THE EFFECT OF SLOPE, ASPECT AND ALBEDO ON POTENTIAL EVAPOTRANSPIRATION FROM HILLSLOPES AND CATCHMENTS

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ABSTRACT

The use of a radiant energy balance appropriate to the slope, aspect and albedo of a hillslope or catchment, in estimation of potential evapotranspiration by Penman's method, is illustrated for horizontal surfaces and slopes of 10, 20, 30 and 40° facing north, south, east or west and having albedos of 0.1 and 0.25. Meteorological data for 1966 from a standard climate station at Taita Experimental Station (latitude 41°S) are used as the basis of the calculations.

The effect of each factor varies with the season — albedo having its greatest influence in the summer months, while slope and aspect have their greatest influence at the equinox. In winter, advection may contribute to the energy used in evaporation, and other factors influencing the transfer of water vapour to the air may be more important than the radiant energy balance.

Data from the Native Forest catchment at Taita Experimental Station illustrate how the conclusions drawn from a catchment water balance may vary with the method used to estimate potential evapotranspiration.

INTRODUCTION

The Native Forest catchment at Taita Experimental Station (latitude 41° 11′ S, longitude 174° 58′ E) faces almost due north and has an effective slope of about 20°. The grass catchment has a similar slope but faces west. In the course of the investigations of the water balances of these catchments the differences in energy regime arising from the effects of slope, aspect and albedo (reflection factor) were considered to be likely to lead to significant differences in evaporation, which is the major means by which water leaves the area. Lee (1963) found a good correlation between the annual discharge from the individual catchments of a group and their 'potential solar beam insolation', indicating that differences in energy regime were a major source of variation of water yield within the group. The present paper reports some results of an attempt to predict evapotranspiration by the method of Penman (1948, 1963) using a radiant energy balance appropriate to the characteristics of either a simple slope or a complete catchment.

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ESTIMATION OF POTENTIAL EVAPOTRANSPIRATION

Energy Balance

The energy-balance approach to estimation of evaporation is based on the principle of the conservation of energy. The radiant energy balance may be written:

$$H = R_i(1-r) - R_b \quad . \; . \; . \; . \; . \; . \; . \; . \quad (1)$$

where H is the net radiation or heat budget, R_i is the incident solar radiation (which varies with the slope and aspect of the site), r is the albedo or reflection coefficient of the receiving surface, and R_b is the net long-wave radiation outward.

The two main uses of the net radiation are latent (evaporative) and sensible heat transfer to the air (the heat stored in the soil and vegetation and the energy used in photosynthesis being relatively small). Although net radiation may be measured or estimated fairly easily, the separation into latent and sensible heat requires measurements of vapour pressure and temperature gradients, which are not generally available. By combining the energy-balance approach with the aerodynamic equations for sensible and latent heat flux, Penman (1948) derived an expression for evaporation requiring standard meteorological data only. For a short green cover the Penman equation may be written:

$$E_T = \left(\frac{\Delta}{\gamma} \cdot \frac{H}{0.1L} + E_{aT}\right) \Big/ \left(\frac{\Delta}{\gamma} + 1\right) \quad . \; . \; . \; . \; . \quad (2)$$

where E_T is the potential evapotranspiration, H is the net radiation, defined by the equation (1), L is the latent heat of vaporization of water, Δ is the slope of the saturation vapour-pressure/temperature curve at mean air temperature, and γ is the wet and dry bulb psychrometer constant;

$$E_{aT} = 0.35(1 + u/100)(e_a - e_d) \quad . \; . \; . \; . \; . \quad (3)$$

where u is the wind speed at a height of two metres in miles per day, and $(e_a - e_d)$ is the vapour-pressure deficit of the air in millimetres of mercury (Penman, 1963).

The present approach is concerned solely with the effects of site characteristics on the net radiation H, the other terms being assumed constant at a particular time on all the sites considered, although some implications of this will be discussed later. In the net radiation, equation (1), R_i is the term influenced by the slope and aspect of the site, while the albedo r depends on the nature of the surface.

Solar Radiation (R_i) on Slopes

Lee (1963) calculated the potential solar-beam irradiation on slopes. He ignored the effects of the earth's atmosphere, so that the irradiation of a surface is a function of the angle between the surface and the sun's rays and may be calculated from the latitude, slope and aspect of the surface and the declination and hour angle of the sun. Lee considered that for a given group of catchments the contribution of diffuse (sky and cloud) radiation would be similar on each catchment irrespective of its slope or aspect. At Taita — at any season — diffuse radiation may contribute 50% of the total solar radiation received on some slopes, and it is the only source of solar radiation on the steep south-facing slopes in mid-winter. A quantitative treatment of both direct and diffuse solar radiation was necessary in calculating the energy balance of sloping sites. The work of Liu and Jordan (1960) provides a means of separating the contributions of direct and diffuse radiation to the total incoming solar radiation (R_i) received on a horizontal surface, and hence the direct, diffuse and total solar radiation received on any slope may be computed.

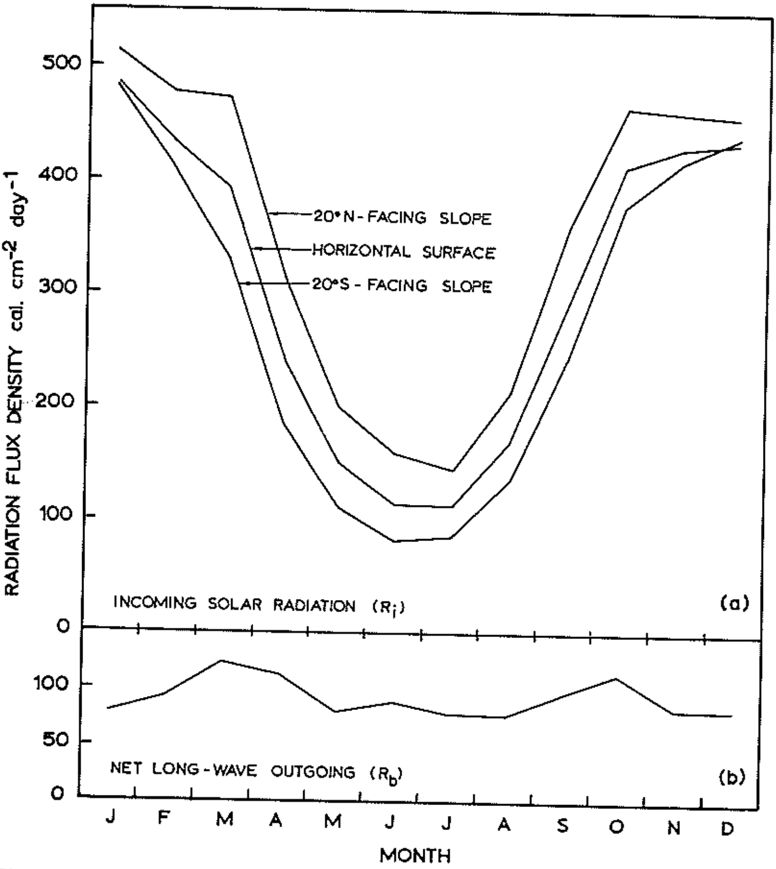

Fig. 1—(a) Incoming solar radiation on a horizontal surface and 20° north and south-facing slopes, and (b) net long-wave radiation. Taita, 1966,

Fig. 1a shows for each month the mean daily total solar radiation received on a horizontal surface at Taita during 1966, measured by an Eppley pyrheliometer, together with the corresponding quantities computed for 20° slopes facing north or south.

In the application of this method to a catchment, the method of Lee (1963) is used to derive an equivalent plane surface by multiple regression, fitting the plane to a sample of evenly-spaced points on the catchment perimeter. The Native Forest catchment at Taita has an equivalent plane with a slope of 16° and an aspect 16° west of north, with a consequent energy regime similar to that of the 20° north-facing slope shown in Fig. 1. To permit direct comparison with other meteorological and hydrological measurements the radiation data are expressed per unit area of a horizontal projection (map area basis) rather than per unit area of the sloping surface (slope area basis).

Net Radiation, H

Net radiation, H, calculated from equation (1) combines the effects of slope and aspect on R_i and of the nature of the surface on the albedo, r. Fig. 2 shows the net radiation calculated for the simple slopes of Fig. 1 with two r values. The albedo 0.25, for which results are shown by solid lines (Figs. 2, 3, 4) is approxi-

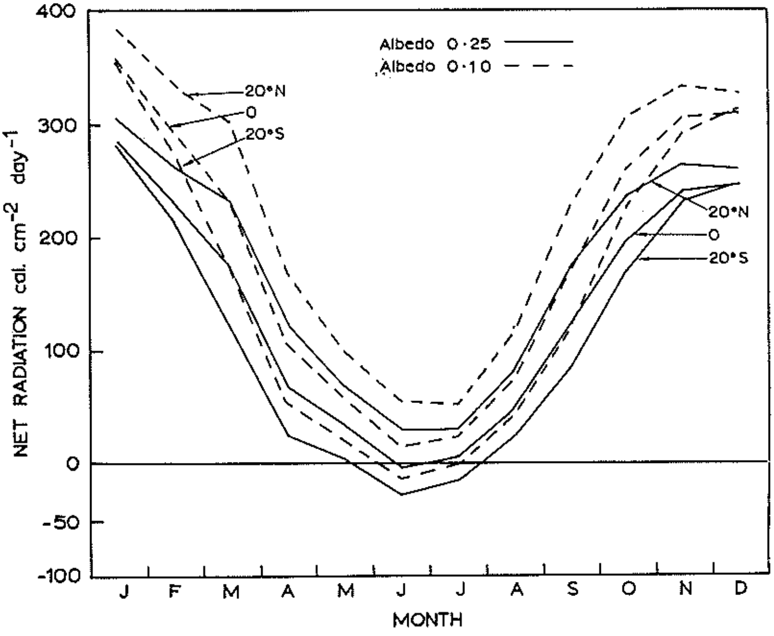

Fig. 2—Net radiation on horizontal surfaces and 20° north and south-facing slopes having albedo 0.10 and 0.25. Taita, 1966.

mately that of a short green cover such as grass, while the figure 0.10 corresponds approximately to some scrub or forest covers. The same net outgoing long-wave radiation R_b (Fig. 1b), which was obtained from measurements made at Taita in 1966, has been used for all slopes.

Potential Evapotranspiration, E_T

When the net radiation (H) values (Fig. 2) are used in the Penman equation (2) the corresponding estimates of E_T (Fig. 3) are obtained. Measurements made at Taita in 1966 were used to give the other terms in (2). Similar calculations have been made for a variety of simple slopes, and Table 1 gives the annual totals of potential evapotranspiration for these slopes.

DISCUSSION

Effects on Annual and Seasonal Potential Evapotranspiration

For a region with an average annual rainfall of 50–55 in., the results in Table 1 imply a considerable variation in the potential annual surplus available for stream flow according to the characteristics of a hill slope or a catchment area. Comparison of the seasonal variation of E_T with rainfall (Fig. 3) shows that the com-

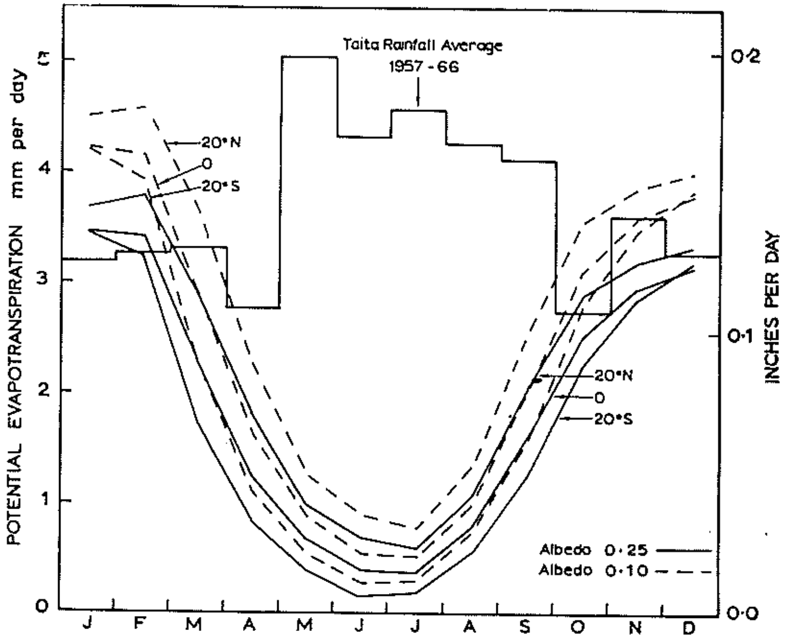

Fig. 3—Estimated potential evapotranspiration rates on horizontal surfaces and 20° north and south-facing slopes having albedo 0.10 and 0.25. Taita, 1966.

TABLE 1 — Estimated potential evapotranspiration on slopes. Annual totals for 1966 at Taita, inches of water on map area basis.

Slope		*Aspect*		
(degrees)	*Albedo*	*North*	*East or West*	*South*
10	0.10	36.5	34.2	31.6
	0.25	29.4	27.6	25.4
20	0.10	39.8	35.5	30.0
	0.25	32.2	28.6	23.9
30	0.10	43.9	37.7	28.8
	0.25	35.6	30.4	23.0
50	0.10	49.8	41.4	28.6
	0.25	40.4	33.5	22.8

Horizontal surface with albedo of 0.10=33.9 in.
Horizontal surface with albedo of 0.25=27.2 in.

bined effects of slope, aspect and albedo may make the difference between water surplus or deficit in any of the months October to March. The contribution of each factor can be considered separately.

Albedo. It can be seen (Table 1) that for any particular combination of slope and aspect there is a decrease of six to nine inches, or about 20%, in the annual E_T as a result of the change in albedo from 0.10 to 0.25. Much of this difference arises during the summer months (Figs. 3 and 4) when the intensity of the incoming solar radiation is greatest. A decrease in E_T of this order is to be expected if vegetation with low albedo is replaced by a cover (such as grass) having an albedo of 0.25. The effect will be modified if other terms in the Penman equation (2) change according to the nature of the vegetation, but the net radiation term is the major one at the time when albedo is of greatest importance.

Slope and Aspect. The estimates of E_T on east- or west-facing slopes (Table 1) increase with increasing slope. This is a result of the increase in ground area per unit map area, and there is in fact a slight decrease in all months in E_T per unit slope area as the steepness of the slope increases. Since — except when it is strongly directed — the amount of rainfall per unit map area is independent of the angle of the slope on which it falls, the results in Table 1 indicate that, as long as other factors (particularly soil depth, water acceptance and retention characteristics) are constant, there will be a reduced amount of water available for stream flow or ground-water recharge from the steeper east- or west-facing slopes.

On north- or south-facing slopes the relation between E_T and steepness of slope varies with the season (Fig. 4) reflecting the interaction of several factors. The situation is simplest at the equinox, illustrated by September in Fig. 4, when the amount of direct solar radiation received decreases continuously from the steepest north-facing slope to the steepest south-facing slope. In the mid-summer months the solar altitude is so high that

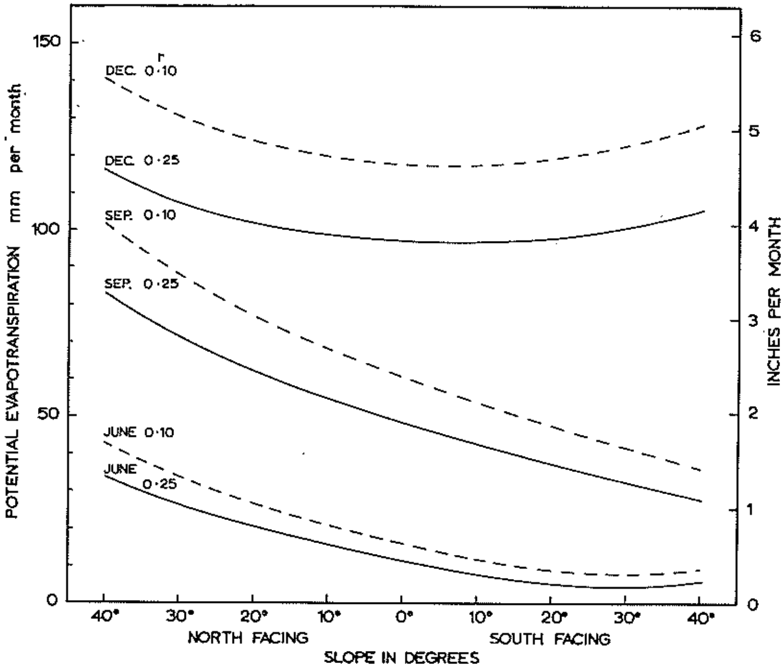

Fig. 4—Potential evapotranspiration on north and south-facing slopes at mid-summer equinox and mid-winter. Taita, 1966.

the intensity and duration of the direct solar-beam irradiation decreases on the steeper north-facing slopes as well as on the south-facing slopes. However, the more uniform contribution of diffuse radiation, combined with the slope-area effect discussed above for the east- and west-facing slopes, leads in mid-summer (December, Fig. 4) to a gradual increase in E_T per unit map area with increased steepness of both north- and south-facing slopes. In mid-winter the low solar altitude leads to a great contrast in radiant energy regime between north- and south-facing slopes, which is partly offset by the fact that H is a minor term in (2) on all but the steepest north-facing slopes. The aerodynamic term E_{aT} in (2) combines with the slope-area effect to give almost constant E_T on the south-facing slopes in June (Fig. 4).

When the aerodynamic term in (2) becomes important the factors such as the roughness of the vegetation, which influence the resistance to transfer of water vapour into the air, may exert a greater influence on the energy balance and on E_T than does the amount of radiation received. Inspection of Figs. 2 and 3 shows that although the net radiation is sometimes negative, the estimated potential evapotranspiration is still positive. The advective transfer of sensible heat from the air to the vegetation provides the necessary energy. Advection is also important when the vegetation is wet as a result of interception of rainfall (Aldridge and Jackson, in prep.). The work of Tanner and Pelton (1960) indicates that the wind function $(1+u/100)$ in E_{aT}, equation (3), should be modified for vegetation rougher than short grass, and that errors in this term are most important when advection occurs.

Water Balance of the Native Forest Catchment, Taita

The results in Fig. 3 and Table 1 show that differences in energy regime may lead to differences in potential evapotranspiration that are too large to be ignored in considering the water balance of simple slopes or of catchments having an effective slope of 10° or more, or an albedo much less than that of grass. The conclusions derived from the water balances of catchments will differ according to the estimate of potential evapotranspiration (or of actual evapotranspiration where this is derived from potential) used in drawing up the water balance, as is illustrated by the following data (Table 2).

TABLE 2 — The water balance of the Native Forest catchment, Taita Experimental Station, 1966 (inches).

Rainfall (P)	65.6
Run-off (Q)	28.6
P—Q	37.0

			E_T	$P-Q-E_T$
Thornthwaite			23.9	13.1
Penman	horizontal surface:	($r=0.25$)	27.2	9.8
		($r=0.10$)	33.9	3.1
	sloping catchment:	($r=0.25$)	31.2	5.8
		($r=0.10$)	38.6	−1.6

Using the Thornthwaite (1948) method leaves a surplus $(P-Q-E_T)$ of 13.1 in. to be accounted for by changes in soil moisture and ground-water storage or by losses from deep percolation. Results obtained by the author show that for the whole period of measurements (1955–66) the difference between annual rainfall and stream discharge is always greater than the Thornthwaite E_T estimate. Thus, use of the Thornthwaite E_T estimates leads to the suggestion that deep-percolation losses are occurring from this catchment, a conclusion also reached by Toebes (1962).

Using the Penman method, the estimate of E_T for a horizontal grassed surface ($r=0.25$) (Penman, 1963, p. 42), also leaves a considerable surplus for 1966, although the use of a lower albedo reduces this surplus considerably (Table 2). When allowance is made for the slope and aspect of this north-facing catchment a surplus remains when the higher albedo is used, but this becomes a slight deficit with r equal to 0.10. The results for earlier years are consistent with those in Table 2. Thus, if an estimate of E_T is used that includes full allowance for the effects of the nature of the catchment on its radiant-energy regime, the water balance may be interpreted entirely in terms of an actual evapotranspiration that is less than potential (E_T) as a result of soil-moisture deficiencies in the later summer months. The size of the deficit decreases in the wetter years (such as 1966) and actual evapotranspiration then approaches E_T. Although when E_T is estimated by this modification of the Penman method it is not necessary to assume losses by deep percolation in order to interpret the water balance, the possibility that such losses do in fact occur has not been eliminated.

Water-balance data from catchments at Taita and elsewhere that have slope, aspect or albedo differing from those of the Native Forest catchment will provide a useful check on the validity of this approach to the estimation of potential evapotranspiration.

CONCLUSIONS

The results that have been discussed show the value of the energy-balance approach to evapotranspiration, and its ability to be adapted to the nature of the site or catchment concerned. Only factors influencing the radiant-energy regime have been considered, and a full analysis of the relation between potential evapotranspiration and site characteristics should include the other factors influencing the transfer of water vapour from vegetation and soil into the air. However, since potential evapotranspiration is greatest when radiation is most important, neglect of these other factors is not too serious in a preliminary analysis. This is only a step towards the estimation of actual evapotranspiration in which the effects of soil-moisture deficiency and intercepted precipitation will also need consideration.

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