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계절과 수문기상학적 조건에 따른 지역 증발산의 특성화
Characterization of Local Evapotranspiration Based on the Seasonal and Hydrometeorological Conditions

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Abstract

Meteorological and soil water content data measured from semiarid watersheds of Lucky Hills and Kendall during the summer rainy and winter periods were used to study the interrelationships between the controlling variables of the evapotranspiration, and to evaluate the effects of variables on daily actual evapotranspiration (ET) estimation. Simple and multiple linear regression (MLR) analyses were employed to evaluate the order of importance of the meteorological and soil water factors involved. The information gained was used for MLR model development. The available energy and vapor pressure deficit were found to be the important variables to estimate actual ET (AET) for both periods and at both watersheds. Therefore, the important variables of evapotranspiration process in these semiarid watersheds appear to be simply the components of energy term in available energy and aerodynamic term in vapor pressure deficit of Penman potential evapotranspiration (PET) equation.

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요 지

여름우기와 겨울기간 동안에 준건조 기후 유역들(Lucky Hills 그리고 Kendall)로부터 측정된 기상학적 그리고 토양 함수량 자료를 이용하여 증발산의 조절변수들 간에 상관관계와 매일의 실제 증발산량 산정을 위한 변수들의 영향을 연구하였다. 기상학적 요소와 토양 함수량의 중요도를 알아보기 위하여 단순, 다변량선형상관분석들이 적용되어졌으며, 얻어진 정보는 다변량선형상관모델을 개발하기 위하여 사용되어졌다. 유효 에너지와 대기 증기압 차는 두 다른 유역과 계절 기간 동안에 증발산을 지배하는 중요한 변수인 것으로 판명되어졌다. 그러므로 준건조 기후 지역에 있어서 증발산 과정의 중요한 변수로는 단순히 Penman에 의해서 제안된 잠재 증발산 모형의 에너지 항에 있어서 유효 에너지와 공기 동력 항에 있어서 대기 증기압차인 것으로 나타났다.

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1. Introduction

Arid and semiarid regions of the southwestern United States are characterized by sporadic precipitation, a limited water supply, and high rates of incident solar energy. Identifying the important meteorological variables on actual evapotranspiration (AET) in the environment with the limited water supply is the major consideration of this study. Simple and multiple linear regression (MLR) analyses were employed to evaluate the order of importance of the meteorological and soil water factors involved. And, the meteorological and soil water data were used for MLR model development. Multiple linear regression of evaporation on the relevant meteorological and environmental factors have been attempted in the past (Holmes and Robertson, 1958; Wilcox, 1963; Burchinal, 1976; Ahmed, 1986; and Pook et al., 1991), and different conclusions have been drawn, depending on the meteorological and environmental parameters measured, and the climatic region in which the measurements were made.

Holmes and Robertson (1957) measured evaporation during the summer of 1954 (May 1 to September 30) using evaporimeters in Canada. They reported that evaporation correlated with mean daily meteorological factors (temperature, wind speed, solar energy and vapor pressure deficit). The results showed that solar energy has the highest correlation and wind speed has the lowest correlation with measured evaporation. Based on AET determined from a lysimeter and measured temperature, radiation, wind and dew-point in Idaho, Wilcox (1963) concluded that temperature gave the highest correlations overall with AET, but on a 2-hour basis radiation was the best. Pook et al. (1991) measured water balances in pine and eucalyptus canopies. They found a consistent pattern in interception losses from the two canopy types that was related to rainfall intensity.

These past attempts have been hindered by using AET measured using experimental methods like lysimeters, which are inaccurate and limited in space, to apply to entire watersheds. The analysis appears more suitable in this study because AET is derived from physically-based flux measurements of higher accuracy. Furthermore, MLR analysis using measured flux data at a watershed scale is unique.

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 (Fig. 1). 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.

Runoff was measured at the outlets of the Lucky Hills and Kendall subwatersheds by a

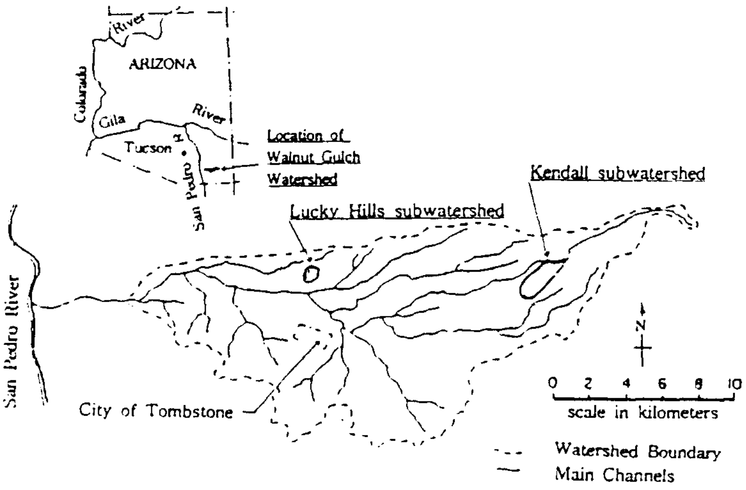


Fig. 1. USDA-ARS Walnut Gulch Experimental Watershed Location Map

calibrated Smith supercritical flume (Smith et al., 1981). In the experimental site, runoff is more variable than precipitation, and stream channels are dry, with runoff occurring on only a few afternoons and evenings during the summer rainy period. Flow durations are from minutes to hours, rather than days. The dominant factor in runoff variability on such small watersheds such as Lucky Hills and Kendall is rainfall variability. The Lucky Hills and Kendall subwatersheds are more affected by rainfall variability than is the larger Walnut Gulch watershed, because runoff per unit area decreases with increasing watershed size.

3. Methods

The flux and meteorological and soil water data were obtained from the Monsoon 90 experiment (Kustus et al., 1991). Data used in this study were collected over native rangeland shrub at Lucky Hills and over grass at Kendall during the summer rainy period (1990) and winter period (1991-1992). Data used for this study were measured during the summer rainy period from DOY (Day of Year) 90198 through DOY 90227 at Lucky Hills watershed, and from DOY 90202 through DOY 90223 at Kendall watershed. During the winter period, data were measured from DOY 92015 through DOY 92070 at Lucky Hills watershed, and from DOY 91347 through DOY 92070 at Kendall watershed.

3.1 Meteorological Measurements

The meteorological data include air temperature (T_a, ℃), wind speed (u, m/s), relative humidity (RH, %), and soil temperature (T_s, ℃). The data were collected by the ARS with automatic recording weather stations (Campbell Scientific, INC, Logan, UT). All data were averaged into 1-hour periods.

Air temperature was measured at heights of 2.0 m above the soil surface at Lucky Hills and Kendall, using an 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 was measured with a cup anemometer at 2 m height above ground. Soil temperatures 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.

3.2 Flux Measurements

The latent heat flux (Q_{LE}) can be measured directly using a variety of methods. However, it has been recognized that it is more reliable for long term measurements to estimate latent heat flux from other more-easily measured fluxes (Q_n, Q_h and Q_g), based on energy balance approach ($Q_{LE} = -Q_n - Q_h - Q_g$). The measurements of three basic fluxes (Q_n, Q_h and Q_g) are described below. All fluxes are averaged over 1-hour periods in units of watts per square meter (W/m^2).

Net radiation was measured with a REBS Q*6 net radiometer at 2.5 m above ground level. The net radiation (Q_n) is the driving factor for energy exchange because in most system it represents the net energy available from sources and sinks.

Soil heat flux (Q_g) is the combination of heat flux (Q_{gh}) at soil heat flux plate (5 cm depth) and thermal energy stored in the soil layer above the sensor (Q_{gs}). 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. The mean temperature of this layer was determined by averaging soil temperatures obtained at 2.5 cm and 5 cm depths. The averaged ground temperature was used to obtain the Q_{gs}. Therefore,

$$Q_{gs} = 0.01 \Delta T_s C_s \Delta z / \Delta t \qquad (1)$$

where C_s is the volumetric heat capacity of the soil [= 1.5 ($MJ/m^3/K$)]; ΔT_s is the soil temperature difference between T_{si} and T_{si-1}; T_{si} is the average soil temperature at time i (hr); T_{si-1} is the average soil temperature at time i-1 (hr); 0.01 is unit conversion coefficient (m/cm); Δt is the one hour time interval (= 3600 s); and Δz is the thickness of soil layer (= 5 cm).

Sensible heat flux (Q_h) was estimated by eddy correlation (EC) during rainy periods in summer (1990) and in winter (1991-1992). The EC values of Q_h were calculated from air temperature, T_a, and vertical wind speed, w, both measured at 9 m above ground level and both sampled at 4 Hz over periods of 20 min. The flux was calculated as follows.

$$Q_h = -\rho_a c_p \overline{w' T'_a} \qquad (2)$$

where ρ_a is air density (kg/m^3), c_p is specific heat of air (J/kg/K), primes denote deviations from period means, and overbars denote period means (Businger et al., 1967). The Q_h measurement is based upon the mean covariance of temperature and vertical wind speed [$cov(wT_a)$] over the measurement period.

A sensitive, propeller anemometer and a fast response thermocouple were used to measure the desired vertical velocities w and air temperature T_a. The one propeller eddy correlation (OPEC; Blanford and Gay, 1992) system is an attractive alternative to the sonic anemometer eddy correlation system (SEC) commonly used in EC systems because it is lighter and inexpensive, and requires no power source and less attention during unfavorable weather.

The inertial effects of the propeller are minimized by placing the sensor 9 m above the ground where the eddies are larger and generally slower. Blanford and Gay (1992) derived the stability corrections for the OPEC sensible heat, based upon theoretical and experimental grounds. The OPEC sensible heat flux was corrected by multiplicative factors of 1.4 and 1.1 for stable (night time) and unstable (daytime) periods, respectively.

Latent heat flux (Q_{LE}) was not measured directly in this study but was computed as the residual term in the surface energy balance. Daily ET was obtained by summing the hourly ET for each day. Actual evapotranspiration (ET) differs from latent energy (Q_{LE}) only in units. ET is the "depth equivalent" of evaporated water (in mm per period) while Q_{LE} is in W/m^2.

3.3 Soil Moisture Measurements

The data on the vertical distribution of soil moisture were collected by ARS (Goodrich et al., 1994) using the time domain reflectometry (TDR) method at Lucky Hills and Kendall watersheds. Continuous daily measurements were made from July 17 through August 16, 1990. The TDR sensors were positioned at 6 different depths about from 0 to 60 cm, which represents the total rooting depth of each watershed. The total water content for the 60 cm depth from the TDR volumetric soil water content was estimated by summing the TDR estimates for each layer in the profile.

The TDR measurements at Lucky Hills were made between and underneath brush (three replications each), and at six locations adjacent to recording raingages in the Lucky Hills watershed which were an average of about 130 m apart. The TDR measurements at Kendall were made on north- and south-facing slopes midway between the stream channel and ridge, and in grazed and ungrazed areas (three reps each). The TDR measurements from ungrazed areas at Kendall were used to estimate conditions of similar areas in the vicinity of the measurement sites.

3.4 Daily Soil Water Content Estimates

The daily soil water content was estimated from the water balance and energy balance approaches at Lucky Hills and Kendall watersheds during the summer rainy period. The TDR measurements of soil water on DOY 90198 and DOY 90207 defined the initial soil water content for Lucky Hills and Kendall watersheds, respectively. For the winter period, the TDR measurements of soil water on DOY 92021 and DOY 91346 were considered to represent the initial soil water content for Lucky Hills and Kendall watersheds, respectively.

On a watershed scale, the hydrologic response characteristics of an entire watershed is also largely determined by the rate of evapotranspiration, which together with precipitation, governs the amount of runoff and infiltration. However, infiltration is not easily determined. Therefore, for practical purposes, it is better to consider the net change in soil moisture content instead. The water balance is then given by:

$$\Delta SM = \Delta P - \Delta ET - \Delta RO \qquad (3)$$

where ΔP is the net daily precipitation (mm/day); ΔET is the net daily evapotranspiration (mm/day); ΔRO is the net daily runoff (mm/day); and ΔSM is the net change in soil moisture content (mm/day). Therefore, soil moisture content is the residual of precipitation minus evapotranspiration and runoff. This is a reasonable approach, because the soil water condition at the watershed scale is not sufficiently homogeneous to be obtained by measurement at the one site.

4. Analyses and Results

Simple and multiple linear regression analyses were employed to evaluate the order of importance of the meteorological and soil water factors involved and finally to develop equations for the calculation of AET. Multiple linear regression analysis is often used for modeling relationships between a dependent variable and more than one independent variables.

The multiple linear regression model assumes that for each set of values for k independent variables (X_1, X_2, ……, X_k) there is a distribution of Y values such that the mean of the distribution is on the surface represented by the equation (Berry and Feldman, 1985)

$$Y = A + B_1X_1 + B_2X_2 + \cdots\cdots + B_kX_k \quad (4)$$

where the coefficients A, B_1, B_2, ……, B_k represent population parameters. B_i is called a partial slope coefficient which is the slope of the relationship between the independent variable X_i and the dependent variable Y holding all other independent variables constant. B_i represents the change in Y associated with one unit increase in X_i when all other independent variables in the model are held constant. If only dependent variable Y and one independent variable X_1 are considered, the model is said to be simple, linear in parameters, and linear in the independent variable

$$Y = A + B_1X_1 \quad (5)$$

For this study, dependent variable Y is AET (mm/day), and independent variable X_1 is the respective meteorological or environmental factor.

4.1 Identifying Useful Variables for MLR Analysis of AET

To identify the useful variables for MLR analysis of AET, there are two major factors which should be considered on the rate of AET from watershed. These are: (a) soil moisture content, and (b) amount of energy available to convert liquid water to water vapor. Vegetation in semiarid rangeland such as the Walnut Gulch watershed is fairly sparse compared to humid regions, so the soil plays a major role in the radiative and hydrologic balance (Kustas et al., 1991).

The available energy ($Q_n + Q_g$) affects ET and soil water content. High available energy creates a high ET rate if there is available soil water. Conversely, low available energy limits the evaporation rate even though there may be available soil water. It is widely recognized that soil moisture suction increases as soil moisture decreases. Therefore, dry surface soils evaporate less, and the surface air becomes drier.

Layers of still air which form immediately above an evaporating surface offer resistance to the diffusion of water molecules into the atmosphere. Wind (u) decreases the resistance by carrying water vapor away from the surface of the still layer, and therefore increases the vapor pressure deficit (VPD) from the evaporating surface. Wind also transports sensible energy horizontally as air that is heated over dry areas to cooler, evaporating surfaces.

The meteorological variables that interact to produce vapor pressure deficit are air humidity and air temperature (T_a). As air temperature increases, vapor pressure deficit increases. As air humidity increases, vapor pressure deficit decreases. Thus, the vapor pressure deficit tends to decrease with high soil water content, and increase as soil dries.

Variables suitable for a MLR prediction model therefore appear to be those that index the available energy term (Q_n+Q_g) and those associated with the aerodynamic or mass transfer term (VPD, T_a, and/or u). These variables are major components of Penman potential evapotranspiration (PET). Since PET is only a "potential" for evaporation, an additional index of the soil moisture content is needed to link the supply of moisture to the actual evaporation rate.

The effects of soil water content and meteorological conditions on AET estimation have also been found elsewhere to be important in the evaporation process (Kucera, 1954; Owe and Griend, 1990). Plants with equal available moisture have more moisture stress on days with larger evaporability (Q_n+Q_g, VPD and u) (Denmead and Shaw, 1962). The explanation of this lies in the fact that when evaporation demand is low, moisture is able to move to the evapotranspiring surface in accordance with the atmospheric demand. But when evaporation demand is large, transport of moisture to the evaporating surface can lag behind the demand, and the actual loss of moisture by evapotranspiration can fall much below the potential ET rate. Based on Kristensen and Jensen (1975), the influence of soil dryness is reduced as evaporability (Q_n+Q_g, VPD and u) is decreased. On the other hand, the influence of soil dryness is increased as evaporability (Q_n+Q_g, VPD and u) is increased.

4.2 Effects of Single Meteorological and Soil Water Factors as Components Influencing Evaporation

In order to determine the relative importance of the various components of meteorological and environmental factors affecting water losses, simple linear regression analyses were performed for the actual ET (AET, mm/day) on net radiation (Q_n, MJ/m^2/day), available energy (Q_n+Q_g, MJ/m^2/day), air temperature (T_a, ℃), vapor pressure deficit (VPD, mb), wind speed (u, m/s), and soil water content(SM, mm) (Table 1). These independent variables are known to directly affect AET.

Simple regression analyses showed that Q_n+Q_g as an explanatory variable was the most important variable for both periods and at both watersheds. The available energy is responsible for 62.7 and 57.9 % of the observed variations in AET during the summer rainy period at Lucky Hills watershed and Kendall watershed, respectively. The analyses also indicated that available energy accounted for 37.6 and 45.4 % of the observed variations in AET during the winter period at Lucky Hills watershed and Kendall watershed, respectively. The wind as an explanatory variable was the least important variable for both periods and at both watersheds.

4.3 Combined Effects of Meteorological and Soil Water Factors on Evaporation

Multiple linear regression (MLR) analysis was employed to evaluate the order of importance of the meteorological and soil water factors involved and finally to develop equations for the calculation of AET (Table 2). Modeling attempts in this study were based on multiple linear regression techniques (stepwise regression method) of the Statistical Package for Social Sciences (SPSS) computer program (Norusis, 1988). To find the parameters for multiple linear regression models, SPSS uses the method of "least squares", and minimizes the objective function to find the optimum parameter values. In this study the objective function to be minimized is the sum of differences between daily observed AET (AET_o) and estimat-

Table 1. Simple Linear Regressions of Daily Evaporation on Meteorological and Soil Water Factors at Lucky Hills and Kendall Watersheds during the Summer Rainy (1990) and Winter Periods (1991-1992).

Model	Regression Equations	r^2	SEE	M	P-value
1	$AET_{LS} = 1.783 + 0.166(Q_n)$	0.400	0.651	3.725	0.000
2	$AET_{KS} = 1.942 + 0.117(Q_n)$	0.330	0.522	3.340	0.006
3	$AET_{LW} = 0.490 + 0.109(Q_n)$	0.200	0.438	1.084	0.001
4	$AET_{KW} = 0.502 + 0.139(Q_n)$	0.243	0.468	1.011	0.000
5	$AET_{LS} = 0.258 + 0.296(Q_n+Q_g)$	0.627	0.514	3.725	0.000
6	$AET_{KS} = 0.707 + 0.221(Q_n+Q_g)$	0.579	0.414	3.340	0.000
7	$AET_{LW} = 0.119 + 0.169(Q_n+Q_g)$	0.376	0.386	1.084	0.000
8	$AET_{KW} = 0.140 + 0.203(Q_n+Q_g)$	0.454	0.398	1.011	0.000
9	$AET_{LS} = 3.669 + 0.005(VPD)$	0.001	0.840	3.725	0.853
10	$AET_{KS} = 3.625 - 0.026(VPD)$	0.042	0.625	3.340	0.374
11	$AET_{LW} = 1.500 - 0.064(VPD)$	0.183	0.442	1.084	0.001
12	$AET_{KW} = 1.274 - 0.052(VPD)$	0.102	0.510	1.011	0.002
13	$AET_{LS} = 3.817 - 0.040(u)$	0.001	0.840	3.725	0.877
14	$AET_{KS} = 3.018 + 0.101(u)$	0.029	0.629	3.340	0.464
15	$AET_{LW} = 0.870 + 0.081(u)$	0.024	0.483	1.084	0.255
16	$AET_{KW} = 0.774 + 0.071(u)$	0.025	0.531	1.011	0.136
17	$AET_{LS} = 1.882 + 0.082(T_a)$	0.058	0.816	3.725	0.199
18	$AET_{KS} = 4.673 - 0.060(T_a)$	0.032	0.628	3.340	0.437
19	$AET_{LW} = 1.401 - 0.037(T_a)$	0.047	0.478	1.084	0.109
20	$AET_{KW} = 1.219 - 0.029(T_a)$	0.027	0.531	1.011	0.127
21	$AET_{LS} = 0.980 + 0.032(SM)$	0.253	0.727	3.725	0.005
22	$AET_{KS} = 0.552 + 0.031(SM)$	0.176	0.579	3.340	0.058
23	$AET_{LW} = -0.734 + 0.020(SM)$	0.032	0.481	1.084	0.189
24	$AET_{KW} = -0.398 + 0.010(SM)$	0.031	0.530	1.011	0.097

LS : summer rainy period at Lucky Hills (n=30), KS : summer rainy period at Kendall (n=21)
LW : winter period at Lucky Hills (n=56), KW : winter period at Kendall (n=89)
n : sample size, r^2 : coefficient of simple determination
SEE : standard error of estimate of the regression (mm/day)
M : mean of observed AET (mm/day), P-value : significance F from F distribution

Table 2. MLR Models for Predicting AET at Walnut Gulch. The Models are for the Summer Rainy Period (1990) and Winter Period (1991-1992) at Lucky Hills and Kendall Watersheds.

Model	Regression Equations	R^2	SEE	M
1	$AET = -1.94-0.03VPD+0.29u+0.31(Q_n+Q_g)+0.02SM$	0.80	0.39	3.73
2	$AET = -2.10-0.35Q_n+0.73(Q_n+Q_g)+0.02SM$	0.88	0.31	3.68
3	$AET = 0.96-0.05VPD+0.24(Q_n+Q_g)$	0.72	0.35	3.34
4	$AET = 3.90-0.15T_a+0.24(Q_n+Q_g)$	0.74	0.34	3.20
5	$AET = -1.72-0.19Q_n+0.05T_a-0.08VPD+0.41(Q_n+Q_g)+0.02SM$	0.76	0.25	1.08
6	$AET = 0.03-0.18Q_n+0.04T_a-0.08VPD+0.39(Q_n+Q_g)$	0.76	0.25	1.06
7	$AET = -0.07-0.20Q_n+0.07T_a-0.11VPD+0.44(Q_n+Q_g)$	0.78	0.26	1.01
8	$AET = -0.05-0.16Q_n+0.06T_a-0.10VPD+0.41(Q_n+Q_g)$	0.85	0.21	0.99

(All the regressions are significant at $P < 0.001$)
1) : summer rainy period at Lucky Hills with all data (n=30)
2) : summer rainy period at Lucky Hills on non-rainy days (n=23)
3) : summer rainy period at Kendall with all data (n=21)
4) : summer rainy period at Kendall on non-rainy days (n=16)
5) : winter period at Lucky Hills with all data (n=56)
6) : winter period at Lucky Hills on non-rainy days (n=49)
7) : winter period at Kendall with all data (n=89)
8) : winter period at Kendall on non-rainy days (n=75)
n : sample size, R^2 : coefficient of multiple determination M : mean of observed AET (mm/day)
SEE : standard error of estimate of the regression (mm/day)

ed AET (AET_e) [$=\Sigma(AET_o - AET_e)^2$] for each period (summer rainy and winter) at each watershed (Lucky Hills and Kendall).

During the summer rainy period, the independent variables for a linear, multiple regression equation were Q_n+Q_g, VPD, SM and u at Lucky Hills with 0.80 of R^2, and Q_n+Q_g and VPD at Kendall with 0.72 of R^2. During the winter period, the independent variables for the regression equation were Q_n+Q_g, VPD, T_a, Q_n and SM at Lucky Hills with 0.76 of R^2, and Q_n+Q_g, VPD, T_a and Q_n at Kendall with 0.78 of R^2.

The Q_n+Q_g and VPD were found to be important variables for estimating AET at Lucky Hills and Kendall (Table 2) during the summer rainy and winter periods. These variables (Q_n+Q_g and VPD) are included for both periods and at both watersheds. Multiple regression analyses showed that the combined effects of available energy and vapor pressure deficit were responsible for 74 and 72 % of the observed variations in AET during the summer rainy period at Lucky Hills watershed and Kendall watershed, respectively. The analyses also indicated that the combined effects of available energy and vapor pressure deficit were responsible for 68 and 71 % of the observed variations in AET during the winter period at Lucky Hills watershed and Kendall watershed, respectively. Therefore, MLR models of AET could be generally represented as the following form during the summer rainy and winter periods at Lucky Hills and Kendall watersheds:

$$AET = A + B(Q_n+Q_g) + C(VPD) \qquad (6)$$

where A is the intercept; and B and C are partial slope coefficients.

The standard error of estimate of regression (SEE) calculated for the all-day MLR models were judged to be small, ranging from 10 % of the mean AET in summer to 25 % of the mean AET in winter. SEE during the summer rainy period was 0.39 mm/day with mean AET of 3.73 mm/day at Lucky Hills (SEE = 10.4 % of mean AET), and 0.35 mm/day with mean AET of 3.34 mm/day at Kendall (SEE = 10.4 % of mean AET). SEE during the winter period was 0.25 mm/day with mean AET of 1.08 mm/day at Lucky Hills (SEE = 23.1 % of mean AET), and 0.26 mm/day with mean AET of 1.01 mm/day at Kendall (SEE = 25.7 % of mean AET).

The null hypothesis that no relationship exists between AET and predictor variables was tested. Since calculated P-value for summer rainy and winter periods at Lucky Hills and Kendall watersheds were smaller than the critical values at 0.1 percent level of significance, null hypothesis of no relationship between AET and predictor variables could be rejected at 0.1 percent level of significance.

4.4 Rainfall Effects on Model Derivation

To obtain accurate relationship between AET and meteorological and soil water variables, the rainfall effects on AET should be clearly defined. The rainfall periods are not exactly coincident with other weather variables, because of different time length and characteristics within the watershed. For example, a short, intense thunderstorm will have a different effect than will a long, gentle rain even if the total precipitation is the same in both storms. Therefore, the effects of rainfall on MLR models of AET are examined by repeating the MLR analysis with data restricted to only those days with little or no rain (precipitation < 2 mm/day) (Table 2). Furthermore, statistical and graphical comparisons between MLR models of AET using non-rainy days and MLR models of AET using all days were performed to find the rainfall effects

Table 3. Relations of MLR Models of AET between All Days and Non-Rainy Days at Lucky Hills and Kendall during the Summer Rainy (1990) and Winter Periods (1991-1992).

Model	Regression Equations	r^2	SEE	$MAET_1$	$MAET_2$	n
1	$AET_1 = -0.264 + 0.930AET_2$	0.88	0.27	3.66	3.65	23
2	$AET_1 = 1.010AET_2$	0.97	0.09	3.23	3.20	16
3	$AET_1 = 0.051 + 0.997AET_2$	0.98	0.05	1.11	1.07	49
4	$AET_1 = 0.033 + 0.986AET_2$	0.99	0.03	1.01	0.99	75

(All the regressions are significant at $P < 0.001$)

1) : Lucky Hills (summer rainy period), 2) : Kendall (summer rainy period)

3) : Lucky Hills (winter period), 4) : Kendall (winter period)

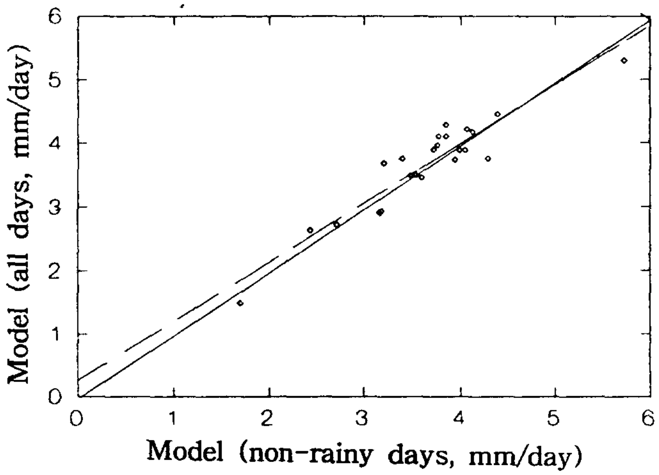
AET_1 : AET of MLR models with all data (mm/day)

AET_2 : AET of MLR models on non-rainy days (mm/day)

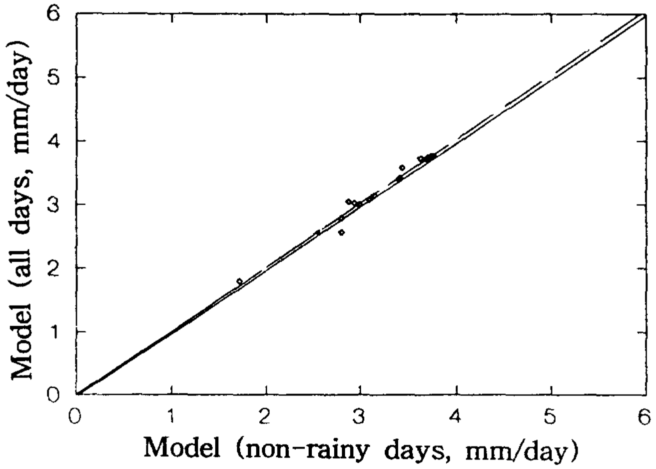
$MAET_1$: mean of AET_1 (mm/day), $MAET_2$: mean of AET_2 (mm/day)

n : sample size, r^2 : coefficient of simple determination

SEE : standard error of estimate of the regression (mm/day)

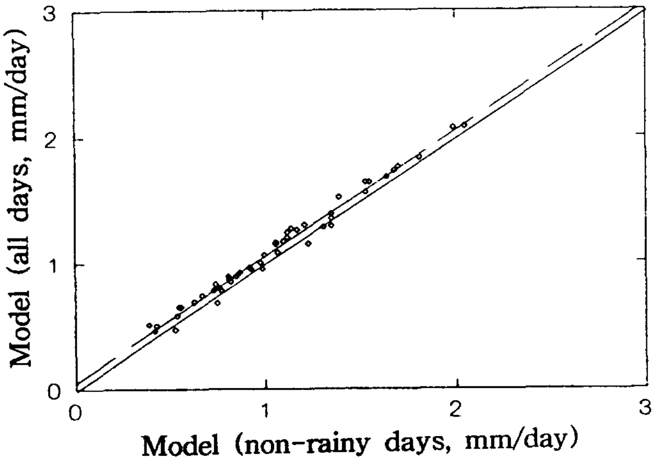


(a) Lucky Hills

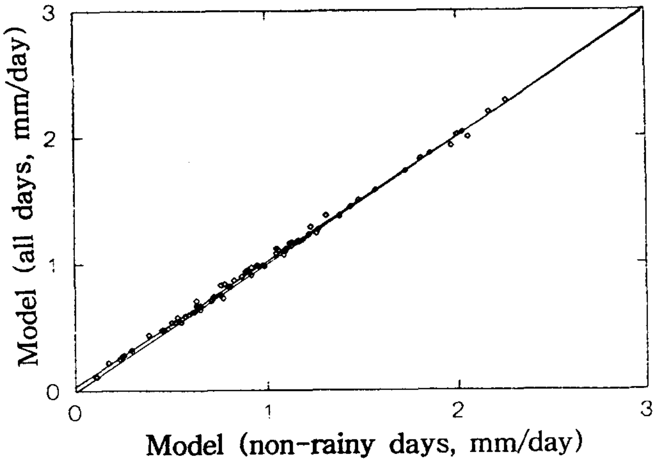


(b) Kendall

Fig. 2. Relations of MLR Models of AET between All Days and Non-Rainy Days at Lucky Hills and Kendall during the Summer Rainy Period (1990)



(a) Lucky Hills



(b) Kendall

Fig. 3. Relations of MLR Models of AET between All Days and Non-Rainy Days at Lucky Hills and Kendall during the Winter Period (1991-1992).

on MLR models of AET (Table 3, and Figs. 2 and 3).

Statistical comparisons were made between MLR models of AET derived from non-rainy days and derived from all days to identify possible rainfall effects on MLR models of AET (Figs. 2 and 3).

The outputs of the two classes of models (all days, non-rainy days) were analyzed by linear regression. The results showed that the two MLR models of AET were essentially identical, with R^2 values approaching 90 % and 100 % for both of AET. SEE was also very small (Table 3, and Figs. 2 and 3). SEE was about 10 % of the mean of estimated AET. The null hypothesis of no relationship between MLR models of AET using all days and MLR models of AET using the non-rainy data set was also tested. The null hypothesis of no relationship between MLR model of AET using all days and MLR model of AET using non-rainy days was rejected at the 0.1 percent level of significance (Table 3).

The scatter plots (Figs. 2 and 3) and the regression analyses (Table 3) reveal that different time length and characteristics of rainfall within the watershed do not affect the relationships between AET and meteorological variables. Performance of MLR models derived from non-rainy days [summarized in Table 2] indicates little or no improvement of MLR models based on all days.

5. Conclusions

Meteorological and soil water content data measured from semiarid watersheds of Lucky Hills and Kendall during the summer rainy and winter periods were used to study the interrelationships between the controlling variables of the AET, and to evaluate the effects of variables on daily actual evapotranspiration estimation. Simple and multiple linear regression (MLR) analyses were employed to evaluate the order of importance of the meteorological and soil water factors involved. Finally, the information gained was used for MLR model development.

The available energy (Q_n+Q_g) and vapor pressure deficit (VPD) were found to be the important variables to estimate actual ET at both watersheds and during the both periods. The VPD was not included in MLR models with data restricted to only those days with little or no rain during the summer period at Lucky Hills and Kendall watersheds. However, when all the data are considered, the important variables of evaporation process in these watersheds appear to be simply a components of energy term in available energy and aerodynamic term in vapor pressure deficit of Penman potential evaporation equation. Therefore, the general form of MLR equations tested for summer rainy and winter periods at Lucky Hills and Kendall watersheds was:

$$AET = A + B(Q_n+Q_g) + C(VPD) \qquad (7)$$

Multiple regression analyses showed that the combined effects of available energy and vapor pressure deficit were responsible for 74 and 72 % of the observed variations in AET during the summer rainy period at Lucky Hills watershed and Kendall watershed, respectively. The analyses also indicated that the combined effects of available energy and vapor pressure deficit accounted for 68 and 71 % of the observed variations in AET during the winter period at Lucky Hills watershed and Kendall watershed, respectively.

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