Seasonal and Regional Characteristics of Penman Evapotranspiration Model

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1. Introduction

The hydrologic cycle can be evaluated with respect to the surface energy balance, as thermal energy from solar radiation is absorbed and transformed into either sensible or latent heat. Improved knowledge of the surface energy exchange is paramount for understanding the water balance. Identifying the important meteorological variables on evapotranspiration in environments with limited water supply during the two different seasons is the major consideration of this study. Meteorological and flux data (net radiation, air temperature, wind speed, and relative humidity) measured from semiarid watersheds (Lucky Hills and Kendall) during the summer rainy and winter periods were used to study the significance of major variables on Penman evapotranspiration estimation.

2. Experimental Site

The site chosen for the experiment is the well-instrumented Walnut Gulch experimental watershed (31° 43'N, 110° 41'W) operated by the Southwest Watershed Research Center of the U.S. Department of Agriculture's Agricultural Research Service (ARS). It is located in southwestern Arizona about 120 km southeast of Tucson, Arizona. The Walnut Gulch watershed encompasses the 150 km^2. The region has 250-500 mm of annual precipitation with the majority falling during a "summer monsoon season" in July and August. The Lucky Hills and Kendall subwatersheds of Walnut Gulch were used in the experimental portion of this study.

Lucky Hills has an area of 8.09 ha nestled in the western portion of the Walnut Gulch watershed, having smoother topography. The dominant vegetation type is shrub. The Kendall subwatershed has an area of 48.56 ha nestled in the eastern portion of the Walnut Gulch watershed. It is typical of southwestern rangeland where cattle grazes on gentle hillslopes dominated by grasses.

3. Methods

Data used in this study were collected over native rangeland shrub at Lucky Hills and over grass at Kendall during the summer rainy period and winter period. Data used for this study were measured during the summer rainy period from DOY 90198 through DOY 90204 at

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Lucky Hills watershed, and from DOY 90202 through DOY 90211 at Kendall watershed. During the winter period, from DOY 92029 through DOY 92035 at Lucky Hills watershed, and from DOY 92022 through DOY 92042 at Kendall watershed.

3.1 Meteorological and Flux Measurements

The meteorological data include air temperature (T_a, °C), wind speed (u_2, m/s), relative humidity (RH, %), and soil temperature (T_s, °C). The data were collected by the ARS with automatic recording weather stations (Campbell Scientific, INC, Logan, UT).

Air temperature (°C) was measured at heights of 2.0 m above the soil surface at Lucky Hills and Kendall, using a unshielded, unaspirated, 76 μm diameter chromel-constantan thermocouple. Relative humidity (%) was measured with a capacitive sensor in a Gill radiation shield. Mean horizontal wind speed (m/s) was measured with a cup anemometer at 2 m height above ground. Soil temperatures (°C) were measured continuously at both sites, using copper-constantan thermocouple at depths of 2.5 cm (3 replications), 5 cm (2 replications) and 15 cm.

Net radiation was measured with a REBS Q*6 net radiometer at 2.5 m above ground level. Soil heat flux (Q_g, W/m^2) is the combination of heat flux (Q_{gh}, W/m^2) at soil heat flux plate (5 cm depth) and thermal energy stored in the soil layer above the sensor (Q_{gs}, W/m^2). Therefore, soil heat flux is $Q_g = Q_{gh} + Q_{gs}$. At 5 cm depth, Q_{gh} was measured directly with soil heat flux plates at 3 sites in each watershed. The mean Q_{gh} was calculated from the measured values. The hourly energy used for ground heat storage above the sensors (Q_{gs}), was estimated from the change in mean temperature of the 0-5 cm soil layer.

4. Analyses and Results

Meteorological and flux data measured from semiarid watersheds (Lucky Hills and Kendall) during the summer rainy and winter periods were used to study the sensitivity of the meteorological variables used in the estimation of evaporation rates. Relative sensitivity was examined to compare the importance of a four meteorological and flux variables (net radiation, wind speed, air temperature, and relative humidity) on Penman potential evapotranspiration (PET) estimation. Since the structure of the Penman model was formulated from consideration of physical principles, it was expected to provide a realistic sensitivity of the meteorological factors in controlling the evaporation process.

4.1. The Penman Model

The form of Penman's potential ET (evapotranspiration) equation has been most extensively applied in hydromeorology. In 1948 Howard L. Penman (Penman, 1948) gave physically sound treatment to the difficult problem of estimating evaporation from natural surfaces. The equation which he developed links evaporation rate to the net flux of radiant energy at the surface and to the effective ventilation of the surface by air in motion over it (Thom and Oliver, 1977).

The Penman PET (mm/day) equation can be written (after Doorenbos and Pruitt, 1975) as

$$PET = W(R_n + G) + (1 - W)E_a \qquad (1)$$

where R_n is the net radiation (mm/day); G is the soil heat flux (mm/day); (R_n+G) is the available energy (mm/day); $W=(\Delta/\Delta+\gamma_z)$ is the dimensionless weighting factor defined by Doorenbos and Pruitt; Δ is the slope gradient of saturation vapor pressure curve (mb/°C); γ_z (= 0.55 mb/°C) is the psychometric constant above mean sea level (z, m) (mb/°C) and can be further represented as γ_o (P/P_o) = $0.66[(288 - 0.0065z)/288]^{5.256}$; γ_o is psychometric constant at sea level (0.66 mb/°C); P/P_o is the ratio of actual atmospheric pressure to that at sea level (P_o = 1013.25 mb); E_a is drying power term, mm/day, of the form: $E_a = c \cdot f(u)(e_{sa} - e_a)$ where f(u) is wind function (= $0.263 + 0.141u_2$); c is the unit conversion coefficient (1/86,400,000); and u_2 is wind speed at 2-m height (m/s).

Saturation vapor pressure (e_{sa}) at air temperature T_a at 2-m height was obtained from the equation of Murray (1967)

$$e_{sa} = A \cdot \exp\left(\frac{B \cdot T_a}{C + T_a}\right) \qquad (2)$$

When air temperature (T_a) is greater than 0 °C, A, B and C are 6.1078 (mb), 17.269 (/°C), 237.3 (°C) respectively. When air temperature is less than 0 °C, A, B and C become 6.1078 (mb), 21.8746 (/°C) and 265.5 (°C), respectively. The actual vapor pressure of the air (e_a) was calculated as $e_a = (e_{sa} \cdot RH)/100$, where RH was relative humidity (%) measured at 2 m height. Therefore, the vapor pressure deficit was $(e_{sa} - e_a)$.

The slope of the saturation vapor pressure curve ($\triangle$) with respect to temperature is obtained by differentiating Eq. (1) to obtain

$$\triangle = \left[\frac{B \cdot C}{(C + T_a)^2}\right] \left[A \cdot \exp\left(\frac{B \cdot T_a}{C + T_a}\right)\right] \qquad (3)$$

4.2. Sensitivity of Penman Model

Relative sensitivity of the Penman PET model was examined to compare the importance of a four meteorological variables (Q_n, u_2, T_a and RH) on Penman PET estimation. Using mean values of four meteorological factors for the summer rainy and winter periods at each watershed, values of the sensitivity functions of the Penman PET procedures were computed and used to derive values of relative sensitivity. Rates of ET from surfaces vary, depending in part on meteorological conditions. The sensitivity of the meteorological factors used in the estimation of PET rates provides a means of quantitatively examining the relative influence of changes in the level of the meteorological factors on computed evapotranspiration rates.

The relative sensitivity function (McCuen, 1974) is defined by

$$R_s = (\partial PET/PET)/(\partial MV/MV)$$

$$= (\partial PET \quad MV) \cdot (MV/PET) \qquad (4)$$

where R_s is the relative sensitivity; ∂PE (mm/day) is the change in PET according to ∂MV; ∂MV is the amount of change in the meteorological variable; and MV is the average value of meteorological variable before change (Table 1).

The results of the sensitivity tests in the summer rainy periods are summarized in Table 2(a). During the summer at Lucky Hills watershed, the Penman equation was the most sensitive to change in Q_n and T_a, and least sensitive to u_2. During the summer at Kendall watershed, the Penman equation was the most sensitive to T_a, and least sensitive to u_2. Thus, variations in PET rates during summer rainy period at both watersheds appears to be controlled by Q_n and T_a.

Results from the winter period are summarized in Table 2(b). RH was the most sensitive at both watersheds. u_2 was the least sensitive at Lucky Hills, and Q_n was the least sensitive at Kendall. Most variables during the winter period were not very sensitive, compared with those during the summer rainy period. Especially, Q_n and T_a during the winter period were less sensitive than those during the summer rainy period, probably because of low net radiation and temperature during the winter period. Thus, variations in PET rates during the winter period at both watersheds appears to

Table 1. Average value of meteorological and flux variables during the (a) summer and (b) winter periods.

(a) summer period

watershed	Q_n	u_2	RH	T_a
Luck Hills	14.08	1.85	69.52	24.31
Kendall	12.67	3.07	59.07	23.16

(b) winter period

watershed	Q_n	u_2	RH	T_a
Luck Hills	3.99	2.47	57.91	8.31
Kendall	3.17	2.94	55.09	8.20

Q_n : net radiation (MJ/m^2/day)
u_2 : wind speed (m/s)
RH : relative humidity (%)
T_a : air temperature (°C)

Table 2. Relative sensitivity estimates during the (a) summer and (b) winter period.

(a) summer period

watershed	Q_n	u_2	RH	T_a
Lucky Hills	0.83	0.11	-0.43	0.83
Kendall	0.67	0.23	-0.43	0.85
M	0.75	0.17	-0.43	0.84

(b) winter period

watershed	Q_n	u_2	RH	T_a
Lucky Hills	0.44	0.34	-0.56	0.54
Kendall	0.37	0.39	-0.64	0.56
M	0.40	0.36	-0.60	0.55

Q_n : net radiation ($MJ/m^2/day$)
u_2 : wind speed (m/s)
RH : relative humidity (%)
T_a : air temperature (°C)
M : mean value of Lucky Hills and Kendall

be controlled by T_a and RH.

u_2 is the least sensitive factor in the two watersheds regardless of season. There was no big difference in sensitivity of u_2 between seasons. This is understandable because there is no seasonal effects of u_2 on PET. However, u_2 is influenced by the geographical characteristics and local weather pattern. Therefore, it is expected that there is some sensitivity difference on PET between watersheds. Linseley et al. (1958), reported that on a long term basis a change of ten percent in wind speed results in a change in evaporation of one to three percent. Such changes would correspond to relative sensitivity values of 0.1 and 0.3.

The sensitivity of RH on PET during the summer period is much greater than that during the winter period, probably because of high rainfall rate and high temperature during the summer rainy period. RH is directly related with water vapor in the air and air temperature.

McCuen (1974) reported that variations in temperature produces the greatest variation in evaporation rates in arid climates (from May to October), such as that of El Paso. In his study, the relative sensitivity of relative humidity, wind, radiation and temperature was -0.35, 0.41, 0.51 and 1.24 respectively.

5. Conclusions

The selected experimental watershseds (Lucky Hills and Kendall) located in the southwest of the United States represent the typical semiarid land. Continuous flux and meteorological data were measured during the summer period and winter period at both watersheds, and the measured data are examined to compare the importance of four meteorological variables (Q_n, u_2, T_a and RH) on Penman PET estimation.

The study results show that variations in Penman PET rates during the summer rainy period at both watersheds appears to be controlled by net radiation and air temperature. During the winter period at both watersheds, variations in Penman PET rates appears to be controlled by air temperature and relative humidity.

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