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A COMBINED WATER AND ENERGY BALANCE STUDY AT KATHERINE, NORTHERN TERRITORY

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ABSTRACT

A study is made of the "typical" monthly evaporation of a growing crop at Katherine, Northern Territory, based on a combined water and energy balance approach.

The values obtained differ significantly during the "dry" season and the early part of the "wet" season from an earlier estimate based on tank evaporation, when solar radiation data were not available.

The consistent nature of the analysis together with the numerous cross-checks available from the combined approach, suggests that satisfactory estimates of water usage can be made from physical arguments alone, thus relegating the detail of plant behaviour to a secondary role. This follows mainly from the sharp division into two major seasons.

The validity of this and similar studies would be considerably advanced if measurements of net radiation were made directly, rather than relying on estimated values of radiation components not recorded by a solarimeter.

1. INTRODUCTION

In a very comprehensive series of papers by members of the C.S.I.R.O. Division of Land Research, the agricultural climatology of the Katherine area of the Northern Territory has been documented from a wide variety of view-points (Slatyer, 1960; C.S.I.R.O., 1965). A small part of these investigations was devoted to assessing the water usage of a crop during the "wet" season, i.e. the only period of any significant growth. This assessment was largely based on the use of a factor to convert tank evaporation to crop evaporation.

Very recently a considerable body of solar radiation and run-off data has become available, thus opening up the possibility of estimating crop evaporation from a combined energy balance and water balance approach.

The simultaneous requirements of the energy balance and the water balance apply considerable constraints on the allowable speculation. It is considered that the values obtained are much more realistic than was previously possible.

The point of view to be adopted aims at establishing the "typical" water usage of a growing crop by evaluating long-term monthly averages of the various parameters involved.

2. GENERAL CHARACTERISTICS OF CLIMATE

The most striking feature of the climate of the Katherine area is the remarkably sharp division into two seasons; the "wet" extending from December to March, and the "dry" from May to October. Almost all of the 38-inch annual rainfall occurs during the wet season, during which the average daily maximum temperature is close to 94°F. Only trivial amounts of rain fall during the dry season, at the end of which in October-November the average daily maximum temperature is about 100°F.

This sharp division into two major seasons allows useful inferences to be made in drawing up a climatic energy and water balance.

3. THE ENERGY BALANCE

Applying the principle of conservation of energy to the air-surface interface leads to the familiar equation

$$E + H = R_N - G \qquad .....(1)$$

where E is the total evaporation from both crop and soil, H the sensible heat transfer to the air, R_N the net incoming radiation, and G the heat flux into the ground.

Equation (1) will be applied either in the form of monthly totals, or of average daily values. Both here and elsewhere, each month will be taken to consist of 30 days.

Since experience has shown that crop evaporation takes place almost exclusively during the daylight hours due to stomatal closure, it is sufficient to draw up an energy balance for this period only.

The radiation data available (*Fisher, private communication) are in the form of global radiation, i.e. incoming short wave radiation from sun and sky, as measured by a Kipp solarimeter for the years 1960-1964, and expressed for each month as a daily average in cal/cm^2/day. It is unfortunate for the present purpose that net radiation data are not available directly, since this is the quantity entering the energy-balance equation. The Kipp solarimeter, because of its glass dome, rejects incoming long wave radiation, and furthermore does not record either the outgoing long wave or short wave radiation. These quantities must therefore be estimated.

To assess the short wave radiation reflected at the surface, representative values for the albedo have been taken from Robinson (1966). Fortunately, the range of possibilities is not very great and values for the albedo have been chosen extending from 18% in the middle of the wet season to 25% for the dry season. No long wave albedo is considered since the surface is very nearly a black body at these wavelengths.

For estimating the net long wave radiation R_{LN}, use is made of a formula due to van Wijk (1963), viz.

$$R_{LN} = R_{LNC}\,(1 - \lambda C) \qquad .....(2)$$

where R_{LNC} is the net long wave radiation for clear skies, λ is a constant (here taken as 0.8) which depends on cloud type, and C is the cloud amount, expressed as a fraction. Typical values of C were obtained from climatological records of Katherine taken by the Bureau of Meteorology.

The quantity R_{LNC} was obtained from the equation,

$$R_{LNC} = \sigma T_1^{\,4} - \alpha T_2^{\,6} \qquad ......(3)$$

which gives the difference between outgoing black body radiation, $\sigma T_1^{\,4}$, from the surface at temperature T_1, and incoming long wave radiation from clear skies, $\alpha T_2^{\,6}$, where T_2 is the screen temperature (Swinbank, 1963). A representative value of temperature for both T_1 and T_2 (in degress absolute) for the daylight hours was taken to be $T_{MIN} + 3/4\,(T_{MAX} - T_{MIN})$, where T_{MAX} and T_{MIN} are the monthly maximum and minimum average temperatures. The computed values of R_{LNC} are not particularly sensitive to absolute temperature, so that the choice of a representative temperature is not critical.

Net radiation values, R_N, can then be determined (see Table 1). Measurements of net radiation for a single year have been presented for the Kimberley area by Fitzpatrick and Stern (1965). As the Kimberley measurements refer to an irrigated area and because of climatic differences, comparison with the present estimates are possible only for the wet season. They report average values for R_N of 380 cal/day for the period January to early March, and 320 cal/day for the period early March to the end of May. These are in excellent agreement with the values in Table 1, for these, the most important periods in the present context.

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* See "Acknowledgements"

Table 1. Assessment of R_N-G from global radiation measurements with a Kipp solarimeter.

	Global Radiation (cal/cm^2/day)	Albedo (%)	Net Short Wave Radiation (cal/cm^2/day)	Net Long Wave Radiation R_{LN} (cal/cm^2/day)	R_N (cal/cm^2/day)	R_N-G (cal/cm^2/day)	R_N-G (Inches of water per month)
January	514	18	422	39	383	306	6.02
February	532	18	436	37	399	319	6.27
March	514	21	406	45	361	289	5.68
April	497	25	373	54	319	256	5.04
May	460	25	345	53	292	234	4.60
June	571	25	428	66	362	290	5.70
July	460	25	345	58	287	230	4.52
August	486	25	365	60	305	244	4.80
September	531	25	398	63	335	268	5.28
October	559	25	419	51	368	295	5.81
November	560	24	426	44	382	306	6.02
December	535	22	417	42	375	300	5.90

In Table 1, G for the daylight hours has been taken as $0.2R_N$. This estimate is based on a series of micro-meteorological measurements made by Swinbank and Dyer (1967). In these experiments G was found to vary from 0.3 R_N, for dry soil with little grass cover, to as low as 0.05 R_N for wet soil with a heavy grass cover. The present choice reflects the placing of emphasis on the wet season with only partial shading of the ground by a growing crop. G may thus be slightly overestimated for the end of the wet season when the crop cover is more complete, and underestimated during the dry season. Where the nature of the crop can be specified more closely some slight refinement could easily be effected, but because of the relatively small contribution of G to the energy balance the assumption adopted is regarded as adequate for the present purpose.

In Table 1, R_N-G is expressed also in units of inches of water per month, this being convenient for the water balance to follow.

Since R_N-G must equal E+H, the latter quantity is thus known on a monthly basis with such reservations as have been indicated.

4. THE WATER BALANCE

The well-known water balance equation can be expressed in the form,

$$P = E + R + \Delta S \qquad .....(4)$$

where P is precipitation, E is evaporation, R is run-off and ΔS represents the change in soil moisture S.

Precipitation is well documented, and run-off R for the catchment area of 3,100 sq. miles can be evaluated on a simple flow-area basis from gauge records of the Katherine River, taken at the Katherine railway crossing for the years 1952-1965 (Eden, 1966). In estimating the run-off the mean value of adjacent months has been attributed to the earlier month, thus allowing an approximate delay of two weeks between the movement of soil water into the underground drainage systems and its appearance in the Katherine River. The Katherine area is undermined with limestone cavities providing a good drainage system, and there is no evidence of long period storage in the annual cycle of run-off values.

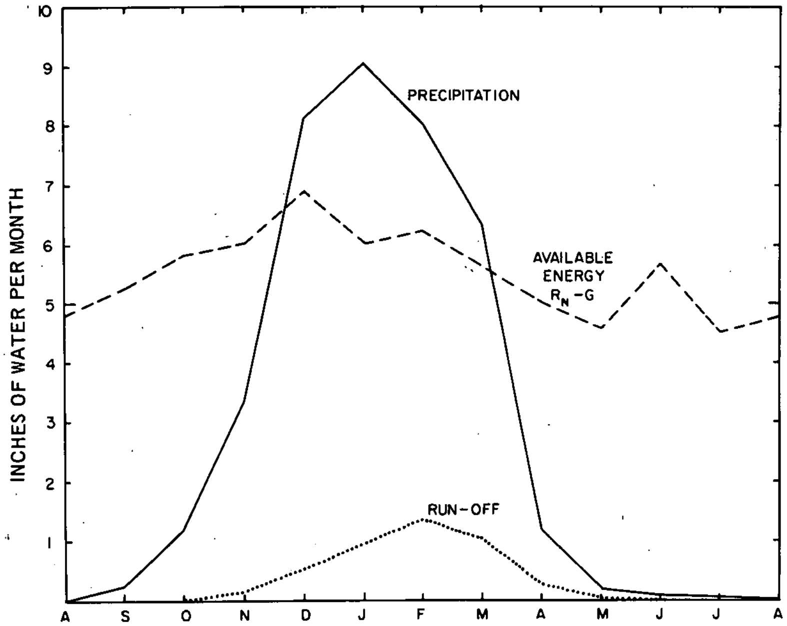

Fig. 1 Monthly averages of basic data; precipitation, run-off and available energy.

In Fig. 1, the long term averages of P, R and E+H are plotted in inches of water per month. The energy term E+H is relatively constant throughout the year, but P and R of course are very non-uniform.

An inspection of Fig. 1 reveals two things of importance. Firstly during the dry season the level of evaporation is governed entirely by the supply of water via precipitation. On the other hand, during the wet season there is a surplus of water and the available energy sets an upper limit to the amount of evaporation which can occur.

The combined energy and water balance can now be drawn up and this is done in Table 2, with the following simplifying assumptions:

(1) For the months June to October, $E = P - R$,

i.e. $\Delta S = 0$ and furthermore $S = 0$;

(2) For the months January to March, $E = R_N - G$,

i.e. $H = 0$.

The first assumption follows immediately from the observation that the ground is virtually dry by the end of May (Slatyer, 1960) and remains so until the rains come in October and November. During the early part of the wet season ΔS is positive as the ground wets up, and towards the end of the wet season ΔS is negative as the ground dries out. The annual sum of ΔS must of course be zero.

The second assumption is harder to justify and may be slightly, but not seriously, in error. Linacre (1964) has observed that the sensible heat transfer from plants in glasshouses becomes negative above an environmental temperature of about 91°F, and suggests that this is determined by the anatomy and morphology of the plant. More recent work has supported this suggestion with a typical critical temperature of about 88°F (Linacre, private communication). Priestley (1966) has raised the possibility that the basic reason is purely physical in character, and obtains generally over an extensive freely-evaporating surface.

Theoretical justification for the second assumption emerges from the physical considerations may be Penman (1948) who combined an energy-balance approach with a bulk aerodynamic formula. Numerous subsequent discussions such as those of van Bavel (1966), have sought to place the empirical transfer coefficient from surface to air on a firmer theoretical basis. A convenient form for the present purpose is provided by Slatyer and McIlroy (1961) who, starting from the energy-balance (Eq. 1) and the transfer equations

$$E = \frac{L}{C_p} \quad h \quad \Delta q \qquad .....(5)$$

and

$$H = h \ \Delta T \qquad .....(6)$$

obtained, through the use of the psychrometric equation, the formula

$$E = \frac{S}{S + \gamma} \quad (R_N - G) \quad + \quad h(T - T_W) \qquad .....(7)$$

which applies when the evaporating surface is saturated.

In the foregoing equations, Δq and ΔT are the specific humidity and temperature differences between the surface and the air at some specified height, L is the latent heat of vaporisation of water, C_p the specific heat of air at constant pressure, S is the slope of the saturated specific humidity curve at wet bulb temperature T_W and $\gamma = C_P/L$, T and T_W are the air temperature and wet bulb temperature at the reference height, and h is a transfer coefficient.

Equation (7) can be evaluated using the present data on a monthly basis, and the first term is found to be 0.75 (R_N - G) for January, February and March. Evaluation of the second term rests on the choice of an empirical expression for h, but van Bavel's (1966) discussion indicates that this does not vary greatly with the type of surface. Using the formula

$$h = 0.5 \ (1 + u) \qquad .....(8)$$

found by McIlroy at Aspendale, with u in m/sec for a thoroughly wetted surface, indicates that the second term of Equation (7) averages out to about 0.23 (R_N - G) for the months in question.

This approach supports the assumption $E = R_N - G$ for the middle of the wet season. A few eddy flux measurements of H made by the author during a short period in February 1967, indicated that H at most amounted to about 3% of R_N - G, and this was supported by temperature profile measurements.

A minor impediment to the assumption that H = 0 for the wet season arises from the climatological information that the average diurnal variation of temperatures for January, February and March is from 73.4°F to 94.2°F, implying a heat input to the atmosphere of the order of 50 cal/day. The answer to this is believed to lie in the following considerations:

(a) The assumption H = 0 for a crop surface is slightly incorrect, and H should perhaps be equated to a few per cent of R_N - G, with a consequent reduction in E.

(b) The climatological temperatures are much more strongly influenced by the large areas under natural vegetation, than by the much smaller areas of cultivated pasture being considered here. The natural vegetation provides a much greater plant cover, not all of which is green growth. G for these areas will be less than 0.2 R_N as a result of shading effects, and a sensible heat flux of the order of 5 to 10 per cent of R_N may be supplied to the atmosphere by this and the drier growth.

(c) During January, February and March a significant fraction of the wind is from the east and south-east, i.e. from areas of much lower rainfall, higher temperatures and greater sensible heat fluxes.

The assumption that H = 0 for the wet season has been made with the above considerations in mind. It is obviously an over-simplification, but it is considered to be a working rule permitting estimates of evaporation to be made which are not in error by more than a few per cent.

Table 2. Average monthly values, in inches of water, of terms contributing to the energy and water balance. Values of E in brackets are estimates for transition months between "wet" and "dry" seasons.

	E + H = R_N-G	P	R	P-R	E	H	ΔS	S(end of month)
January	6.0	9.0	1.0	8.0	6.0	0.0	2.0	4.6
February	6.3	8.0	1.4	6.6	6.3	0.0	0.3	4.9
March	5.7	6.3	1.0	5.3	5.7	0.0	-0.4	4.5
April	5.0	1.2	0.3	0.9	(4.0)	1.0	-3.1	1.4
May	4.6	0.2	0.1	0.1	(1.5)	3.1	-1.4	0.0
June	5.7	0.1	0.0	0.1	0.1	5.6	0.0	0.0
July	4.5	0.0	0.0	0.0	0.0	4.5	0.0	0.0
August	4.8	0.0	0.0	0.0	0.0	4.8	0.0	0.0
September	5.3	0.2	0.0	0.2	0.2	5.1	0.0	0.0
October	5.8	1.2	0.0	1.2	1.2	4.6	0.0	0.0
November	6.0	3.3	0.2	3.1	(2.8)	3.2	0.3	0.3
December	6.9	8.1	0.5	7.6	(5.3)	1.6	2.3	2.6
Annual Total	66.6	37.6	4.5	33.1	33.1	33.5	0.0	-

Table 2 has been compiled on the basis of the above assumptions. For the transition months, November-December and and April-May, a certain amount of guesswork is necessary. With the onset of the "wet" season it is clear that E must be less than P-R so that wetting up of the soil can take place. The values chosen for E permit a smooth transition between the evaporation values for the "wet" and "dry" seasons. A similar argument in reverse applies to the April-May period when the ground is drying out, so that E is greater than P-R. S must become zero by the end of May, as observed by Slatyer, again with the values chosen representing a smooth transition between the "wet" and "dry" values.

An important constraint on possible values of E is imposed by the criterion that during the wet season the soil will only wet up to a total of about 4 inches, any surplus appearing as run-off (Slatyer 1960). This value has been slightly exceeded in Table 2, but any adjustment to limit S to 4 inches would only result in a slight increase in E during December to March, with H becoming negative for part of this period.

5. DISCUSSION

In Fig. 2, the present estimate of crop evaporation is compared with Slayter's earlier estimate, E_S, and Australian sunken tank evaporation.

The two estimates of evaporation differ significantly during the dry season and the earlier months of the wet. It is difficult to reconcile Slatyer's value for evaporation during the dry season with the trivial amounts of water available from precipitation. Excessive tank evaporation occurs during this period, largely due to higher temperatures, and it appears that a much lower tank coefficient should be used.

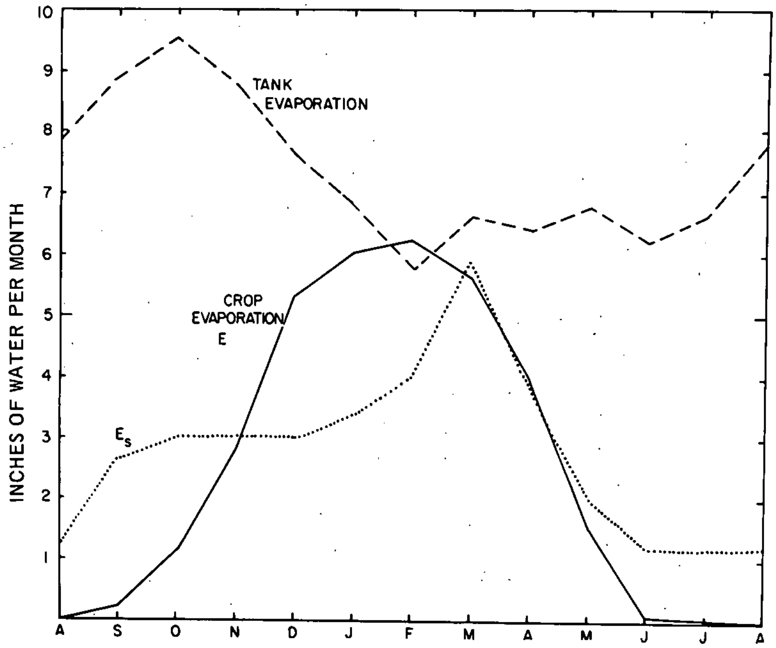

Fig. 2 Monthly averages of estimated crop evaporation E, compared with Slatyer's estimate E_S and tank evaporation.

From December to February, the present estimate of evaporation E is approximately 2 inches per month greater than E_S. Any reduction in E would require water to be held in deep drainage at this time, but this must subsequently appear in run-off if the underground water storage level is to be even approximately maintained. This would amount to 6 inches of water in the annual run-off total of 4.52 inches; which seems an excessive amount of adjustment and moreover would result in disagreement with the river gauge measurements. A possible alternative is that water is held in deep storage at this time and subsequently used by the natural ecological areas. Here, the native species such as eucalypts have rooting systems which allow them to make use of this water during the early part of the dry season. There is certainly no evidence of deep storage appearing as run-off. Although the Katherine River is the southernmost permanent river in the Northern Territory, being spring-fed throughout the dry season, the river flow at this time is only one per cent of the maximum during the wet season.

Excellent agreement is achieved for March, April and May, thus supporting Slatyer's choice of tank factor for this period.

The broad agreement between E and tank evaporation for January and February is consistent with the observation that the ground is thoroughly wetted up at this time.

An important feature which seems to emerge from the present analysis is that a satisfactory evaluation of water usage can be devised which involves only physical considerations, and relegates to secondary importance the detailed aspects of plant behaviour, except perhaps for the very early stages of the growth cycle. This comes about very largely because of the sharp division into two major seasons.

It also holds considerable hope that a reasonable estimate of water requirements could be made for an arid-zone where irrigation was contemplated, if reliable measurements of net radiation were available. The unsatisfactory procedure of estimating net radiation values from global radiation measurements cannot be too greatly emphasized. A correction would have to be applied for variations in surface temperatures and other conditions, but this procedure would not be nearly so vulnerable to error.

The present study has been concerned only with the long-term climatic aspects, but an extrapolation to the "dry-spell" situation which is sometimes an embarrassment during the "wet" could be made with reasonable confidence.

It is in this context that the assessment by Slatyer of the reduction in evapotranspiration as soil moisture is reduced, would be particularly helpful. The individual response of plants to varying conditions of water stress may also be important at this time.

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