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WATER USE BY SUGARCANE

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Interest in the consumptive use of water by crops was stimulated when Penman[50] showed in 1948 that evaporation from plants freely supplied with soil moisture was dependent entirely upon measureable meteorological factors. Measurements of "potential evapotranspiration" from sugarcane followed shortly, the work of Fuhriman and Smith[29] in Puerto Rico being reported in 1951, and that of Cowan and Innes[23] in Jamaica in 1955. Lysimetric work with sugarcane in South Africa began in 1959 and results were first reported by Pearson, Cleasby and Thompson[49] in 1961. Estimates of water use by sugarcane crops were required to facilitate scheduling of irrigation.

In order that the term "potential evapotranspiration" should be meaningful, it as necessary to establish the soil conditions under which water would be "freely available" to a crop. It was also pertinent to know how much water could be removed from a soil profile before crop growth was adversely affected. For these reasons the comprehensive classification of soils in the Natal cane belt, carried out by Beater[12, 13, 14] and others from 1944 onwards, was particularly important. The subsequent studies of the soil moisture relationships of Natal soils, considered first by Maud[48] in 1962, provided the necessary information regarding specific soil types. The dynamic relationships between soil moisture and the root distribution of a sugarcane crop were studied by means of a neutron probe in the field, and the first results were reported by Gosnell and Thompson[35] in 1965.

When remaining soil moisture is no longer "freely available" to the crop, actual apotranspiration falls below he potential rate. After Denmead and Shaw[24] reported in 1962 that the availability of soil moisture to a crop was a function of the evaporative demand of the atmosphere, work was carried out to study this relationship for sugarcane growing in Natal soils, and results were given by Hill[41] in 1965.

Since moisture stress, particularly for a vegetative crop such as sugarcane, implies reduced growth and therefore lower yields, the relationship between water use and crop yield also needed to be studied. The results of field experiments, in which different amounts of irrigation water were applied to various treatments, were therefore accumulated, and the possibility of a linear relationship was initially oposed by Thompson and de Robillard[63] in 1968.

In this review an attempt will be made to collate the data which have become available for sugarcane over the past two decades concerning potential evapotranspiration, moisture availability in sugar belt soils, actual evapotranspiration and the relationship between water use and crop yield. The purpose of this exercise is primarily to focus attention on those aspects of water use by the crop which require further investigation.

Symbols and abbreviations which appear frequently in the text of this paper are as follows:

E_o = evaporation from a Class A Pan
E_t = evapotranspiration
E_{pt} = potential evapotranspiration
E_a = actual evapotranspiration
FAM = freely available moisture
TAM = total available moisture

otential evapotranspiration

The loss of water by evaporation from a field of sugarcane may conveniently be considered in terms of the five stages illustrated in Fig. 1. The stages are:

1. Fallow land which may either be bare or covered with weeds; newly planted land prior to the emergence of the crop; and ratoon fields before leaf emergence of the new crop
2. Partially canopied sugarcane
3. Fully canopied, erect sugarcane
4. Lodged sugarcane
5. Fields that are being dried off prior to harvesting.

Although potential evapotranspiration refers to consumptive use by the crop when it is freely supplied with water, it has been convenient to include Stage 5, when the crop is deliberately subjected to moisture stress, in this section of the review.

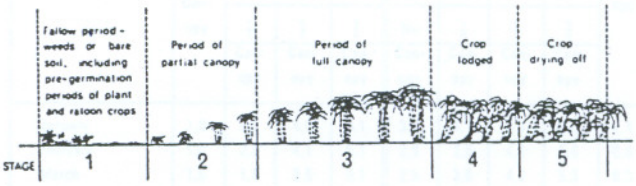
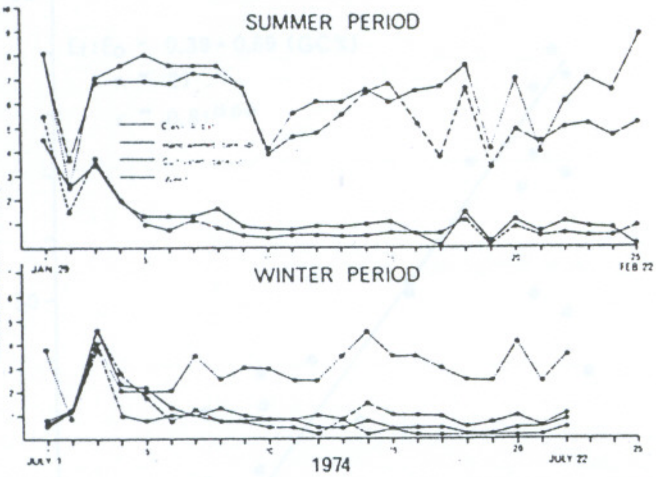


FIG. 1: Diagrammatic representation of five successive stages in the life of a sugarcane crop.

Stage 1 — Fallow land or bare soil

It seems now to be generally accepted that logical scheduling of irrigation can best be accomplished by conducting a soil moisture profit and loss account[62, 63]. The necessity for estimating water loss from fallow land can be avoided if rainfall can be supplemented by excess irrigation water early in the development of the plant crop to ensure that at some definite time the soil profile is known to be saturated. However, data are available[15, 58] concerning evaporation from fallow or bare land, and it is useful to have an estimate of the total water lost by evaporation during an entire crop so that yield can be expressed in terms of the amount of effective water used. Effective water may be defined as the sum of all amounts of water lost by evaporation from the soil surface and by transpiration from the crop.

The amount of evaporation which takes place from a bare soil depends upon the frequency of wetting because of the self-mulching effect which surface drying has on water loss, and the rapidity with which the mulching effect takes place depends on the evaporative demand of the atmosphere. This is illustrated in Figs 2a and 2b by means of data from weighing lysimeters at Pongola[15]. Referring to Fig 2a it can be seen that evaporation from both hand-weeded and cultivated bare soil was significant on January 29 when 41 mm of rain fell, and for the ensuing three days, but for the remainder of the 24-day dry period which followed, evaporation was generally less than 1 mm per day. In July, 17 mm of rain fell on the 1st, 10 mm on the 2nd and 3 mm on the 3rd. No further rain fell during the ensuing 19 days. It can be seen in Fig. 2b that, during this period of low evaporative demand, evaporation from bare soil matched Class A Pan evaporation for the first five days of July before the mulching effect reduced daily losses to an amount generally less than 1 mm per day.



G. 2: Evaporation losses from bare soil (undisturbed and cultivated), weeds and Class A pan during dry periods following rain in January and July, 1974.

The effects of weeds on water loss from the soil are also illustrated in Figs. 2a and 2b. During five successive 5-day periods from 29 January to 22 February, evapotranspiration from the weed-covered lysimeter was 98%, 95%, 90%, 75% and 75% of evaporation from a Class A Pan on a nearby site. In contrast, water losses from drought stricken weeds in July were little different from those which took place from bare soil. The total evaporation over the 22-day period from July 1 to July 22 was 21 mm from the hand-weeded soil, 18 mm from the cultivated bare soil, and 22 mm from the weedy plot.

Reliable lysimeter data were obtained on 122 days during the period from November 1973 to March 1974, and the total amounts of evaporation for these days were as follows:

Hand weeded lysimeter	:	238 mm
Cultivated bare soil	:	228 mm
Weed-covered lysimeter	:	491 mm
Class A Pan	:	729 mm

Soil moisture content in the surface 18 cm of a Rydalvale clay loam at Mount Edgecombe [56] was determined daily by gravimetric methods from January 1962 to January 1963. The experimental area was exposed to natural rainfall but no irrigation water was applied. The results were used to calculate the data given in the "No canopy" columns of Table1 [5] some allowance being made for the increased frequency of wetting which would occur under irrigated conditions. As can be seen, average losses from a trash-covered soil were always less than those from a bare soil.

Table 1

ESTIMATES OF EVAPOTRANSPIRATION (E_t) FOR THE SOUTHERN AREAS

Month	Mm per day								
	Trash layer +				Bare soil +				Full Canopy
	No Canopy	¼ Canopy	½ Canopy	¾ Canopy	No Canopy	¼ Canopy	½ Canopy	¾ Canopy	
January	0,8	2,0	3,6	4,8	2,5	3,3	4,3	5,3	6,1
February	0,8	2,0	3,3	4,6	2,5	3,3	4,3	5,1	5,8
March	0,8	1,8	3,0	4,1	2,0	2,8	3,6	4,3	5,1
April	0,5	1,3	2,3	3,0	1,5	2,0	2,8	3,3	3,8
May	0,5	1,3	1,8	2,3	1,3	1,8	2,0	2,5	3,0
June	0,5	1,0	1,5	1,8	0,8	1,3	1,5	2,0	2,3
July	0,5	1,0	1,5	2,0	1,0	1,5	1,8	2,0	2,5
August	0,5	1,0	1,5	2,0	1,0	1,5	1,8	2,0	2,5
September	0,5	1,3	2,3	3,0	1,5	2,0	2,8	3,3	3,8
October	0,8	1,5	2,0	2,8	1,5	2,0	2,5	3,0	3,6
November	0,8	1,8	2,8	3,8	2,0	2,8	3,3	4,1	4,8
December	0,8	2,0	3,0	4,1	2,3	3,0	3,8	4,6	5,3

Evaporation from a bare soil varies not only according to the frequency of wetting and the evaporative demand of the atmosphere, but also between soil types. Total evaporation from undisturbed soil cores (10 cm diameter; 7,5 cm deep) during 80 hours of natural exposure following saturation and draining at a tension of 0,1 bar, was measured at Shakaskraal [58] in August 1964, with the following results:

Clansthal sand	3,7 mm	Shortlands clay	7,5 mm
Fernwood sand	4,5 mm	Inanda sandy clay	9,1 mm
Rydalvale clay	6,1 mm	Milkwood sandy clay	10,2 mm
Cartref sand	7,1 mm	Waldene sandy clay loam	11,3 mm

Differences in evaporation from different soils in the cane belt are not surprising in view of the wide range of textural and structural characteristics that occurs. Heat capacities and temperatures also differ, and contributory to the latter must be the differences in reflectivity of various soil surfaces [2]. A dry Clansthal sand was found to reflect 28% of incident radiation, but a dry Shortlands clay reflected only 15%. Furthermore, the mean reflection coefficient for eleven soil series was 0,21 when they were dry, but only 0,15 when they were wet.

To account for the higher evaporative demand in the northern areas of the South African cane belt, the estimates of evaporation from trash-covered and bare soils shown in Table 1 for the southern areas were increased to the amounts which are shown for each month in the "No canopy" columns of Table 2 [5]. It is reassuring to note that the mean evaporation measured in a lysimeter experiment during the 18 days immediately following planting on 12 November, 1967 [57], was 2.5 mm per day, the same as the estimate given for November in the "Bare soil", "No canopy" column of Table 2.

Table 2

ESTIMATES OF EVAPOTRANSPIRATION (E_t) FOR THE NORTHERN AREAS

Month	Mm per day								Full Canopy
	Trash layer +				Bare soil +				
	No Canopy	.30 Et ¼ Canopy	.60 Et ½ Canopy	.80 Et ¾ Canopy	.40 Et No Canopy	.55 Et ¼ Canopy	.70 Et ½ Canopy	.85 Et ¾ Canopy	
January	1,0	2,3	4,0	6,1	3,0	4,1	5,3	6,6	7,6
February	1,0	2,0	4,1	5,1	2,8	3,8	4,8	5,6	6,6
March	1,0	1,6	3,8	5,1	2,5	3,6	4,6	5,3	6,3
April	0,8	1,5	2,8	3,8	2,0	2,5	3,6	4,1	4,8
May	0,8	1,5	2,3	2,8	1,5	2,3	2,5	3,0	3,8
June	0,8	1,5	2,0	2,8	1,5	2,3	2,5	3,0	3,6
July	0,8	1,3	2,0	2,5	1,3	1,8	2,3	2,8	3,3
August	0,8	1,3	2,5	2,8	1,5	2,3	2,8	3,6	4,1
September	1,0	2,3	3,6	4,8	2,5	3,6	4,1	5,1	6,1
October	1,0	2,3	3,6	4,8	2,5	3,6	4,1	5,1	6,1
November	1,0	2,3	3,8	5,1	2,5	3,6	4,6	5,3	6,3
December	1,0	2,5	4,1	5,1	2,8	3,8	4,8	5,6	6,6

Stage 2 — Partial Canopy

Evapotranspiration (E_t) increases progressively as the crop foliage develops and intercepts more radiant energy, and as root proliferation through the soil profile enables the crop to exploit moisture at depth. The ability of weeds to remove moisture from an appreciable depth of soil has already been illustrated in Fig 2a. Results for the plant and first ratoon crops from the lysimeter experiments at Shakaskraal and Pongola [57], where canopy development was measured by means of vertical sightings after the method described by Cackett [19], have provided the data shown in Fig 3.

The linear regression equation indicates that evaporation in the absence of any crop foliage was 39% of Class A Pan evaporation (E_0), and that evapotranspiration became equal to E_0 when the estimate of canopy formation or vertical ground cover was 88%. In both of the lysimeter experiments from which these data were obtained, the cane rows ran approximately in a north-south direction. In a field where the rows have an east-west orientation, less radiant energy would be intercepted, and the E_t/E_0 ratio would probably increase more slowly as the crop canopy developed, and a 1:1 ratio might only be reached as the estimate of vertical ground cover approached 100%.

In view of the relatively short duration of the period of incomplete canopy, or until E_t is the same as E_0, the assumption of a linear increase in the E_t/E_0 ratio should introduce only small errors into estimates of total water use by the crop. The data in the columns of Tables 1 and 2 which are headed "¼ canopy", "½ canopy" and "¾

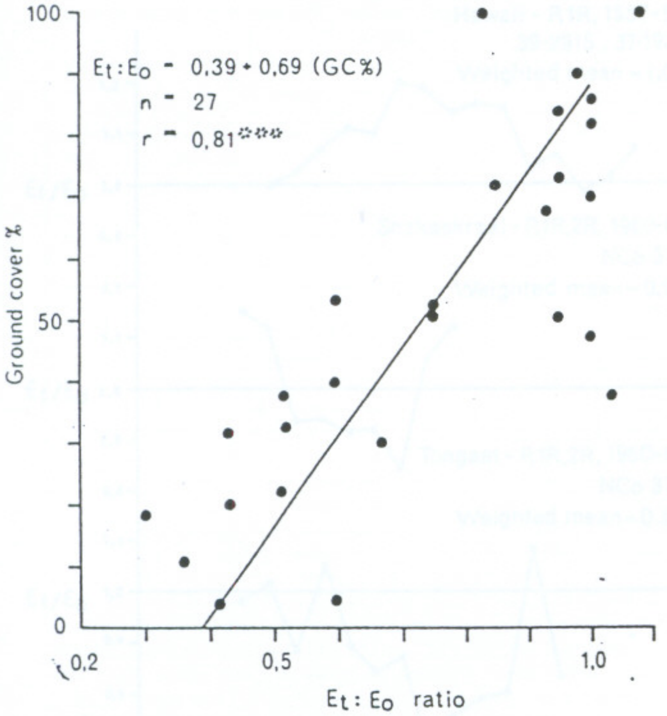


FIG. 3: Relationship between vertical ground cover % and the Et/Eo ratio.

canopy" were calculated on the basis that E_t would increase linearly between the amount of evaporation from a bare soil surface and evapotranspiration from a fully canopied crop, according to the proportion of vertical ground cover which had developed, for each month of the year.

The duration of the period of incomplete canopy varies according to variety, row width and the time of the year when the crop starts. Ratoon crops of variety NCo 6 starting in September, October or November in rows 1,37 m apart, took approximately 160 days to reach full canopy on sites at Mount Edgecombe and Shakaskraal [57]. The same variety in rows 1,52 in. apart at Pongola formed a full canopy in about 120 days when the crop started in October or November [57]. However, on average at both Shakaskraal and Pongola E_t first equalled Eo after only 90 days. In Mauritius variety M147/44 reached full canopy after about 115 days when crops started in June, July or August, but after only 70 days when the third ratoon crop started in September [37]. Based on lysimeter data obtained in Mauritius it is suggested that during the period of incomplete canopy, E_t should be estimated as 0,4 x E_0.

The lysimeter data from Hawaii $_{20}$ showed that E_t increased progressively until it equalled E_0 after about 90 days when the crop was planted in July, after about 125 days when it was planted in April, and after about 190 days when it was planted in March. During the 12 days following the harvesting of the previous crop, water loss from hydraulic load cell lysimeters in Hawaii [27] was 33% of Class A Pan evaporation. In the Philippines [28] E_t was estimated to be 16% of Eo over the period when the crop was 61 — 90 days old, 85% when it was 91 — 120 days old, and 104% when it was 121 — 150 days old.

Stage 3 — Full Canopy

Evapotranspiration during this stage of crop growth consists almost entirely of transpiration. It was shown in Jamaica [23] that evaporation from an open water surface placed beneath the crop canopy was only 10% of that from a freely exposed surface. Taking into account the mulching effect which further inhibits evaporation from the soil surface, it may reasonably be assumed that evaporation on average comprises less than 5% of E_t during the period of full canopy.

It is during this stage of crop development that Penman's [50] physical explanation of water loss from the crop area becomes pertinent, and a number of methods have been described [11, 67, 18, 68] to relate potential evapotranspiration (E_{pt}) to meteorological factors. Each of these proposals is an attempt to estimate E_{pt} from readily available meteorological data, ranging from air temperature measurements alone [11] to a combination of radiation, temperature, wind and humidity data [50].

Further research into the mechanisms of moisture loss by transpiration from a [illegible] led to the construction of formulae [18, 48] which were intended to express E_{pt} more precisely. Data from the lysimeter experiments at Shakaskraal and Pongola were used to test the adequacy of the most comprehensive equation [48] for sugarcane. The average roughness length of sugarcane variety NCo 376 was found from wind profile measurements to be about 12,6 cm, and the surface resistance of the crop foliage was calculated from Shakaskraal data to be 0,75 sec/cm for most of the period of full canopy. When these values were used in the formula to calculate daily E_t at Pongola, good agreement was obtained with measured values [81]. (For 208 sets of daily figures the correlation coefficent was 0,91.)

Although calculated values of Ept were found to be reasonably accurate, all of the work done with sugarcane in South Africa since 1958 has shown that potential evapotranspiration from a fully canopied crop can most easily and reliably be estimated from Class A Pan open water evaporation. This is illustrated in Fig. 4, where mean weekly results from Shakaskraal (first ratoon crop) and Pongola (plant and first ratoon crops) are shown [3, 57]. Deviations about the mean E_t/E_0 ratios for each crop (0,98; 0,98 and 0,96) were not excessive, but there was a tendency for values to be consistently below the mean during the winter months of June, July and August at Pongola. The estimates of E_t given in the columns headed "Full canopy" in Tables 1 and 2 are based on mean Class A Pan evaporation for the southern and northern areas, and similar data can be provided for any site close to a meteorological station for which a reasonably long history of recording exists. There are 32 stations throughout the cane areas of South Africa and Swaziland from which evaporation data have been obtained for a number of years [7].

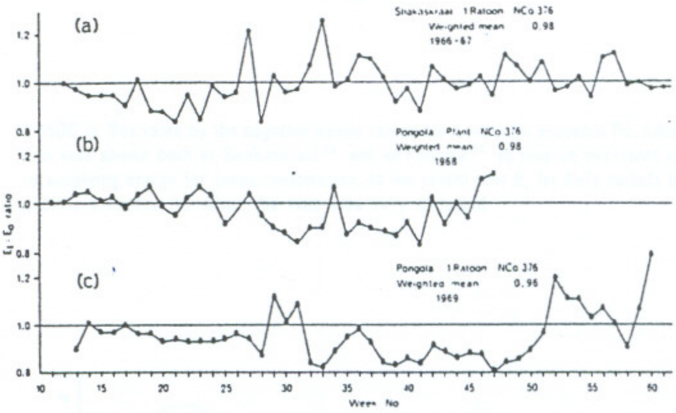


FIG. 4: Mean weekly Et/Eo ratios obtained from lysimeter experiments at Shakaskraal and Pongola.

Monthly data obtained by means of non-weighing lysimeters at Shakaskraal and Tongaat [85, 55], and calculated figures for Hawaii [21], Mauritius [38] and Argentina [28], show that a mean E_t/E_0 ratio close to 1,0 has been obtained under a wide range of climates and with several different varieties of sugarcane (see Fig. 5). The Hawaiian data are based on measurements from a Class A Pan elevated to the height of the crop canopy, whereas the remainder refer to pans located in the standard manner in a meteorological station. The South African results and those from Mauritius indicate lower E_t/E_0 ratios for the periods of full canopy in ratoon crops compared with plant cane. The weighted mean ratios for the three sites in Mauritius were 0,99 for plant cane, 0,90 for first ratoons and 0,91 for second ratoons. In the subsequent more precise experiment at Shakaskraal the mean ratio for the period of full canopy in the plant crop was 0,99 and for the first ratoon it was 0,98 [57]. Comparable results obtained at Pongola were 0,98 for plant and 0,96 for first ratoon cane [57].

Even on a daily basis during the period of full canopy in a plant crop at Pongola, the E_t/E_0 ratio was satisfactorily and consistently close to 1,00 [4]. For 126 days when the crop was erect and E_0 exceeded 4 mm, the mean E_t/E_0 ratio was 0,99 ± 0,16 [57], and the correlation coefficient between E_t and E_0 was 0,84.

Open water evaporation varies according to the construction, colour and location of the measuring tank or pan. The mean evaporation from a Symons tank at Mount Edgecombe over the 10-year period from 1966 to 1975 was 3,57 mm per day, whereas the comparable figure for a Class A Pan was 4,41 mm per day [57]. It is thus clearly fortuitous that potential evapotranspiration from a fully canopied sugarcane crop and Class A Pan evaporation are similar. Hourly measurements of E_t and E_0 at Pongola [4] showed that pan evaporation in fact lagged consistently behind crop evapotranspiration during the day as shown in Fig. 6, primarily because the heat capacity of the pan and its contents was so much bigger than that of the crop canopy.

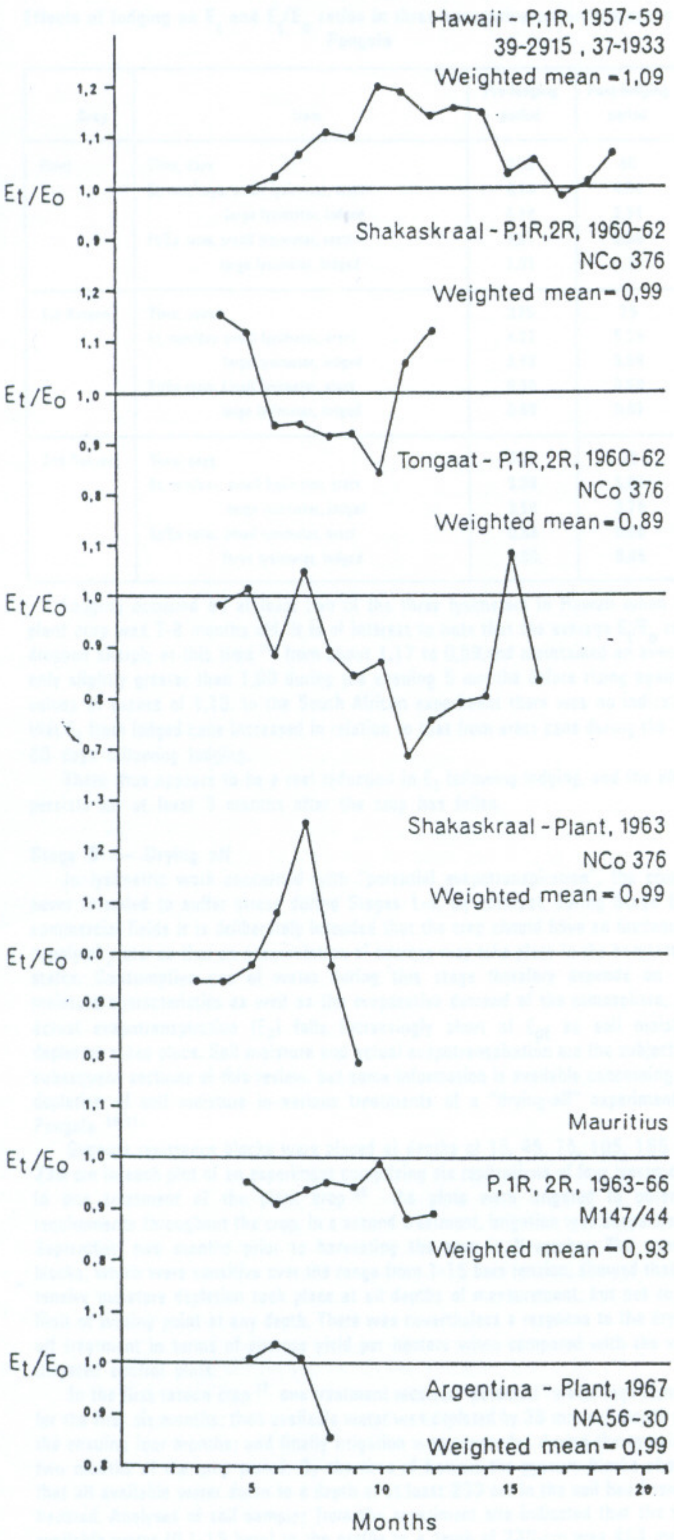


FIG. 5: Mean monthly Et/Eo ratios Hawaii, South Africa, Mauritius and Argentina.

The hourly energy balance was also studied at Pongola[4]. Total incoming shortwave radiation (RI), net radiation (R_n), evapotranspiration (E_t) and soil heat flux (S) were measured, whilst the sensible heat flux of the air (A) was calculated from:

$$R_n = Et + S + A$$

Typical data for a cloud-free day (12 March, 1968) are shown in Fig. 7. The heavy dependence of E_t on net radiation is apparent, but the contribution of advected heat energy to latent heat of vaporization (E_t) during the afternoon period from 15h00 to 19h00 is illustrated by the negative hourly values for A when E_t exceeded Rn. Advection was shown both at Shakaskraal[58] and at Pongola[57] to play an important role in supplying energy for evapotranspiration, to the extent that E_t for daily periods frequently exceeded Rn when the crop was fully canopied.

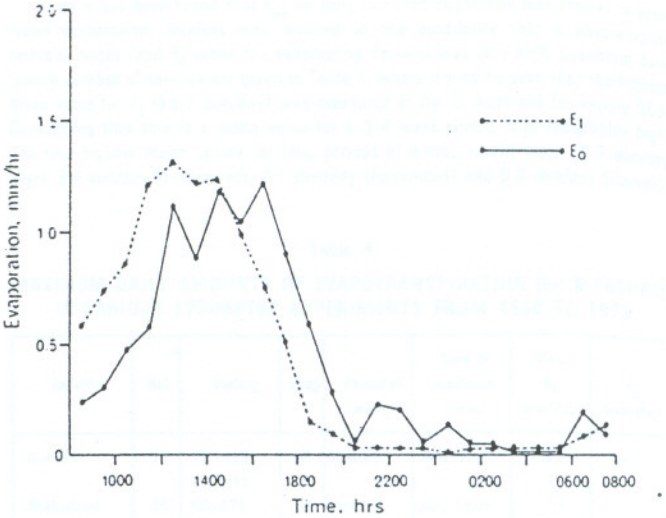


FIG. 6: Hourly amounts of evapotranspiration (Et) and Class A Pan evaporation (Eo) on 6-7/2/68.

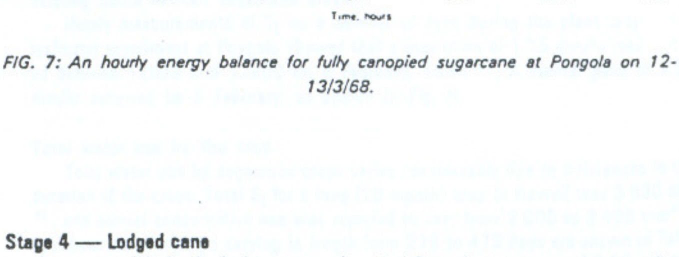


FIG. 7: An hourly energy balance for fully canopied sugarcane at Pongola on 12-13/3/68.

Stage 4 — Lodged cane

It was possible in the lysimeter experiment at Pongola to compare consumptive use of water during the period of full canopy before and after the cane in a large lysimeter lodged[60]. The crops in small, weighed lysimeters (244 cm x 152 cm surface area) were held erect by means of barbed wire supports, whereas those in a large (0,0405 ha) unweighed lysimeter lodged freely at certain times in the plant, first ratoon and second ratoon crops. The data are given in Table 3. Average E_t in the small lysimeters, where the cane was held erect, during the periods when lodging occurred in the large lysimeters, was 4,76 mm per day. The average water loss from the large lysimeter containing lodged cane over the same periods was 3,56 mm per day. Lodging thus appeared to cause a 25% reduction in consumptive use of water. Whereas the E_t/E_o ratio for the small lysimeters was 0,93 during the periods of lodging, that in the large lysimeters with lodged cane was only 0,70.

Table 3

Effects of lodging on E_t and E_t/E_o ratios in three successive sugarcane crops at Pongola

Crop	Item	Pre-lodging period	Post-lodging period
Plant	Time, days	230	80
	Et, mm/days, small lysimeter, erect	4,16	4.04
	large lysimeter, lodged	4,14	3,34
	Et/Eo ratio, small lysimeter, erect	1,01	0,94
	large lysimeter, lodged	1,01	0,78
1st Ratoon	Time, days	325	75
	Et, mm/day small lysimeter, erect	4,22	5,28
	large lysimeter, lodged	3,92	3,59
	Et/Eo ratio, small lysimeter, erect	0,96	0,99
	large lysimeter, lodged	0,89	0,67
2nd Ratoon	Time, days	200	79
	Et, mm/day, small lysimeter, erect	3,96	5.00
	large lysimeter, lodged	3,58	3,76
	Et/Eo ratio, small lysimeter, erect	0,88	0,86
	large lysimeter, lodged	0,80	0,65

Lodging occurred on at least two of the three lysimeters in Hawaii when the plant crop was 7-8 months old. It is of interest to note that the average E_t/E_o ratio dropped sharply at this time [20] from about 1,17 to 0,89,and maintained an average only slightly greater than 1,00 during the ensuing 5 months before rising again to values in excess of 1,10. In the South African experiment there was no indication that E_t from lodged cane increased in relation to that from erect cane during the 75-80 days following lodging.

There thus appears to be a real reduction in E_t following lodging, and the effect persists for at least 3 months after the crop has fallen.

Stage 5 — Drying off

In lysimetric work concerned with "potential evapotranspiration", the crop is never intended to suffer stress during Stages 1-4. By contrast, during Stage 5 in commercial fields it is deliberately intended that the crop should have an inadequate supply of water so that an accumulation of sucrose may take place in the harvestable stalks. Consumptive use of water during this stage therefore depends on soil moisture characteristics as well as the evaporative demand of the atmosphere, and actual evapotranspiration (E_a) falls increasingly short of E_{pt} as soil moisture depletion takes place. Soil moisture and actual evapotranspiration are the subjects of subsequent sections of this review, but some information is available concerning the depletion of soil moisture in various treatments of a "drying-off" experiment at Pongola [59, 17].

Gypsum resistance blocks were placed at depths of 15, 45, 75, 105, 165 and 230 cm in each plot of an experiment comprising six replications of four treatments. In one treatment of the plant crop [59] the plots were irrigated to potential requirements throughout the crop. In a second treatment, irrigation was suspended in September, two months prior to harvesting the crop in November. The gypsum blocks, which were sensitive over the range from 1-15 bars tension, showed that extensive moisture depletion took place at all depths of measurement, but not to the limit of wilting point at any depth. There was nevertheless a response to the drying-off treatment in terms of sucrose yield per hectare when compared with the well-irrigated control plots.

In the first ratoon crop [17] one treatment received "potential" water requirements for the first six months; then available water was depleted by 38 mm per month over the ensuing four months; and finally irrigation was suspended during the remaining two months of the crop period. By the time of harvest the gypsum blocks showed that all available water down to a depth of at least 230 cm in the soil had been exhausted. Analyses of soil samples from the experiment site indicated that the total available water (0,1-15 bars) in the profile to a depth of 230 cm was 464 mm. A total of 203 mm of effective irrigation water was applied during the final six months duration of the crop. The estimated E_{pt} for the same period was 899 mm, indicating that the crop, at worst, fell short of potential requirements by only 232 mm on this deep, fertile Makatini sandy clay. In this instance, this drying-off treatment did not cause the yield of sucrose per hectare to improve compared with that from an adequately irrigated control treatment, but the same treatment could have been disastrous, for example, on the PE1 sandy clay loam in Rhodesia [44] where the total available water was only 104 mm in the average 75 cm depth of soil on the site of a drying-off experiment.

Maximum water use by sugarcane

Once it had been found that E_{pt} for fully canopied sugarcane was similar to open water evaporation, interest was aroused in the possibility that a physiological restraint might limit E_t when the evaporative demand was very high. Lysimeter data from a number of sources are given in Table 4, where it may be seen that the highest mean value for E_t (15,7 mm/day) was measured at Ayr in Australia for variety Q63. Considering that this is a mean value for a 3-4 week period, it is remarkably high. The next highest mean values for long periods of measurement were 10,7 mm/day (Ayr), 9,6 mm/day (Fairymead), 9,1 mm/day (Fairymead) and 8,6 mm/day (Hawaii).

Table 4

MAXIMUM DAILY AMOUNTS OF EVAPOTRANSPIRATION (E_t) MEASURED IN VARIOUS LYSIMETER EXPERIMENTS FROM 1958 TO 1973

Location	Ref.	Variety	Crop	Period of meas.	Date of maximum meas.	Max. E_t (mm/day)	E_o (mm/day)
Hawaii	20	37-1933 39-2915	P	Monthly	June, 1958	8.6	—
Shakaskraal	65	NCo 376	P	Monthly	Jan., 1960	7,1	
Tongaat	65	NCo 376	P	Monthly	Jan., 1960	6,4	6,0
Australia	43	Q70	P	Monthly	Nov., 1962	9,1	—
(Fairymead)		Q70	1R	Monthly	Jan., 1963	9.6	—
Shakaskraal	55	NCo 376	P	Mnthly	Feb., 1963	5,7	6,0
Mauritius	36	M147/44	P	Monthly	Feb., 1964	7,5	6,4
		M147/44	1R	Monthly	Dec., 1964	6,2	6,5
		M147/44	2R	Monthly	Jan., 1966	6.6	7,0
Shakaskraal	58	NCo 376	P	Daily	16.10.65	6,8	7,4
Shakaskraal	3	NCo 376	1R	Weekly	Dec., 1966	6,5	5,8
Argentina	28	NA 56-30	P	Monthly	Jan., 1967	7,1	[illegible]
Pongola	57	NCo 376	P	Daily	6.2.68	10,3	[illegible]
		NCo 376	P	Weekly	Feb., 1968	7,9	7,6
		NCo 376	1R	Daily	21.1.69	12,4	14,5
		NCo 376	1R	Weekly	Jan., 1969	8,9	9,1
Australia (Ayr)	43	Q80	1R	3-4 wks	1966-67	10,7	—
		Q63	P	3-4 wks	1972-73	15,7	—

In South Africa, where E_t was measured by means of weighing lysimeters at Pongola on a daily basis, maximum rates of E_t occurred in a plant crop of NCo 376 in February, 1968 (10,3 mm/day), and in the first ratoon crop in January, 1969 (12,4 mm/day). Since E_o was only 9,7 mm on 6 February, no physiological restraint on transpiration can be suggested, but on 21 January E_o was 14,5 mm, 17% more than E_t. Nevertheless, in the light of the Australian figure of 15,7 mm/-day, the Pongola result still need not necessarily imply a restraint at this high level of evaporative demand. Mean E_t during a week in January 1969 was 8,9 mm/day when E_o averaged 9,1 mm/day, giving a mean E_t/E_o ratio of 0,98. There seems to be little reason, therefore, to propose that physiological restraints on transpiration during periods of high evaporative demand need be a matter of any great concern in the existing South African sugarcane areas.

Hourly measurements of E_t on a number of days during the plant crop of the lysimeter experiment at Pongola showed that a maximum of 1,35 mm/hr was recorded between 12h00 and 13h00 on 8 February, 1968 [57]. A similar peak of 1,32 mm/hr occurred on 6 February, as shown in Fig. 6.

Total water use by the crop

Total water use by sugarcane crops varies considerably due to differences in the duration of the crops. Total E_t for a long (20 month) crop in Hawaii was 3 530 mm [22], and annual consumptive use was reported to vary from 2 000 to 2 400 mm [21]. Lysimeter data for crops varying in length from 279 to 473 days are shown in Table 5. Mean E_t for the full duration of the crop varied from a minimum of 3,19 mm per day at Shakaskraal to a maximum of 4,35 mm per day in Australia. Calculated mean total amounts of water per annum are:

Location	Mm/annum
S. Natal (Shakaskraal and Tongaat)	1 267
Pongola	1 555
Mauritius	1 449
Australia	1 522

(to be continued)

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WATER USE BY SUGARCANE

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Table 5

al Amounts of water used by sugarcane crops grown in lysimeters on various sites

Location	Ref.	Variety	Crop	Crop Days	Total Et, mm	Mean mm/day
akaskraal	65	NCo 376	P	362	1 496	4,13
			1R	318	1 110	3,49
			2R	335	1 069	3,19
gaat	65	NCo 376	P	358	1 260	3,52
			1R	326	1 115	3,42
			2R	473	1 557	3,29
akaskraal	55	NCo 376	P	304	1 201	3,95
	57		1R	441	1 446	3,28
uritius	36	M47/144	P	400	1 613	4,03
			1R	372	1 421	3,82
			2R	412	1 673	4,06
gola	60	NCo 376	P	310	1 271	4,10
			1R	400	1 768	4,42
			2R	279	1 191	4,27
stralia	43	Q80	1R	365*	1 460	4,00
		Q63	P	395*	1 720	4,35

*Approximate No. of days.

l Water availability

By irrigating lysimeters frequently it is possible to ensure that the crop growing e tanks never suffers from moisture stress. When commercial fields of an exten- crop such as sugarcane are to be irrigated, however, economic considerations de- d that the soil moisture reservoir be exploited as fully as possible, even to the ex- of the crop incurring some stress. In these circumstances it is an advantage to as much as possible, not only about the soil profile itself, but also about the ant-atmosphere continuum. The availability of soil water to the crop depends

(i) the depth of the soil profile
ii) the moisture release characteristics of the soil
iii) the hydraulic conductivity of the soil
iv) the capillary conductivity of the soil
(v) the depth of crop rooting
vi) the density and efficiency of absorbing roots in each horizon of the soil
ii) the evaporative demand of the atmosphere.

actors

sustain good crop growth on a very shallow soil, irrigation would have to be sed so frequently that it would probably be uneconomic. Soils selected for ed sugarcane production should therefore preferably be one metre deep or . In a computer exercise[8] it was shown that rainfall efficiency increased from o 80%, when the available water holding capacity of the soil was increased 0 mm to 125 mm, in an irrigation scheme where 25 mm of water could be every 12 days if required.

e moisture release characteristics of soils in the South African sugar industry een studied in some detail and the results reported by a number of authors[46] Of the data available for 23 soil series[42], results for nine common series are ted in Table 6. Classically, available moisture has been defined as that held n tensions of 0,1 and 15 bars in the soil, but it has also been suggested that crop growth generally takes place within the range 0,1 to 1 bar[30]. Both ts are shown in the table, and for the nine series listed, the mean "freely" le water (FAM = 0,1 to 1 bar) is 55% of the mean "total" available water = 0,1 to 15 bars).

Table 7, field capacities determined gravimetrically on samples from the field equilibrium obtained 48-96 hours after final wetting) are compared with ory determinations (0,1 bar, undisturbed soil cores) for each of nine soil Considering that the sites from which the samples were taken for any one were quite different, the agreement between results is surprisingly good.

ilst the available moisture contents and moisture release curves for different rovide one means of assessing their relative abilities to provide water for a e possible contribution of gravitational water should not always be ignored. In deep sandy soils particularly, where aeration is unlikely ever to be impaired, a significant amount of the water used for transpiration could be provided by gravitational water during the days immediately following a saturating rain or irrigation.

Table 6

Available moisture contents of Profiles of nine selected soil series[42]

Soil form	Soil series	Depth cm	Avail. moisture content	
			0,1 to 1 bar (FAM)	0,1 to 15 bars (TAM)
			mm	mm
Arcadia	Rydalvale	0— 30	9,9	33,6
		30— 90	28,8	70,2
		Total	38,7	103,8
Inanda	Inanda	0— 89	70,3	124,6
		89—132	23,2	43,0
		Total	93,5	167,6
Cartref	Cartref	0— 30	15,6	33,0
		30—120	54,0	78,3
		Total	69,6	111,3
Glenrosa	Williamson	0— 46	23,0	46,0
Longlands	Waldene	0— 25	30,2	50,0
		43—110	34,0	69,4
		Total	64,2	119,4
Estcourt	Estcourt	0— 22	16,9	29,9
		22— 60	20,5	40,7
		Total	37,4	70,6
Hutton	Shorrocks	0— 18	20,2	27,0
		18—100	51,7	93,5
		Total	71,9	120,5
Shortlands	Shortlands	0— 30	15,6	33,0
		30—120	33,3	73,8
		Total	48,9	106,8
Hutton	Clansthal	0— 30	16,2	25,5
		30—120	61,2	86,4
		Total	77,4	111,9

Table 7.

A COMPARISON OF FIELD CAPACITY DETERMINATIONS MADE ON NINE SOIL SERIES IN THE FIELD[40] AND IN THE LABORATORY[42]

Soil series	Field capacity, mm/cm	
	Field	Laboratory
Cartref	1,67	1,54
Williamson	2,67	2,17
Waldene	2,96	2,80
Windermere	3,17	3,87
Avoca	2,25	2,39
Shortlands	3,46	4,11
Rydalvale	4,18	4,29
Clansthal	1,55	1,26
Fernwood	1,26	1,29

Capillary conductivity, or the movement of water in the soil in the unsaturated state, also has a bearing on the ability of a crop to transpire freely. Measurements made on samples of a Clansthal sand and a Shortlands clay[39] showed that between 0.2 and 0.3 bars tension, capillary conductivity of the sand was 0.037 cm per day, and of the clay 0.021 cm per day. Between 0.6 and 0.8 bars tension, the measurements were 0.00055 and 0.0041 cm per day for the same two soils respectively. Thus at low tensions the Clansthal sand can provide more water more quickly at the soil-root interface than the Shortlands clay, whereas at higher tensions the reverse becomes true.

Plant factors

Providing that soil depth is not a limiting factor, sugarcane root systems penetrate efficiently to considerable depths. On a Clansthal sand the roots of variety NCo 376 were observed in an excavated pit to extend to a depth of at least 400 cm[1] and neutron probe data obtained in the same soil series showed that water removal was effective to a depth of 180 cm when the crop was adequately irrigated, and to a depth greater than 210 cm under rainfed conditions. In contrast, irrigated cane on a Windermere clay did not remove water from depths greater than 90 cm, whilst rainfed cane exploited moisture to a depth of at least 120 cm, but probably not much deeper[64]. Gypsum resistance block data have shown that sugarcane can deplete soil moisture to the wilting percentage throughout profiles to a depth of 120 cm on a Rydalvale clay[66], 120 cm on a Waldene sandy loam[34], and 230 cm on a Makatini sandy clay[17].

Root systems of varieties NCo 376 and N50/211 planted on 14 January 1966, were studied extensively in the root laboratory at Mount Edgecombe[31, 32]. The first sett roots were observed to start growing within 24 hours of planting, and on the third day after planting some were extending at a rate of 10 mm per day[31]. By the fifth day elongation was 20 mm per day. Sett roots reached a peak rate of growth of 24 mm per day and quickly developed a much-branched network of thin sub-roots. Sett root growth ceased after about 11 days when they averaged 20 cm in length, and their subsequent life was short, none being traceable 2 months after planting.

Primary shoot roots started developing from 5 to 7 days after planting, and reached a maximum elongation rate of 75 mm per day. The average rate over 10-day periods in light soils, however, was only about 40 mm per day, and in heavier soils the comparable figure was 28 mm per day. The general shape of the root system which developed subsequently in soils where physical impedance was not a factor, depended on the moisture regime at different depths during root development. In all soils the branching of the roots was always approximately at right angles to the parent root, and turgid root hairs were observed to persist on roots for as long as four months.

In Clansthal sand NCo 376 had an extensive, fine, well-branched root system at all depths down to at least 140 cm[32]. That in a Cartref sand was slightly less extensive, and tended to be better developed in the top 60 cm of soil than at greater depths. In a disturbed Rydalvale clay there was a well-developed thick primary root system with poorer secondary and subsequent branching than occurred in the sands. In an undisturbed Rydalvale clay, primary roots were few in the soil immediately below plough depth until they penetrated an illuvial horizon which impeded their growth. They then branched profusely in the lighter subsoil.

On an irrigated undisturbed Rydalvale clay root growth was initially sparse and slow, and frequent light irrigation was necessary to sustain growth.

In the Clansthal sand the pattern of the active root system changed very markedly as the soil wetted and dried. After a winter drought, the first spring rains caused root initials on some basal nodes to grow actively and to form a new superficial root system in the moist surface soil layer. Only when heavier summer rains re-charged the soil profile did these roots extend downwards to re-create the original root pattern in the soil.

A quantitative assessment of sugarcane roots in the soil was made on the Ivory Coast[10] at the end of a 12-month plant crop of variety B37/172. The data summarized in Fig. 8 represent the percentage distribution of oven-dry roots in various soil strata for three irrigation treatments, viz. plots irrigated at 7, 14 and 21-day intervals. In the plots irrigated weekly, only 32% of the roots occurred below a depth of 35 cm, whereas comparable figures for the plots irrigated every 14 and 21 days were 40% and 50% respectively.

Evaporative demand

The final columns of Tables 1 and 2 illustrate the seasonal variations in evaporative demand. For fully canopied sugarcane in the northern areas, the average daily E_t varies from a maximum of 7.6 mm in January to a minimum of 3.3 mm in July. Daily measurements using the lysimeter at Pongola showed that E_{pt} reached a maximum of 10.3 mm per day in the plant crop and 12.4 mm per day in the first ratoon crop. The minimum value for a fully canopied crop was 1.1 mm per day on 14 August, when E_0 was 1.0 mm. The lowest mean daily E_t for a weekly period (2.5 mm per day) occurred in July when the mean E_0 was 2.9 mm per day.

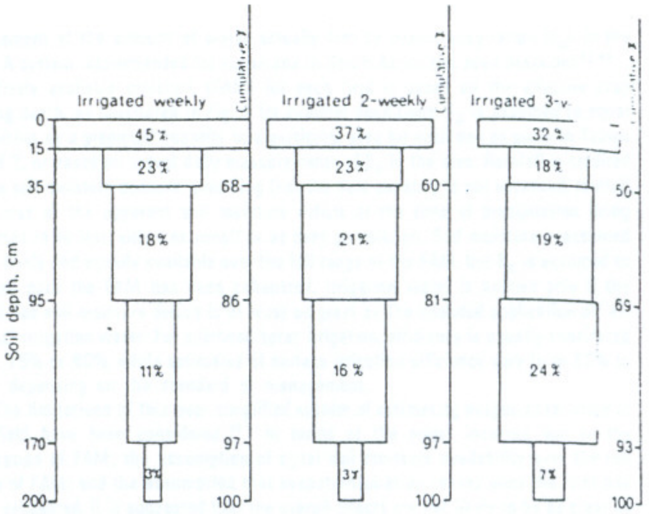

FIG. 8: Root distribution by weight in successive strata of soil, after Baran et al[10]

Soil-plant-atmosphere continuum

Water removal by a crop from the soil is entirely a dynamic phenomen dent upon the moisture release characteristics of the soil, the capillary c of the soil, the distribution and absorbing capacity of the crop roots, and t evaporative demand of the atmosphere. In order to predict the pattern of s moisture depletion and thus to facilitate irrigation control procedures, a number models have been proposed, some being more sophisticated than others[53, 45]. A ve simple static representation of the complex phenomenon has been used for sugarca in South Africa. In Fig. 9 can be seen a simplified two-dimensional representation the conditions which obtain during the period of low evaporative demand in win (a), and during the period of high evaporative demand in summer (b). Since wa availability is high in winter when the evaporative demand is low and the appl of irrigation water need be relatively infrequent, use of the model depicted i should ensure that water availability would not be overestimated in any

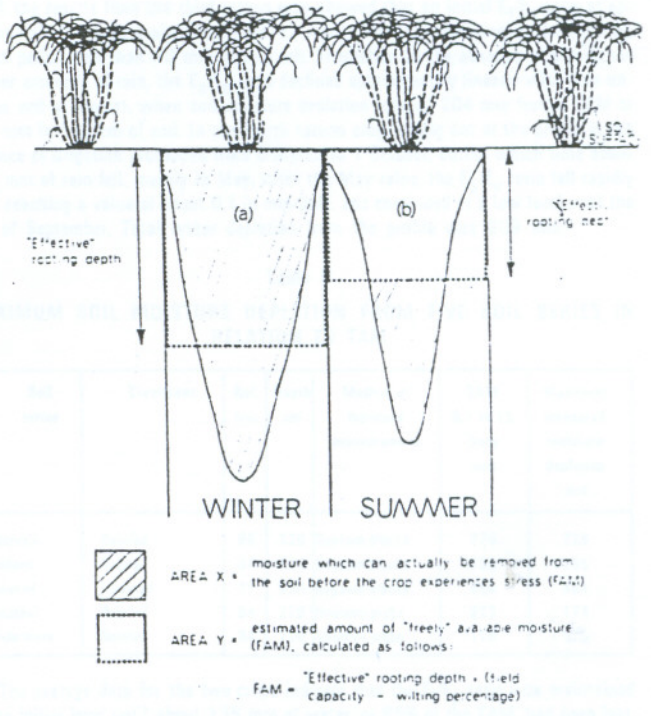

FIG. 9: Diagrammatic representation of freely available moisture (FAM) in the

The "effective" rooting depth of the crop is an ill-defined quantity, based o observations of soil depth and root distributions, and on experience gained wh ducting soil moisture profit and loss accounts. The estimated freely av moisture content of the soil (FAM) is accurate to the extent that the area (Y) in the diagram (Fig. 9b) approximates the area (X). The implications of the errors incurred when using this simple representation of available soil moisture have been considered in relation to various field experiments[83, 17].

Table 8

CROP ROOTING IN AND MOISTURE REMOVAL FROM AN IRRIGATED CLANSTHAL SAND AND AN IRRIGATED WINDERMERE CLAY

Item	Clansthal sand	Windermere clay
Depth of rooting, m	1,83	0,91
TAM, full rooting depth, mm	203	99
Maximum water removal, mm	124	58
Maximum water removal % TAM	61	59
Calculated "effective" rooting depth, m	1,14	0,52

Data obtained by means of a neutron probe in two experiments near Mount Edgecombe[64] have been used to provide the results shown in Table 8. In adequately irrigated plots on a Clansthal sand, roots removed moisture from the soil to a depth of 1,83 m. The available moisture (0,1 to 15 bars) in this depth of soil was 203 mm, but probe data showed that the total of the maximum amounts of moisture removed from successive 30 cm depths (at different times) was only 124 mm, or 61% of the TAM for the full profile. On a Windermere clay, the maximum water removal was 59% of the TAM for the full profile. Referring again to Table 6, it has been stated that the average amount of "freely" available water (FAM) in nine soil series was 55% of "total" available water (TAM). For the purpose of establishing approximately the amount of water freely available to a sugarcane crop in a particular soil even when the evaporative demand is high, therefore, it may be reasonable to take 59% of the total available moisture (0,1 to 15 bars) over the full rooting depth of the crop. Alternatively, providing that total available moisture per unit depth of soil does not vary too widely down the profile, the "effective" rooting depth of the crop (Fig. 9) may be estimated as 50% of the actual rooting depth. On this basis the amount of water freely available to a sugarcane crop on a Makatini sandy clay at Pongola would be 232 mm.

In Hawaii[52] neutron probe measurements of soil moisture showed that crop growth was not inhibited until 65,3 mm of water had been removed from a profile 152 cm deep, and crop growth did not cease until 90,7 mm had been removed. Thus 72% of the apparent total amount of available water was "freely" available.

Because rainfall repeatedly interfered with the study of moisture removal from the soil in the field by means of the neutron probe during important summer months, a new project was initiated in 1965 at Mount Edgecombe using rudimentary rain shelters. Transparent polythene sheets were drawn over metal frames so that about 40 m^2 of crop land on a number of soil series was sheltered from rainfall. The intention was to measure soil moisture depletion and crop heights during prolonged drying cycles, whilst also measuring crop heights on adjacent sites which were freely watered. In this way it was intended not only to establish patterns of soil moisture depletion by a vigorously growing, fully-canopied sugarcane crop, but also to determine the amount of moisture which could be removed before crop growth was first inhibited, and before crop growth was entirely suppressed. Various problems, mainly concerned with the maintenance of and radiation transmission through the polythene sheets, led to the abandonment of this project. Other programmes subsequently took priority over the mobile rain-shelter project which was proposed to overcome the limitations of the abandoned project.

Replenishment of soil moisture by rainfall or irrigation always takes place from the surface downwards. It is predictable, therefore, that despite the ability of the crop to exploit water from deeper strata, most of the moisture used by the crop will in fact be removed from a relatively shallow surface depth of soil. In the experiment on a Clansthal sand[64], during a total of 228 days when runoff and deep percolation were unlikely to have occurred, neutron probe data showed that 96% of the total E_t in adequately irrigated plots as supplied from the surface 60 cm of soil. In rainfed plots during the same days, 72% of E_t was supplied from the surface 60 cm of soil. On the Windermere clay, during 84 days of reliable measurement, 97% of E_t was supplied from the surface 30 cm of soil in adequately irrigated plots, and 59% from the same depth in rainfed plots.

Actual evapotranspiration

The reduction of evapotranspiration below the potential level (E_{pt}) has already been given some consideration in this review. If irrigation practice is to be managed by means of a soil moisture profit and loss account, it is important to have a realistic assessment of the amount of water actually lost by evapotranspiration (E_a) in the field. A system recommended for sugarcane in South Africa has been described[62, 63]. The freely available moisture (FAM) for each field is based on the effective crop rooting depth, as illustrated in Fig. 9 for summer conditions. E_a is assumed to equal E_{pt}, either as a predicted quantity in a particular area for each day as given in Tables 1 and 2, or based on actual daily measurements of E_0 in the area. Rainfall is credited to the soil moisture account, providing that the field capacity is not exceeded, rainfall in excess of the apparent soil moisture deficit at the time of precipitation being assumed to be lost, either as runoff or as deep percolation. Soil moisture is assumed to be freely and equally available over the full range of the FAM, but E_a is assumed to be zero once the FAM has been exhausted. Irrigation water is applied only if the calculated soil moisture deficit is at least as great as the intended application of "efficient" irrigation water. For overhead spray irrigation, efficiency is usually considered to be 75% or 80%, while estimates of surface irrigation efficiency vary from 50% to 80%, depending on the standard of management.

The limitations of this over-simplified system of estimating evapotranspiration in the field have been considered[83] in terms of the errors incurred due to the estimation of FAM; the assumption of equal soil moisture availability over the full range of FAM; and the assumption that evapotranspiration ceases once the FAM has been exhausted. It is suggested that the overall effects are not likely to be as great as the grossness of the assumptions may seem to imply. This may be true in circumstances when the crop is well irrigated throughout its duration, but errors may be significant when drying-off is prolonged, and particularly so if the crop rooting is deep, as has been illustrated for the Makatini sandy clay at Pongola. The FAM of this soil would be 232 mm, whereas gypsum resistance block data showed that one drying-off treatment depleted the entire TAM of 464 mm in a soil depth of 230 cm. Under such conditions it would be advisable to make different assumptions concerning E_a after the FAM (232 mm) has been exhausted.

It has already been suggested that the total amount of freely available water (i.e. when $E_a = E_{pt}$) should be estimated as 50% of the available water (0,1 to 15 bars) in the total crop rooting depth. It is also apparent that the sugarcane crop, given time, is capable of depleting soil moisture to 15 bar tension throughout the crop's total rooting depth. This is illustrated in Table 9 for five soil series in which either gypsum blocks or the neutron probe were used to monitor soil moisture content throughout the crop rooting depth. The remaining problem, therefore, is to predict the rate at which E_a declines below E_t as soil moisture depletion proceeds. The lysimeters at Pongola were used in two successive years to study actual evapotranspiration in the absence of irrigation during the dry winter months[47]. In 1971 the results from the third ratoon crop showed that an initial E_t/E_0 ratio of approximately 0,8 was maintained from 12 April until the beginning of July, during which period less than 40 mm of rain fell. Thereafter, in the absence of significant further amounts of rain, the E_a/E_0 ratio declined approximately linearly with time until the end of August, when soil moisture depletion totalled 204 mm from a TAM of 207 mm in 105 cm of soil. In the fourth ratoon crop, drying out of the profile in the absence of irrigation proceeded from 6 March to 1 October, during which time about 150 mm of rain fell, mainly in May. After the May rains, the E_a/E_0 ratio fell rapidly until reaching a value of about 0,1 in mid-July, and continued at a low level until the end of September. Total water depletion from the profile was 209 mm.

Table 9

MAXIMUM SOIL MOISTURE DEPLETION FROM FIVE SOIL SERIES IN RELATION TO TAM

Soil series	Treatment	Ref. No.	Depth cm	Method of moisture measurement	TAM 0,1 to 15 bars mm	Maximum measured moisture depletion mm
Rydalvale	Rainfed	66	120	Gypsum blocks	226	226
Waldene	Rainfed	34	120	Gypsum blocks	185	185
Makatini	Irrigated	17	230	Gypsum blocks	464	464
Clansthal	Rainfed	64	210	Neutron probe	223	178
Windermere	Rainfed	64	120	Neutron probe	118	170

The average data for the two crops indicate that the E_t/E_0 ratio was maintained at the initial level until about 135 mm of water, or 65% of the TAM, had been lost. The next 41 mm or 20% was released at a mean E_a/E_0 ratio of 0,5. The final 31 mm or 15% was released at an average E_a/E_0 of 0,17.

In Australia, investigations showed that during the peak months of growth E_a/E_0 ratios declined rapidly from 1,2 to about 0,6 over the range of average soil moisture tensions from 0,1 to 0,8 bars in a profile 120 cm deep[43]. These results imply, predictably in the light of a comparison of Figs. 9a and 9b, that the decline in E_a/E_o ratios as soil moisture is depleted will be faster in summer than in winter.

General proposals for predicting consumptive use of water by sugarcane in the field, therefore, might be based on the following criteria:

(i) effective rooting depth = 0.5 × total rooting depth
(ii) FAM = (available moisture, 0,1 to 15 bars) × effective rooting depth
or
FAM = (available moisture 0,1 to 1 bar) × total rooting depth
(iii) TAM = (available moisture, 0,1 to 15 bars) × total rooting depth
(iv) for fully canopied, erect cane, $E_a = E_t = E_o$ over the full range of FAM
(v) for lodged cane, first 3 months, $E_a = 0{,}75\ E_t$ over the full range of FAM
(vi) for lodged cane, after 3 months, $E_a = E_t = E_o$ over the full range of FAM
(vii) after soil moisture depletion exceeds FAM, $E_a/E_t = 0{,}5$ for next 30% of TAM
$E_a/E_t = 0{,}2$ for remaining 20% of TAM
(viii) when TAM has been exhausted, $E_a = 0$

A hypothetical example of the application of these criteria is given in Table 10 for an adequately irrigated crop grown in the northern areas on a Makatini sandy clay. The estimated TAM is 464 mm, the FAM 232 mm. E_{pt} is based on values given in Table 2. When the crop lodges at the beginning of May, E_a is reduced to 0,75 E_t. The soil is assumed to be at Field Capacity on 30 June. During the first month of drying off, which is the third month of lodging, E_a remains 0,75 E_t. During August E_a again equals E_t, this being the fourth month of lodging, and remains so until 232 mm of soil moisture have been lost. This amount is reached on 5 September. Thereafter, 30% of TAM or 139 mm is used at a rate of 0,5 E_t, and this total is reached on 20 October. Until harvest on 31 October, E_a then proceeds at a rate equal to 0,2 E_t. It is assumed that no rain fell during the entire period of drying off. The estimated total consumptive use for the crop is 1 529 mm, whereas the simpler model based on FAM only would have given a value of 1 378 mm for the same crop.

Table 10

A SIMPLE HYPOTHETICAL EXAMPLE OF CROP WATER USE ON A MAKATINI SANDY CLAY HAVING A TAM = 464 MM

Month	Dates	Crop stage	Degree of canopy	Ea/Et ratio	Ea mm
November	1-30	2	$\frac{1}{4}$	0.55	108
December	1-31	2	$\frac{1}{2}$	0.70	149
January	1-31	2	$\frac{3}{4}$	0.85	198
February	1-28	3	Full	1,00	185
March	1-31	3	"	1,00	197
April	1-30	3	"	1,00	145
May	1-31	4	Lodged	0,75	89
June	1-30	4	"	0,75	75
July	1-31	5	Drying off	0,75	77
August	1-31	5	"	1,00	126
September	1-5	5	"	1,00	30
	6-30	5	"	0,5	76
October	1-20	5	"	0,5	61
	21-31	5	"	0,2	13
TOTAL					1 529

In well irrigated crops, E_a is only likely to fall appreciably below E_{pt} during the period of drying off, as shown in Table 10. For supplementary irrigated and rainfed cane, however, E_a is likely to deviate from E_{pt} more often. Of the sugarcane produced in South Africa, almost 85% is rainfed, and water is invariably the single most limiting resource. It is convenient, therefore, to express productivity in terms of water use so that yields from field to field, and year to year, and for crops of different ages and grown in different seasons, may be comparable. In these circumstances, a reasonably accurate assessment of E_a for rainfed crops is particularly valuable, and improvements on the still relatively crude proposals given above may be warranted for certain soil profiles.

Yield/Water use relationships

Since transpiration or the diffusion of water vapour away from the substomatal cavities requires an opening of the stomates, which implies a concomitant diffusion of carbon dioxide into the cavities and, in the presence of sunlight, photosynthetic activity, it is reasonable to propose some direct relationship between consumptive use of water and crop yield. This is particularly so in the case of a vegetable crop such as sugarcane. By 1968 [63] the accumulated results of irrigation experiments had led to the conclusion that a linear relationship between crop water use and sugarcane yield might exist.

The results of experiments with sugarcane, where different amounts of water were applied to various plots in a number of countries, have been collated to provide the data given in Appendix I [20,63,57,59,17,8,60,36,43]. The sources were:

(i) Hawaii, where different Class A Pan "management ratios", ranging from 0,55 to 1,00, were used to control the amounts of water applied to four treatments
(ii) Cornubia and Ottawa, two sites near Mount Edgecombe, where various water treatments were applied to first, second, third and fourth ratoon crops
(iii) Shakaskraal, where three water treatments were applied to a plant crop
(iv) Pongola, where treatments in a "water duty" experiment ranged from 50 mm of water every 5 days to 50 mm every 42 days, and where the lysimeter experiment was entirely adequately watered
(v) Mauritius, where plant, first ratoon and second ratoon crops were harvested in a lysimeter experiment
(vi) Australia, where a plant crop of Q63 and a first ratoon crop of Q80 were grown in a lysimeter experiment.

The Hawaiian and Australian results did not include information regarding sucrose yields. There are therefore 91 sets of data for E_t and tons cane per hectare, but only 85 for E_t and tons sucrose per hectare. The linear regression equation for tons cane per hectare was:

$$t\ cane/ha = 9{,}69\ (mm\ E_t/100) - 2{,}4,$$

and there was no statistically significant evidence of deviations from linearity. The correlation coefficient (r) was 0,95 and the standard error of an estimate of yield was ±15,1 tons cane per hectare. The linear regression line is shown in Fig. 10.

For E_t and tons sucrose per hectare the linear regression equation (see Fig. 10) was:

$$t\ suc/ha = 1{,}354\ (mm\ E_t/100) - 1{,}32$$

The correlation coefficient was 0,75 and the standard error of an estimate of yield was ±3,43 tons sucrose per hectare. In this instance, however, there were statistically significant deviations from linear regression, and the following quadratic relationship (Fig. 10) was therefore determined:

$$tons\ suc/ha = -22{,}65 + 4{,}923\ (E_t\ mm/100) - 0{,}1419\ (E_t\ mm/100)^2.$$

The multiple correlation coefficient (R) was 0,78. The wide range of the amounts of E_t appearing in Appendix I is due not only to the different water treatments in individual experiments, but also to the varying ages of the crops in different experiments. It has been shown [33] that respiration losses increase as dry matter accumulates in the sugarcane crop, and the "falling off" of yield with increasing amounts of evapotranspiration might for this reason be associated to some extent with increasing age. The relationship between tons sucrose per hectare and E_t was therefore tested using only the 54 sets of data for crops harvested between 11 and 13 months of age. In the event, deviations from linearity were still significant and the correlation coefficient (r) decreased to 0,71. The curvilinearity of the relationship is thus probably real, but it is nevertheless useful to bear in mind the approximate implications of the linear relationships that 9,7 tons cane or 1,35 tons sucrose can be produced for each 100 mm of water lost through evapotranspiration by the crop over the range from 600 mm to 3 800 mm for tons cane per hectare, and from 600 mm to 1 800 mm for tons sucrose per hectare. The maximum productivity per unit of water obtained in the lysimeter experiment at Pongola [60] was 12,3 tons cane and 1,51 tons sucrose per hectare per 100 mm of E_t in the first ratoon crop on the small lysimeters, and 11,5 tons cane and 1,34 tons sucrose per 100 mm E_t in the second ratoon crop on the large (405 m²) lysimeter.

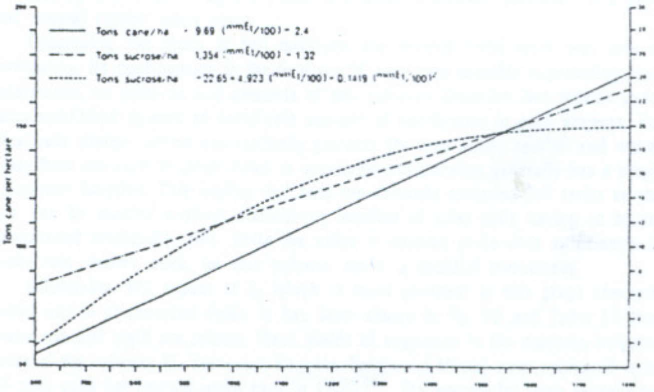

FIG. 10: Relationships between crop yield (tc/ha and ts/ha) and measured or estimated evapotranspiration

The mathematical representation of the relationship between cane yield and water use is valuable not only from the points of view of predicting and assessing crop yields when water use can be estimated, but also because it can be used to establish in broad terms whether an irrigated crop should be produced intensively on a small area or extensively on a large area. Where rainfall is significant, and where water availability rather than land area is the most limiting factor, there can be little doubt that extensive production will be the most financially rewarding. The rainfall efficiency on two sites near Mount Edgecombe [83] was found to decline from about 85% when total precipitation comprised 760 mm of rainfall alone, to 50% when rainfall plus irrigation amounted to 1 575 mm per annum. Inasmuch as the relationship between water use and sugar yield may be slightly curvilinear, there is further argument in favour of extensive rather than intensive production of irrigated sugarcane.

If rainfall is negligible or not to be taken into account when programming irrigation practice, significant deviations from linearity in the relationship between yield and water use become more important, and practical advantages of intensive production may outweigh a yield advantage to be gained from extensive production.

In the context of the existing South African sugar industry, average rainfall for all areas is such that it should not be ignored, and irrigation schemes should never be designed to meet the entire water requirements of the crop unless it is inadvisedly planted on shallow soils.

Discussion

In order to control irrigation practice logically by means of a soil moisture profit and loss (P & L) account, it is apparent that reasonably accurate estimates of E_{pt} are required because consumptive use of water during crop Stages 2, 3, 4 and 5 may all be related to this parameter. The data presented in this review indicate that significant deviations of the E_t/E_0 ratio from a value of 1.00 deserve consideration in two sets of circumstances:

(i) during the winter months, when the ratio may apparently be consistently well below 1.00

(ii) in ratoon crops, when the ratio may be lower than it is in plant cane.

The data plotted in Fig. 4 illustrate quite clearly the low winter values for E_t/E_0 in both plant and first ratoon crops at Pongola. The effects of these low values on the weighted means for the full duration of the period of full canopy, however, were demonstrably small, because E_t values were themselves small during winter. No such consistent phenomenon appeared in the weekly Shakaskraal data, also shown in Fig. 4, and modification of the predicted E_t/E_0 ratio for winter months does not seem to be warranted on these grounds yet.

The weighted mean E_t/E_0 ratios for fully canopied cane in Mauritius [36] were 0.99 for the plant crop, 0.90 for the first ratoon and 0.91 for the second ratoon. At Pongola, reported results [60] were 0.99 for plant cane, 0.94 for first ratoon and 0.88 for second ratoon. Recalculated data for the plant and first ratoon crops, based on weighted weekly means rather than monthly means, were 0.98 and 0.96 respectively [57]. From 12 April until 20 June the mean E_t/E_0 ratio in the third ratoon was 0.79, and for an adequately watered lysimeter in the fourth ratoon from March to September the average E_t/E_0 ratio was close to 0.8. At Shakaskraal the weighted mean monthly E_t/E_0 ratios for plant, first ratoon and second ratoon crops were 1.08; 0.93 and 0.94 respectively, whilst at Tongaat the values were 0.94; 0.86 and 0.89. In the second experiment at Shakaskraal the weighted mean ratio for plant cane was 0.99 and for the first ratoon 0.98. In all instances, therefore, the highest E_t/E_0 ratio was obtained in the plant crop, but the decrease in the first ratoon crop was not always appreciable. The mean ratios for second and later ratoons, however, were always significantly lower than those for plant crops.

The efficiency of water use in the lysimeter experiments for which both yield and total E_t data were available, did not apparently decline consistently from the plant crop through succeeding ratoons, as did the E_t/E_0 ratios. This is shown in Table 11. It is possible that some factor progressively reduced yields in relation to the climatic potential, and concurrently E_t in relation to E_0, as the crop cycle proceeded. The lysimeters contained freshly disturbed soil at the beginning of the experiment, and this may have affected crop growth. Data are available to compare yields from the $405\ m^2$ large lysimeter with those from an adjacent area of undisturbed soil of the same size. In terms of tons cane per hectare these were:

	Lysimeter area	Undisturbed area	Ratio
	(A)	(B)	A/B
Plant	151	136	1.11
1st Ratoon	183	179	1.02
2nd Ratoon	148	149	0.99

The E_t/E_0 ratios for the large lysimeter during the period of full canopy prior to lodging were 1.01; 0.89 and 0.80 for the three crops respectively. The implication could be that an E_t/E_0 ratio equal or close to 1.00 is only likely to obtain in the plant crop in newly established lysimeters. By the time that the soil profile has stabilized, the ratio may have declined to an average value below 0.90.

Table 11

COMPARISON OF MEAN E_t/E_0 RATIOS FOR PERIODS OF FULL CANOPY AND WATER USE EFFICIENCY FOR PLANT, FIRST RATOON AND SECOND RATOON CROPS GROWN IN LYSIMETERS

Location of experiment	Ref.	Crop	Mean Et/Eo, full canopy	Tons cane/ha/ 100 mm Et	Tons cane/ha/ 100 mm Eo
Shakaskraal	65	P	1.08	14.0	—
		1R	0.93	16.1	—
		2R	0.94	14.3	—
Tongaat	65	P	0.94	13.6	—
		1R	0.86	17.2	—
		2R	0.89	9.6	—
Pongola (small lysimeters)	60	P	0.98	11.7	11.2
		1R	0.96	12.3	10.8
		2R	0.88	11.3	8.9
Pongola (large lysimeter)	60	P	1.01	11.2	10.2
		1R	0.89	11.3	8.7
		2R	0.80	11.5	8.0
Mauritius	36	P	0.96	8.5	—
		1R	0.92	10.3	—
		2R	0.90	8.3	—
Means		P	0.99	11.8	
		1R	0.91	13.4	
		2R	0.88	11.0	

There are some indications that even on undisturbed soil productivity in relation to the climatic potential may decline in successive crops. The yields in terms of tons cane per hectare per 100 mm E_0 in the undisturbed area mentioned above were 9.2; 8.5 and 8.0 for the plant, first ratoon and second ratoon respectively. For the NCo 376 plots in an adjacent variety trial (9), the tons cane per hectare per 100 mm E_0 was 8.0; 8.6; 7.7; 7.2 in the first, second, third, fourth and fifth ratoons respectively. On the other hand, the same relatively consistent trend was not apparent in the results of the nearby Pongola irrigation experiment [59, 17], where the yields were 7.9; 7.9; 7.3; 9.2; 8.1; 6.5; 7.1 and 8.4 tons cane per hectare per 100 mm E_0 for eight successive ratoon crops.

Thus there appears to be some evidence that productivity declines in succeeding crops in newly established lysimeters, and perhaps in commercial fields, and small reductions of water applications to successive ratoons may be warranted. Since the Pongola lysimeters have now been in operation for ten years, it might be worth while to study E_t in relation to E_0 and yields in relation to climatic potential, for a plant and several ratoon crops again.

Concerning the study of soil moisture, the neutron probe work was very illuminating. Its continuation in the field would have been valuable in providing more information on patterns and amounts of soil moisture depletion, but rainfall under local conditions caused an inordinate amount of interference in such projects. The ideal rain shelter, which automatically protects the crop during rainfall and moves away from the crop at other times, is expensive and therefore generally has a single permanent location. This implies that only the naturally occurring soil series on the site can be studied without disturbance, profiles of other soils having to be reconstructed artificially. This limits the value of neutron probe data sufficiently to make rain shelter work, for this purpose alone, a doubtful investment.

Indubitably, the aspect of E_t which is most pertinent at this stage concerns water use in commercial fields. It has been shown in Fig. 10 and Table 11 that water use and yield are related. Mean yields of sugarcane in the northern irrigated areas of the industry (E. Transvaal, Pongola, Golela and Mkuzi) were estimated to be 90 tons cane per hectare under cane in 1970 [25]. The average for three seasons for Pongola (1970-71 to 1972-73) was estimated to be 87 tons cane per hectare under cane [38]. For the Eastern Transvaal [54], the estimates ranged from 117 tons cane per hectare under cane in 1969/70 to 79 tons per hectare in 1973/74. Average commercial yields from irrigated lands in the north are thus clearly much lower than the 140 tons cane per hectare per annum obtained experimentally at Pongola, and the question arises whether or not the amounts of irrigation water provided for commercial crops should not be adjusted accordingly. In order to answer this question all of the possible causes of low yields from commercial fields must be given consideration:

(i) if the low yields are caused by moisture stress, then either more water or better timing of irrigation may remedy the situation, and a soil moisture P & L account

(ii) if the low yields are caused by excess water or inadequate drainage, or both conditions, efficient surface and sub-surface water control measures should be introduced, and the estimates of E_t being used should not be a critical factor. Obviously, in affected areas, irrigation should only be applied judiciously until the drainage problem has been solved.

(iii) if the low yields are due to inadequate fertilization of an otherwise satisfactory crop, then the water demand of the crop is likely to be less than Ep_t, and amounts of irrigation water should be reduced accordingly. However, it would be far more economical to apply the required amounts of fertilizer at the correct time, whereupon the estimates of E_t used need not be a critical factor.

(iv) if the low yields are due to weed competition, then the crop should not be deprived of available water, as well as nutrients and sunlight, by reducing the estimates of Ep_t. The investment in irrigation and fertilizer makes adequate weed control an essential corollary.

(v) if the low yields are due to patches of poorly grown cane within the field, the water allocation for the healthy cane should not be reduced to account for this cause in yield loss. If, on the other hand, low yields are due to poor cane growth or sub-normal stalk populations generally throughout the field, irrigation should probably be reduced by accepting an E_t/E_0 ratio less than 1.00. This condition should make the field concerned an early candidate for ploughing out and re-planting.

(vi) if low yields are due to an ill-defined combination of management, soil and crop factors, it would probably be wise to reduce the amount of irrigation water applied somewhat below that indicated when Ep_t is used in a soil moisture P & L account.

Conclusions

The degree of sophistication of irrigated sugarcane farming in South Africa today is probably such that little will be gained from further research into the water requirements of the crop in the immediate future. Nevertheless, since well-established lysimeters are available at Pongola, the opportunity could be taken to check E_t/E_0 ratios and yield relationships again on this site.

Available information regarding the physical characteristics of the soils in the cane belt is also probably sufficient at this juncture to meet the immediate demands of the cane grower. Future requirements are likely to be concerned with particular conditions obtaining in irrigated fields or on land to be developed under irrigation. Of particular importance will be the reasonably accurate estimation of the rooting depth of the crop, and this can most satisfactorily be determined after the crop has been established by using gypsum resistance blocks. (The manufacture and installations of these units must meet rigorous criteria if their operation is to be satisfactory[51]).

Irrigation control on farms and estates should be exercised on the basis of a soil moisture P & L account. Because commercial yields frequently fall below those climatically feasible, the estimates of Et used should probably be adjusted according to the productivity being obtained on a particular farm. For a fully canopied crop, E_t might be estimated as 0.8 E_0: 0.85 E_0 or 0.9 E_0 depending on the average yields being obtained in relation to potential yields.

Climatic potential yields of variety NC_0 376 can be estimated from Class A Pan evaporation for the full duration of the crop approximately as follows:

$$T_c/ha = 8.0 \ (mm\ E_0/100)$$

Poor yields may be caused by a number of remediable factors, and as these are eliminated and yields rise, the amounts of irrigation water applied should then be increased accordingly.

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Appendix I

Water use and sugarcane yields (tons cane/hectare and tons sucrose/hectare) in Hawaii, South Africa, Mauritius and Australia.

Data source	Ref. No.	Et mm	tc/ ha	ts/ ha
Hawaii	20	2 640	279	—
		3 020	313	—
		3 250	326	—
		3 840	342	—
Cornubia	63	1 671	155	23,4
		1 595	133	20,8
		1 488	131	20,0
		1 377	118	18,2
		1 021	86	13,1
	57	1 770	156	21,9
		1 636	148	22,1
		1 466	140	20,6
		1 349	132	19,4
		1 024	101	14,9
		1 050	93	9,7
		1 002	83	8,8
		975	91	9,0
		972	75	7,9
		901	76	8,2
Ottawa	63	1 514	151	18,4
		1 410	132	17,5
		1 242	108	14,3
		1 095	106	13,5
		790	63	7,0
		1 438	144	18,7
		1 346	136	16,6
		1 163	116	13,8
		762	58	6,7
Pongola (Cont'd)	17	1 177	126	19,2
		1 481	141	20,6
		1 627	146	19,2
		1 590	160	20,9
	8	1 330	131	20,2
		1 381	137	21,0
		1 534	136	20,1
		1 711	153	21,7
		1 082	91	12,6
		1 184	93	13,4
		1 286	106	15,1
		1 438	124	17,5
		893	96	13,8
		943	115	17,5
		993	121	18,6
		1 243	148	20,9
		1 014	103	14,3
		1 164	134	17,4
		1 264	140	20,2
		1 364	149	20,7
		1 773	134	15,9
		1 540	121	15,1
		1 340	130	16,8
		1 290	122	15,6
Pongola (lysimeter)	60	1 348	143	14,3
		1 619	181	20,3
		1 287	148	17,2
Ottawa (Cont'd)	57	1 796	184	23,4
		1 595	168	23,1
		1 359	166	22,8
		1 118	149	20,5
		937	77	10,3
		1 167	102	11,2
		1 039	84	8,4
		931	78	7,5
		879	72	6,8
		725	61	5,4
		1 623	165	22,3
		1 494	151	21,1
		1 326	148	20,8
		1 283	142	19,5
		963	83	7,6
		964	82	7,6
		838	81	8,4
		1 055	85	8,5
Shakaskraal	57	1 201	116	17,1
		1 011	97	14,0
		660	57	8,2
Pongola	59	1 402	124	16,7
		1 540	135	16,9
		1 540	128	16,1
		1 540	137	16,6
		1 540	131	16,6
	17	973	96	12,5
		1 177	129	19,3
		1 458	142	19,4
		1 590	141	17,6
		973	87	12,2
Mauritius	36	1 613	137	13,7
		1 421	146	13,7
		1 673	139	15,2
Australia	43	1 560	136	—
		1 080	103	—