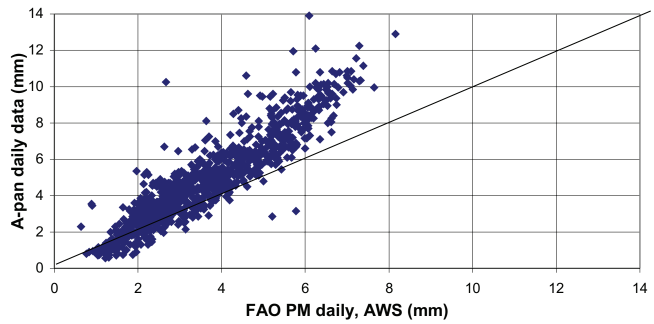

Figure 3. Scatter plot showing Eapan vs EFAOpm daily values, data were recorded by the automatic weather station.

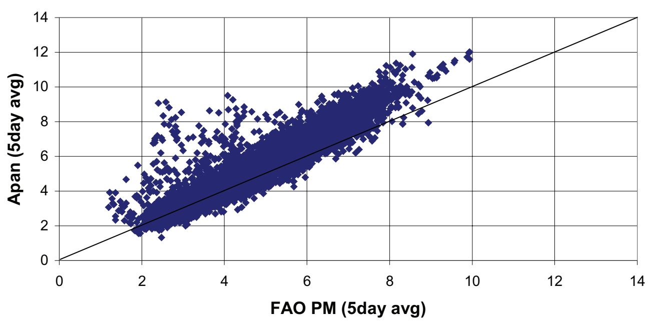

Figure 2. Scatter plot showing Eapan vs EFAOpm , values are five day moving averages, data were recorded at the manual weather station.

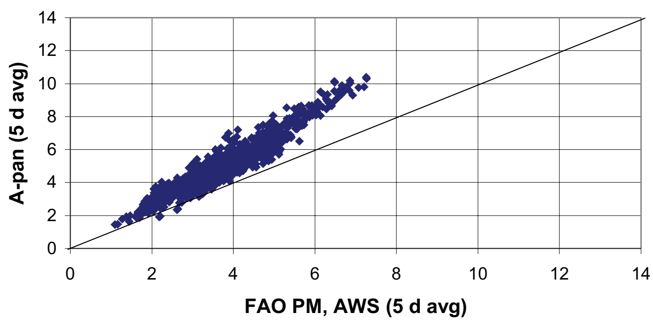

Figure 4. Scatter plot showing Eapan vs EFAOpm, values are five day moving averages, data were recorded by the automatic weather station.

- it needs to be calibrated in the field against a solarimeter in a special calibration programme that covers different seasons, and
- its accuracy is ± 10 to 20% (Doorenbos, 1976).

At ZSAES, it seems that only one calibration equation was used, despite large variations in mean air temperatures. As the Bellani pyranometer is no longer at ZSAES, the derivation of temperature dependent calibration relationships in order to 'correct' all the historical radiation data was not feasible. The inaccuracies in the Bellani pyranometer radiation measurements would have translated to similar inaccuracies in the estimates of E_{FAOpm}. For this reason, E_{FAOpm} and associated relationships derived using data from the MWS were considered unreliable.

For the relatively short period for which concurrent ETgage, E_{apan} and AWS data were available, *viz*. within 1 February 2000 to 22 March 2001, E_{etg} data and E_{apan} data were compared with E_{FAOpm} estimates derived from the AWS. Scatter plots of these comparisons are shown in Figures 5 and 6, and comparative statistics for the five day moving averages are shown in Table 2. When compared to the average of two A-pans read with a hook gauge, the resolution of the reading from the single ETgage, read from a sight tube, was relatively coarse at a daily time scale, *viz*. it was apparent from the data that the data-recorder *normally* read the site tube to the nearest 1.0 mm (cf. Figure 5). However, this had little effect on the five day averages because the sight tube readings on the ETgage were inter-dependent. Compared to the E_{apan} data, E_{etg} data were much closer to E_{FAOpm} estimates. The RMSE, for E_{etg} compared to E_{FAOpm} was 0.98 mm and the difference between the means, 13.6%, compared to a RMSE of 1.3 mm and difference between means of 32.7% for the corresponding comparison between E_{apan} and E_{FAOpm}. However, if E_{apan} readings were used as input to a linear regression model used to calculate an estimate of E_{FAOpm}, the model performance was excellent, in fact, better than a similar linear regression model using E_{etg} data, *viz*. the RMSE is lower, a greater proportion of the RMSE is unsystematic and the index of agreement, d, is closer to 1.0 (cf. Table 2). This indicates that for the period under consideration, the A-pan was an excellent *predictor* for E_{FAOpm}, in fact better than the ETgage.

The refined median monthly A-pan and ETgage factors calculated to relate data from these instruments to ET_{FAOd} (cf. Equations 2 and 3) are given in Table 3. Both sets of factors show a definite seasonal trend, being lower in winter than in summer. The pan factor values compare well with irrigation trial data collected at ZSAES, which are shown in Figure 7. The data in Figure 7 are from the irrigation of full canopy sugarcane using various pan factors to determine irrigation intervals. These trials showed that optimum ET estimates result from pan factors which are greater than 0.8 and less than 1.0, but gave little information on how pan factors may vary throughout a season. It is likely, therefore, that taking cognisance of the seasonal trends in the pan factors shown in Table 3 may lead to improved estimates of sugarcane ET, however, an appropriate trial is needed to test this hypothesis. When considering the likely gains in irrigation efficiency from slight under-irrigation (Lecler, 1998), the use of a constant pan factor of 0.85 is also well justified. The derivation of median monthly FAO K_cs ($K_{c(u2,RH)m}$), shown in Table 3, should facilitate the use of E_{apan} as a predictor of E_{FAOpm} which can then be used without windspeed and relative humidity data to estimate ET_{FAOd}. A further independent data set is, however, needed in order to

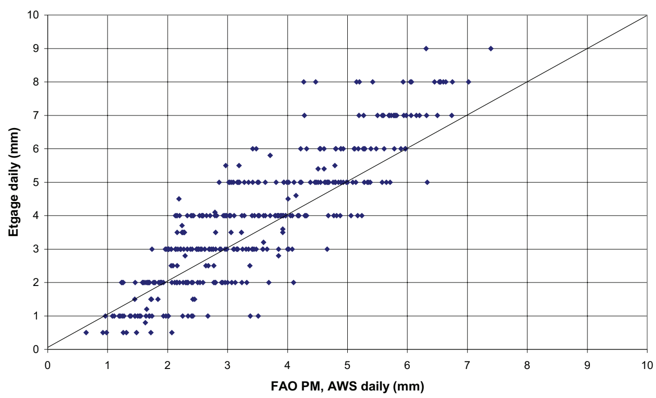

Figure 5. Scatter plot showing Eetg vs EFAOpm, daily values.

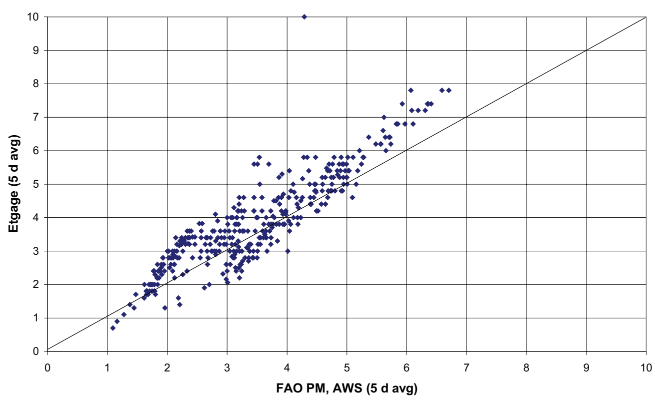

Figure 6. Scatter plot showing Eetg vs EFAOpm, values are five day moving averages.

Table 1. Regression statistics for linear regression equations used to predict E_{FAOpm} from E_{apan}, (y = bx + a), showing differences between relationships derived using the AWS and the MWS*.

Dependent Variable (y)	Independent Variable (x)	Slope (b)	Constant (a)	Std Error of E_{FAOPM} estimate (SEy)	Correlation Coefficient (Pearson's r)
E_{FAOpm} MWS	E_{apan} 1970 -1990	**0.734**	**0.82**	0.57	0.92
E_{FAOpm} AWS	E_{apan} 1998 -2001	**0.676**	**0.31**	0.34	0.95

*All units except b and r are mm/d

Table 2. Quantitative measures of five day reference evaporation comparisons for concurrent data from the ETgage, the AWS and the A-pan, *viz.* within 1 February 2000 to 22 March 2001.**

Name of P	Mean E_{FAOpm}	Mean P	N	a	b	RMSE	$RMSE_u$	$RMSE_s$	d	r
E_{apan}	3.44	4.57	370	-0.3	1.4	1.3	0.42	1.23	0.8	0.97
E_{etg}	3.44	3.91	370	0	0.9	0.98	0.85	0.49	0.88	0.85
E_{FAOpm} predicted from E_{apan}	3.44	3.44	370	0.19	0.94	0.29	0.28	0.07	0.99	0.97
E_{FAOpm} predicted from E_{etg}	3.44	3.44	370	0.95	0.72	0.64	0.54	0.34	0.91	0.85

** Terms N, b, d and r are dimensionless, while remaining terms have units of mm/d

RMSE = root mean squared error

$RMSE_u$ and $RMSE_s$ = 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)

a (intercept) and b (slope) of a least squares regression between P as the dependent variable (predicted) and E_{FAOpm} as the independent variable (observed)

N = number of data points

Table 3. Derived full canopy 'pan factors', 'ETgage factors' and median monthly FAO-based sugarcane crop coefficient ($K_{c(u2,RH)m}$) values for the south east lowveld of Zimbabwe.

Factors	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Refined "Pan Factors" (K_{pr})	1.01	1.01	0.96	0.96	0.90	0.85	0.88	0.87	0.91	0.96	0.96	0.97
Median Monthly FAO $K_{c(u2,RH)m}$	1.22	1.18	1.18	1.21	1.25	1.23	1.25	1.27	1.30	1.31	1.29	1.25
Refined "ETgage Factors" (K_{etgr})	1.11	1.03	1.15	1.04	0.95	0.90	1.06	0.87	1.02	1.12	1.11	1.21

verify this approach, and to compare it with the use of pan factors alone.

Conclusions

- There is a large difference between E_{apan} data and equivalent estimates of E_{FAOpm}, especially when the A-pan reads above 8 mm. At such high evaporation values, E_{apan} can exceed E_{FAOpm} by more than 30 %. However, the relationship between the E_{apan} and E_{FAOpm} was very consistent, and E_{FAOpm} estimates were reliably predicted from E_{apan} data using a linear regression relationship.
- Differences between the E_{FAOpm} : E_{apan} relationship using data collected from instruments read manually, and data recorded by the AWS were likely due to:
  - the different time periods for which data were recorded, but more importantly,
  - the likely errors in the manually recorded radiation data.

  E_{FAOpm} estimates, calculated using data from the AWS were, therefore, considered more reliable for deriving E_{FAOpm} : E_{apan}, E_{FAOpm} : E_{etg} and associated relationships.
- When considering general uncertainties in irrigation water budgeting, including rainfall measurement and effectiveness, soil water properties, estimates of irrigation water applications, crop canopy conditions, nutrition status and also irrigation (non-) uniformity, the relative errors in ET estimates arising from the use of the ETgage and/or the A-pan are not likely to be significant in most practical applications. This is especially so if appropriate locally calibrated ETgage or pan factors are used to adjust recorded E_{apan} or E_{etg} values to associated sugarcane ET estimates, and the ET estimates are for periods of five days or longer.

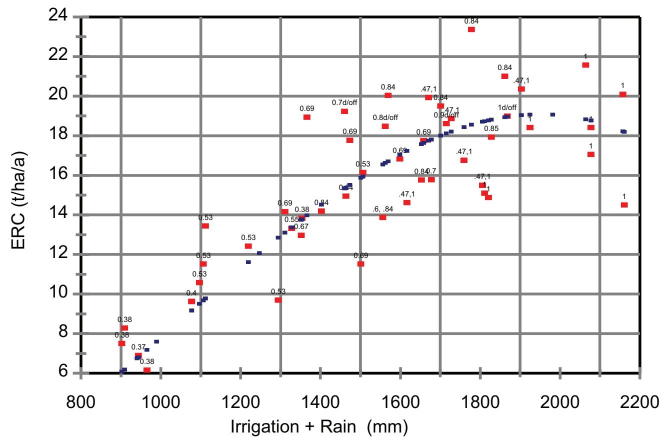

Figure 7. Estimated Recoverable Crystal (ERC) vs total water (irrigation + rain) for various 'pan factors', shown as data labels.

- The average of two A-pans read with a hook gage in a research environment, proved a better predictor than E_{etg} in a linear regression model to estimate E_{FAOpm}. Nevertheless, the relative simplicity, low and simple maintenance, standardisation and robustness of the ETgage are likely to prove it a more reliable and practical instrument in many on-farm/estate contexts. There is evidence, however, that the use of standard FAO-based sugarcane crop coefficients with E_{etg}, will lead to slight over-estimation of ET_{FAOd}. Refined monthly ETgage factors, suitable for use in the lowveld of Zimbabwe, have been derived in order to adjust E_{etg} to give better estimates of ET_{FAOd}. These new derived ETgage factors need to be tested on independent data once more E_{etg} data become available.
- Refined monthly pan factors, suitable for use in the lowveld of Zimbabwe were derived using data recorded by the AWS. These refined pan factor values showed a definite seasonal trend and were relatively higher in summer than in winter. The values, which ranged from 0.85 in June to 1.01 in January tally with results from irrigation pan factor trials. Taking cognisance of the apparent seasonal trend in pan factor values which was revealed in this study, may lead to improved irrigation water use efficiencies.
- World wide research studies show that the 'Rolls Royce' method for the prediction of crop ET is likely to be the use of data from an AWS to determine E_{FAOpm} combined with the FAO recommended K_cs adjusted for influences of windspeed and relative humidity. To benefit from this technology, will, however, require careful application of a good water budget and regular maintenance, calibration and representative placement of the AWS sensors. Drip irrigation water management, which entails daily irrigation water applications, is likely to benefit the most through the use of AWS data.

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