HOURLY VARIATION OF PENMAN EVAPOTRANSPIRATION CONSIDERING SOIL MOISTURE CONDITION

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Abstract: The purpose of this study is to understand the characteristics of hourly PET(Potential Evapotranspiration) variation estimated using Penman ET model. The estimated PET using Penman model was compared with measured ET. For this study, two subwatersheds were selected, and fluxes, meteorological data and soil moisture data were measured during the summer and winter days. During the winter days, the aerodynamic term of Penman ET is much greater than that of energy term of Penman ET for dry soil condition. The opposite phenomena appeared for wet soil condition. During the summer days, energy term is much more important factor for ET estimation compared with aerodynamic term regardless of soil moisture condition. Penman ET, measured ET, and energy term show the similar hourly variation pattern mainly because the influence of net radiation on the estimation of Penman ET is much more significant compared with other variables. Even though there are much more soil moisture in the soil during the wet days, the estimated hourly ET from Penman model and measured hourly ET have smaller values compared with those of dry days, indicating the effect of cloudy weather condition.

Keywords: Penman, actual evapotranspiration, potential evapotranspiration, soil moisture

1. INTRODUCTION

Evapotranspiration (ET) which includes evaporation of precipitation from plant surface and evaporation of moisture from the soil surface and from plants through transpiration is an important factor in the water balance. The amount of ET can be determined in several ways, including estimation by means of some formula involving the climate, which controls the rate of evapotranspiration. Many different controls relate the water-loss by ET from a well watered surface to the weather, and these expressions typify the climate either in terms of temperature alone, or some combination of temperature, radiation intensity, humidity, and wind. In the extreme case, Penman took all four climatic factors into account.

In 1948 Howard L. Penman gave the first physically sound treatment of the difficult problems of estimating evaporation from natural surfaces. The so-called combination approach, in which both energy-balance and aerodynamic terms appear explicitly in a single relationship, is attractive for two reasons. Firstly, it promotes an understanding of the physical process of evaporation from natural surfaces. Secondly, the Penman equation requires meteorological information at one level only. So evaporation equations of the Penman or 'combination' type are amongst the most widely used in hydrology today.

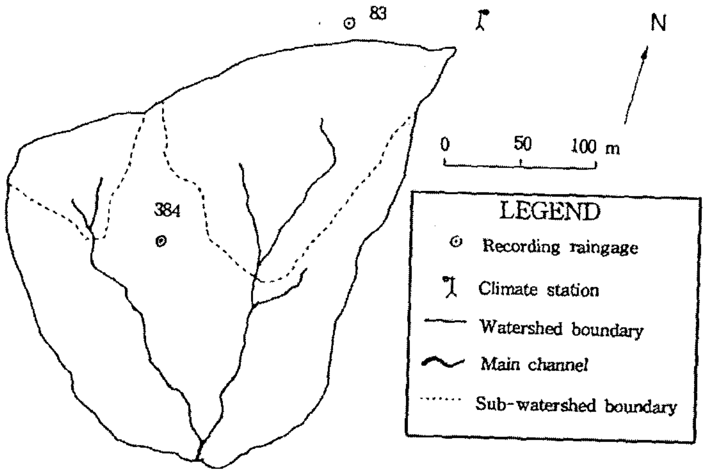
There have been many modifications of the Penman equation to better represent specific local conditions a data sets. Richard (1987) reviewed the forms of the Penman equation (1948 Penman, 1963 Penman, Kohler-Nordensen-Fox, 1972 Kimberly Penman, 1982 Kimberly Penman, FAO Penman, FAO corrected Penman, Thom-Oliver resistance (1977), Penman-Monteith resistance and Priestley-Taylor) and compared them with lysimeter estimates at three locations (Kimberly, Idaho; Coshocton, Ohio; and Davis, California). These sites are representative of an arid, irrigated region; a humid, naturally rain-fed region; and a Mediterranean climate, respectively. Richard (1987) concluded that the Penman-Monteith, Thom-Oliver, 1982 Kimberly Penman, FAO Corrected Penman, Kohler-Nordense-Fox, and 1963 Penman methods all provide good estimates of daily ET from a reference grass crop over growing seasons at all three locations.

However, Penman type models examined so far are daily basis, ignoring the importance of the physical meaning of meteorological and flux variables on the estimation of hourly ET. To understand the physical meaning of meteorological and flux variables on the estimation of hourly ET, energy term and aerodynamic terms of hourly Penman model were plotted and compared for different soil moisture, vegetation, and seasonal conditions. Furthermore, the hourly characteristics of Penman evapotranspiration equation have been examined considering especially the variation of soil water content. To study the effects of surface condition (soil water content) on the estimates of ET, the hourly values of the measured and estimated ET using Penman equation for wet and dry soil condition during summer and winter days at two different watersheds were plotted and compared.

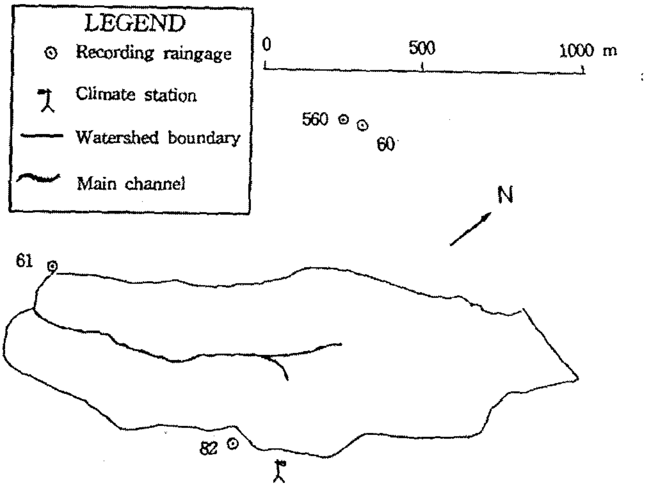
2. STUDY AREA

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). Renard, et al. (1993) has summarized ARS research and facilities at Walnut Gulch. The watershed is located in southeastern Arizona about 120 km southeast of Tucson, Arizona. It is about 150 km^2 in area, and elevation ranges from about 1300 m above mean sea level at the outlet in the west, up to a maximum of about 1800 m in the eastern highlands. The City of Tombstone, Arizona, is located near the center of the watershed, at an elevation of 1405 m (Fig. 1).

Important regional climatic characteristics are evident in the Tombstone climate station records. The thirty-year mean annual precipitation (1941-70) at Tombstone is 325 mm (Sellers and Hill, 1974), which fits well with the "semiarid" descriptor of the Walnut Gulch climate. However, about two-thirds (210 mm) of the annual total falls during the summer rainy season (July-August-September) in association with the inflow into southern Arizona of moist maritime air from the Gulf of Mexico to the southeast. As a result, precipitation during the summer rainy period is much higher than expected for semiarid climates. Rainfall during the summer rainy season comes mainly from thunderstorms, with



(a)



(b)

Fig. 1. The Locations of measurement stations at (a) Lucky Hills watershedand (b) Kendall watershed

precipitation characterized by extreme spatial variability, short duration, and limited areal extent. Air temperatures at Walnut Gulch Experimental Watershed are moderated somewhat by elevation, and mean monthly maximum air temperatures reach about 33-34 °C in July and August.

Two subwatersheds of Walnut Gulch Experimental Watershed were selected for use in these experiments; the two are separated by about 12 km. The smaller, Lucky Hills, has an area of 8.09 ha (0.08 km^2) and is located in the north-west portion of the main watershed, which has more gentle topography. Dominant vegetation is desert shrub. Kendall is the larger of the two subwatersheds; it has an area of 48.6 ha, or 0.486 km^2, in the eastern portion of the main watershed. Kendall is typical of southwestern rangeland where cattle graze on gentle hillslopes dominated by grasses.

Soil characteristics at the two sites differ somewhat. At Lucky Hills watershed, the soil type in the upper 25 mm layer is very gravelly sandy loam with a few very fine roots. Between 25 and 600 mm depth, the soil type is gravelly sandy loam with very fine and fine roots. At, Kendall watershed, the soil type in the upper 50 mm layer is very gravelly sandy loam with a few fine roots. Between 50 and 178 mm depth, the soil type is clay loam with very fine and fine roots. The soil type between 179 and 381 mm is clay with very fine and fine roots. The soil type between 382 and 457 mm depth is gravelly clay loam with common very fine and fine roots and a few medium roots. Between 457 and 600 mm depth is gravelly sandy loam with few very fine and fine roots. The root system is not considered significant below 600 mm.

The 600 mm rooting depth is the same at both watersheds, but water holding capacities differ. Soil textural information for each soil layer, and water-holding characteristics of different soils were used to obtain approximate values of soil water content at field capacity and permanent wilting point (USDA, 1955). Available soil water content at Lucky Hills is about 65 mm, the wilting point is 35 mm and the field capacity is about 100 mm. Available soil water content at Kendall is about 82 mm, the wilting point is 76 mm, and the field capacity is about 158 mm.

3. METHODS

3.1 Penman Potential Evapotranspiration(ET)

Penman model is the original and typical example of energy balance model. The form of Penman's potential ET (PET) model has been most extensively applied in hydrometeorology. 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.

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

$$ET_0 = W(R_n + G) + (1-W)E_a \quad (1)$$

where $W(R_n + G)$ is the energy term of Penman PET model; $(1-W)E_a$ is the aerodynamic term of Penman PET model; R_n is the net radiation in mm/day; G is the ground heat flux in mm/day; W = [Δ /Δ + r_z] is the dimensionless weighting factor defined by Doorenbos and Pruitt; Δ is the slope gradient of saturation vapor pressure curve (mb/°C); r_z (= 0.55 mb/°C) is the psychometric constant above mean sea level (z, m) (mb/°C) and can be further represented as r_o (P/Po) = 0.66[(288 - 0.0065z)/288]$^{5.256}$; r_o is psychometric constant at sea level (0.66 mb/°C); P/Po 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:

$$E_a = c \cdot f(u)(e_s - e_a) \quad (2)$$

$$f(u) = 0.263 + 0.141u_2 \quad (3)$$

where c is the unit conversion coefficient (1/86,400,000); e_s, e_a, and u_2 are saturation vapor pressure, actual vapor pressure and wind speed at 2-m height (m/s), respectively.

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

$$e_s = A \cdot \exp[B \cdot T_a /(C + T_a)] \tag{4}$$

When air temperature (T_a) is greater than 0 °C, , and are 6.1078 (mb), 17.269 (/°C), 237.3 (°C), respectively. When air temperature is less than 0 °C, , and 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_s · RH)/100, where RH was relative humidity (%) measured at 2 m height. Therefore, the vapor pressure deficit was (e_s - e_a).

The slope of the saturation vapor pressure curve (Δ) with respect to temperature is obtained by differentiating Eq. (4) to obtain

$$\Delta = \left[\frac{B \cdot C}{(C + T_a)^2}\right]\left[A \cdot \exp(\frac{B \cdot T_a}{C + T_a})\right] \tag{5}$$

3.2 MEASUREMENTS

3.2.1 Surface Energy Balance

The surface energy balance concept is well known and described in many meteorological texts. However, it is useful to review this concept in order to define symbols used in our analysis. For practical work, the energy balance at the earth's surface can be defined by four energy flux density components. These are net radiation (Qn, net exchange of allwave radiation), ground heat flux (Qg, thermal storage rate, primarily in the ground), sensible heat flux (Qh, thermal convective exchange between the earth and atmosphere), and latent heat flux (QLE, energy used to vaporize water). Units of energy flux density in this analysis will be either the flux density rate in W/ m^2 (averaged over a specified time period, such as an hour), or flux density totals for a specified period (typically MJ/m^2d). Energy totals can be expressed as the depth of water containing equivalent latent energy by the relation 1 mm depth is equivalent to 2.45 MJ/m^2. The surface energy balance equation is

$$Qn + Qg + Qh + QLE = 0, \tag{6}$$

with the proviso that an individual flux component is positive when it is directed toward the exchange surface, and negative when directed away from the surface.

All measurements associated with evaluation of the energy fluxes were made with CSI CR-10 data acquisition systems (Campbell Scientific, Inc., Logan, UT 84321-1784, USA).

3.2.2 Net Radiation and Soil Heat Flux.

Net radiation (Qn) was measured with REBS Q*6 net radiometers (Radiation and Energy Balance Systems, Inc., Seattle, WA 98115-0512, USA). The net radiometers were placed 2.5 m above ground level. Qn is the driving factor for energy exchange because in most systems it represents the net energy available from sources and sinks.

Soil heat flux (Qg) is the heat flux (Qgh) detected by a REBS soil heat flux plate at 5 cm depth, plus any change in thermal energy (Qgs) stored in the soil layer between the heat flux plate and the surface. Therefore, soil heat flux is Qg = Qgh + Qgs. At 5 cm depth, Qgh was measured directly with soil heat flux plates at 3 sites in each watershed. The mean Qgh was calculated from the measured values. The hourly energy used for ground heat storage above the sensors (Qgs) was estimated from the change in mean hourly temperature of the 0-5 cm soil layer. The mean temperature of this layer was determined by averaging soil temperatures obtained at the 2.5 cm and 5 cm depths. The averaged ground temperature was used to obtain the Qgs. Therefore,

$$Qgs = 0.01 \Delta Ts Cs \Delta z / \Delta t \quad (7)$$

where Cs is volumetric heat capacity of the soil [= 1.5(MJ/m^{3}K)]; ΔTs is the soil temperature difference between Tsi and Tsi-1, in °C ; Tsi is the average soil temperature at time i (hr); Tsi-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).

3.2.3 Sensible Heat Flux

Sensible heat flux (Qh) in this analysis was measured with the eddy covariance (EC) method during the Monsoon 90 experiment. Values of Qh were calculated from covariance of vertical wind (w, m/s, and air temperature, Ta, °C) both measured at 9 m above ground level and both sampled at 4 Hz over periods of 20 min. The flux was calculated using standard formulation, as

$$Qh = -\rho a \cdot cp \cdot \overline{w' Ta'} \quad (8)$$

where ρa is air density (kg/m^3), cp is specific heat of air (J/kgK), primes denote deviations from period means, and overbars denote period means (Businger et al., 1967).

EC sensors for sensible heat consist of a sensitive, Gill propeller anemometer (Homes, et al., 1964), oriented vertically to sense fluctuations in vertical wind speed, and a CSI fast response, fine-wire thermocouple of 75 micrometers diameter. The anemometer is manufactured by R.M. Young Co., Traverse City, MI 49686, USA. The thermocouple measures fluctuations in air temperature Ta. The "one-propeller eddy covariance" (OPEC) system (Blanford and Gay, 1992) was chosen as an attractive alternative to the sonic eddy covariance (SEC) sensors commonly used in EC systems. The OPEC system is lighter, less expensive, operates from battery power, and requires little attention, even in unfavorable weather. OPEC computations of sensible heat require only modest amounts of memory and calculation capacity and these calculations are done online for the 20- to 30-min averaging periods. It is necessary to avoid inertial effects on propeller response by placing the OPEC sensors at least 6 m above the surface, in the region where eddies are slower and larger. The higher position is beneficial for this study since it enlarges the area being sampled. Blanford and Stannard (1991) used a footprint model to predict that a Walnut Gulch systems at 9 m height will respond in neutral conditions to surface effects the surface as much as 150 m away in the upwind direction.

The effect of atmospheric stability on the OPEC estimates of Qh must also be taken into account. Blanford and Gay (1992) developed stability corrections for the OPEC sensible heat, based upon theoretical and experimental ground. They concluded that OPEC sensible heat flux should be corrected by multiplicative factors of 1.4 in stable atmospheres (as at midnight), and 1.1 in unstable atmospheres (as at midday). These corrections are similar to those proposed by Amiro and Wuschke (1987) from their em-

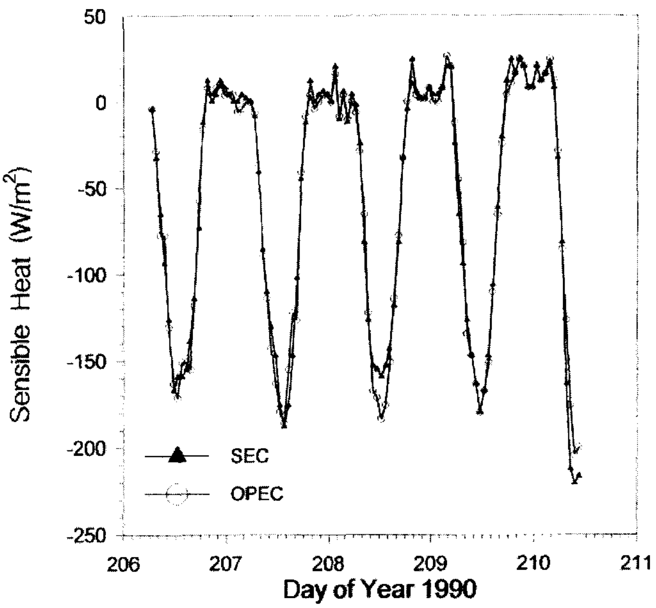


Fig. 2. Comparison of OPEC sensible heat against SEC sensible heat at Walnut Gulch

pirical comparisons between propeller-based EC and sonic-based EC.

The question to be answered at this point is whether or not Qh from a simple OPEC system satisfactorily duplicates Qh from a more expensive SEC system. Short-term calibrations of OPEC elsewhere have shown excellent agreement (Blanford and Gay, 1992; Gay, et al., 1996a). In addition, Blanford and Stannard (1991) compared an OPEC system with a SEC system for 4.25 consecutive days (DOY 206.25 to 210.44) in July 1990 at Walnut Gulch during the Monsoon 90 experiments. The results (hourly means in W/m^2) are plotted as a time series in Fig. 1. It is evident that Qh from OPEC at Walnut Gulch is in excellent agreement with Qh from SEC. Regressing SEC sensible heat against OPEC sensible heat confirms the agreement that is obvious in Fig. 1. The sensible heat regression based upon 101 consecutive 1-hr means at Walnut Gulch shows that SEC (W/m^2) = 1.0 OPEC + 0.2, with a standard error of 10.2 and R2=0.981. This comparison provides conclusive evidence that the OPEC and SEC sensors in Fig. 2 are measuring the same sensible heat flux.

3.2.4 Latent Heat Flux and Evapotranspiration

Latent heat flux (QLE) was not measured directly in this study but was computed as the residual term in the surface energy balance using Eq. (6). Daily ET was obtained by summing the hourly ET for each day. Actual evapotranspiration (AET) differs from latent energy (QLE) only in units. ET is the "depth equivalent" of evaporated water (in mm per period) while QLE is in MJ/m^{2}d.

3.2.5 Soil Moisture

The data on the vertical distribution of soil moisture was collected by the Agriculture Research Service (Goodrich et al., 1994) using the time domain reflectometry (TDR) method at Lucky Hills and Kendall watersheds. The TDR sensors were positioned at 6 different depths from 0 to 60 cm, which represents the total rooting depth of each watershed. The total water content for 60 cm depth was estimated from the TDR volumetric soil water content 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) approximately 50 m southeast of the Lucky Hills meteorological and flux station. 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 replications each). The TDR measurements from ungrazed areas at Kendall were used to estimate conditions of similar areas in the vicinity of the measurement sites. The average of the TDR replications in each watershed was used to represent the soil water content.

Table 1. Energy balance for a 24-hour period of evaporating surfaces, average daily wind speed, vapor pressure deficit and soil moisture

No.	DOY	Condition	Qs	Qn	Qh	Qg	QLE	VPD	$\bar{u}$	SM	Remarks
1	90201	shrub(wet)	26.17	14.88	1.21	-0.61	14.29	8.33	2.23	102.61	
2	90203	shrub(wet)	27.40	14.08	2.67	1.49	9.91	12.75	1.83	100.75	
3	90212	shrub(dry)	28.20	12.85	5.11	0.64	7.10	17.72	2.70	71.64	
4	90222	shrub(dry)	29.12	13.47	4.61	0.70	8.16	19.30	2.74	63.12	
5	90214	grass(wet)	19.92	11.58	2.87	-1.99	10.61	3.86	1.91	104.40	*
6	90215	grass(wet)	19.64	11.20	2.54	-1.32	9.99	5.20	1.91	101.16	*
7	90211	grass(dry)	24.82	12.07	4.23	0.47	6.82	14.86	2.90	78.95	
8	90212	grass(dry)	25.55	12.49	4.86	0.97	6.65	15.86	3.49	76.21	
9	92033	shrub(wet)	3.79	1.07	0.34	-0.94	1.67	1.93	1.38	92.55	*
10	92034	shrub(wet)	6.09	2.07	0.51	-0.99	2.55	1.71	1.60	92.00	*
11	92059	shrub(dry)	21.27	7.08	4.99	0.45	1.64	12.25	2.36	80.23	
12	92060	shrub(dry)	18.80	6.40	4.25	0.51	1.64	13.65	3.28	79.56	
13	92044	grass(wet)	6.84	2.92	0.13	-0.95	3.74	2.69	4.48	153.23	*
14	92045	grass(wet)	17.29	6.31	2.60	-0.63	4.34	4.56	2.55	151.44	
15	92059	grass(dry)	19.97	6.26	4.07	0.24	1.95	12.80	3.11	137.31	
16	92060	grass(dry)	16.78	5.13	3.43	0.00	1.69	13.26	3.58	136.61	

DOY: day of year, Qs: incoming solar radiation(MJ/m^2d), Qn: net radiation(MJ/m^2d), Qh: sensible heat flux(MJ/m^2d), Qg: ground heat flux(MJ/m^2d), QLE: latent heat flux(MJ/m^2d), VPD: vapor pressure deficit(mb), $\bar{u}$: wind speed(m/sec), SM: soil moisture content(mm), * : rainy day

4. RESULTS AND DISCUSSION

Based on the energy balance concept, surface radiative imbalance is accounted for by convective exchange (Qh, QLE) to or from the atmosphere, and conduction into or out of the underlying soil (Qg). The radiative surplus and deficit is mainly governed by the nature of the surface condition. Table 1 shows the energy balance for a 24-hour period of evaporating surfaces, average daily wind speed, vapor pressure deficit and soil moisture.

The Qn was not sensitive to a change of soil water content for both grass land and shrub land. Similar results were also reported by Granger (1989) and Morton (1968). This results may indicate that both the albedo and emissivity properties of the surface are not sensitive to the change of soil moisture availability.

However, QLE, Qh, and Qg were sensitive to the variations of soil water content, with the Qh term being most sensitive. As the soil surface is wet, QLE increased; but Qh and Qg decreased. There was an especially strong relationship between QLE and Qh. If the surface is wet, the majority of the energy being convected into the atmosphere was in the latent heat form. However, if the surface is dry, the majority of the

Table 2. Comparison of 24-hour values for measured evapotranspiration to estimated evatranspiration

No.	DOY	Condition	$W(R_n+G)$	$(1-W)E_a$	ET_o	ET	ET/ET_o
1	90201	shrub(wet)	4.785	0.921	5.706	5.801	1.016
2	90203	shrub(wet)	4.004	1.241	5.245	4.120	0.785
3	90212	shrub(dry)	3.855	2.054	5.909	3.081	0.521
4	90222	shrub(dry)	3.312	0.915	4.227	2.847	0.673
5	90214	grass(wet)	3.876	0.491	4.367	4.435	1.015
6	90215	grass(wet)	3.686	0.644	4.330	4.170	0.963
7	90211	grass(dry)	3.544	1.918	5.462	3.152	0.577
8	90212	grass(dry)	3.557	2.244	5.801	2.889	0.498
9	92033	shrub(wet)	0.403	0.296	0.699	0.695	0.994
10	92034	shrub(wet)	0.654	0.298	0.951	1.036	1.089
11	92059	shrub(dry)	1.893	2.051	3.944	0.832	0.210
12	92060	shrub(dry)	1.720	2.711	4.431	0.788	0.158
13	92044	grass(wet)	0.864	0.815	1.680	1.488	0.885
14	92045	grass(wet)	1.754	0.858	2.612	1.830	0.700
15	92059	grass(dry)	1.713	2.503	4.217	0.920	0.218
16	92060	grass(dry)	1.453	2.869	4.322	0.796	0.184

DOY: day of year, $W(R_n+G)$: energy term of Penman ET model(mm/d), $(1-W)E_a$: aerodynamic term of Penman ET model(mm/d), ET: measured evapotranspiration(mm/d), ET_o: estimated Penman evapotranspiration (mm/d), ET/ET_o: ratio of measured over estimated evapotranspiration energy being convected into the atmosphere is in the sensible form. Qg during dry days also showed higher values than those during wet days. It is obvious that vapor pressure deficit(VPD) increase as the soil surface is dry.

To understand the physical meaning of meteorological and flux variables on the estimation of hourly ET, energy term and aerodynamic terms of hourly Penman model were plotted and compared for different soil moisture, vegetation, and seasonal conditions. As shown in Table 2, the ratio of ET/ET_0 is almost 1.0 when the soil is wet, and the ratio decreases when the soil is dry. This phenomena appeared regardless of seasons and vegetation conditions. During the winter days at both watersheds, the aerodynamic term of Penman ET is much greater than that of energy term of Penman ET for dry soil condition because of vapor pressure deficit. It also indicates that energy is not much more important factor for ET estimation compared with wind speed during the days. On the other hand, the opposite phenomena appeared for wet soil condition.

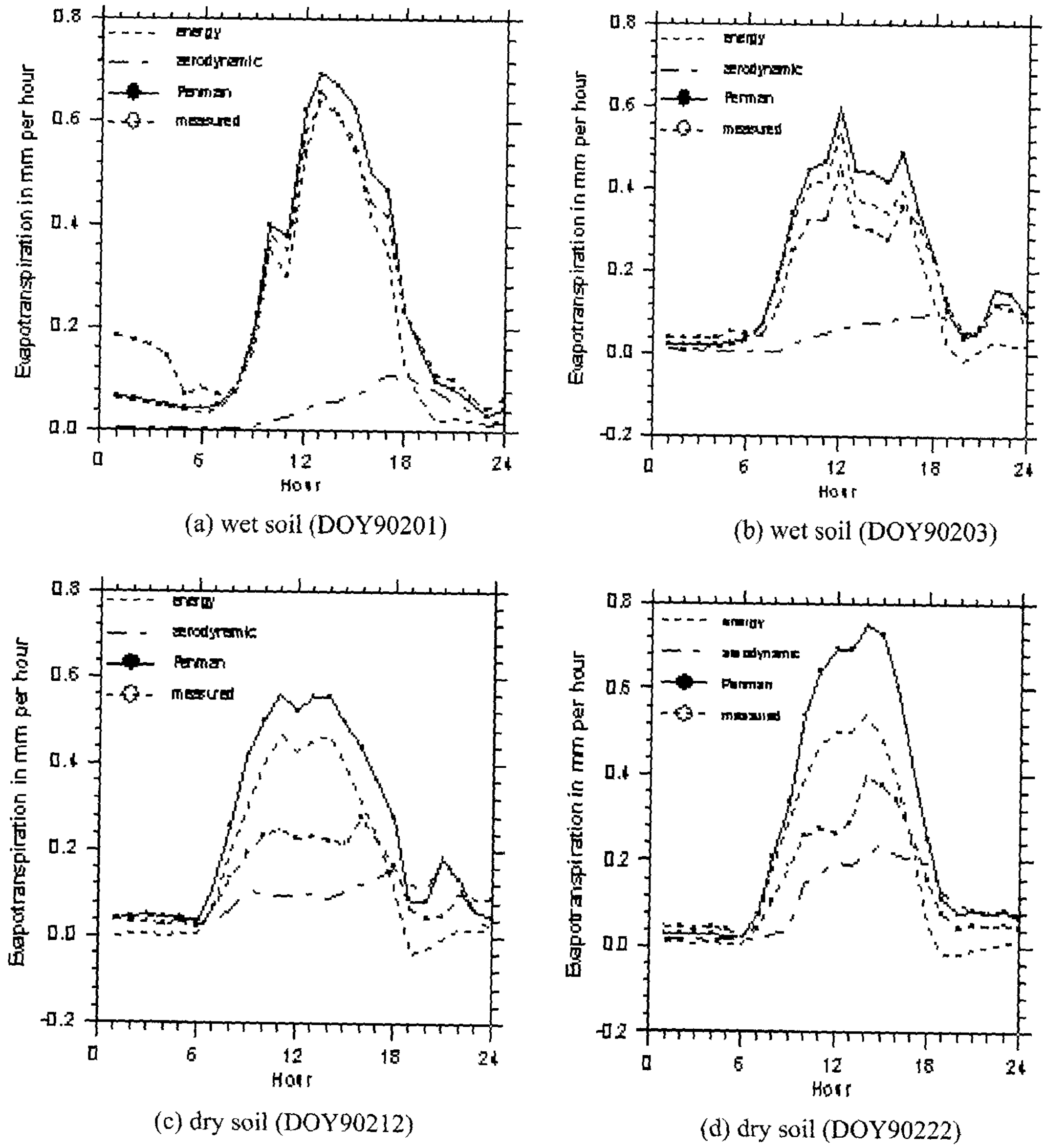
During the summer days at both watersheds, the energy term of Penman ET is much greater than that of aerodynamic term of Penman ET regardless of soil moisture condition because of strong solar radiation during the summer days. It indicates that energy is much more important factor for ET estimation compared with wind speed during the days.

To study the effects of surface condition (soil water content) on the estimates of ET, the hourly values of the measured and estimated ET using Penman equation for wet and dry soil condition during summer and winter days at two different watersheds were plotted and compared (Figs. 3 to 6). As shown in Figs. 3 to 6, when the potential ET is computed for a dry soil condition, it exceeds measured ET regardless of season and vegetation condition. On the other hand, the assumption of surface wetness leading to the potential ET concept is certainly met during the wet day.

There were very similar variation patterns of hourly energy term for both wet and dry days showing the highest values at midday. This study results may indicate that the variation of Qn is not sensitive to the change of soil water content, and that both the albedo and emissivity properties of the surface are not sensitive to the change of soil moisture availability. On the other hand, hourly variation of aerodynamic term for both wet and dry days at both watersheds showed the highest values in the afternoon due to a strong wind. Therefore, in the estimation of ET using Penman model, the energy term has significant effect at midday, and the aerodynamic term has significant effect in the afternoon.

Even though there are much more soil moisture in the soil during the wet days shown in Figs. 4(a) and 4(b), the estimated hourly ET from Penman model and measured hourly ET have smaller values compared with those of dry days shown in Figs. 4(c) and 4(d). That is mainly because the energy term values during the rainy day are small due to small net radiation. The aerodynamic terms of wet days also show the lower values compared with those of dry days, indicating the weak wind with low vapor pressure deficit. This phenomenon is also appeared in the rainy days shown in Figs. 5(a), 5(b) and 6(a).

Considering the hourly variation patterns of Penman ET in Figs. 3 to 6, it seems that Penman ET, measured ET, and energy term show the similar hourly variation pattern mainly because the influence of net radiation on the estimation



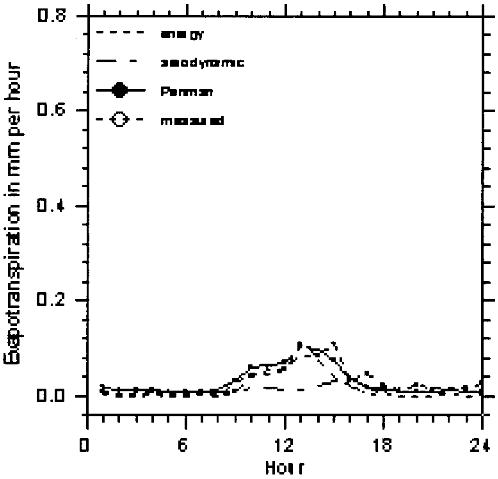
(a) wet soil (DOY90201)

(b) wet soil (DOY90203)

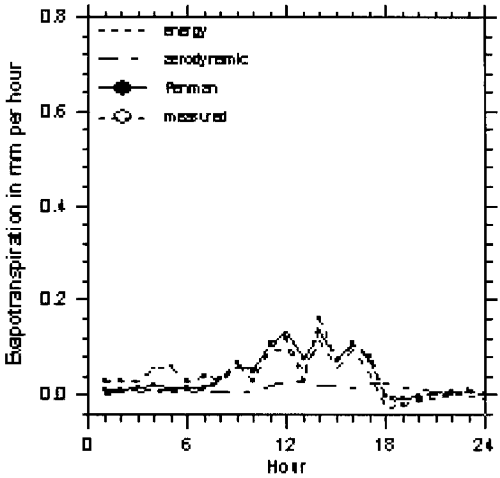
(c) dry soil (DOY90212)

(d) dry soil (DOY90222)

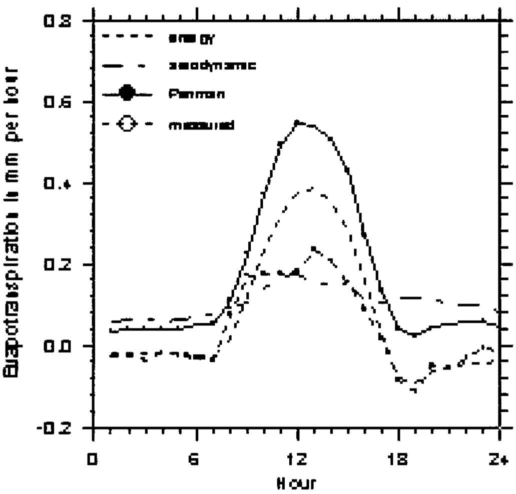
Fig. 3. A comparison of calculated versus measured values of the hourly evaporation rate from shrub land (summer days)



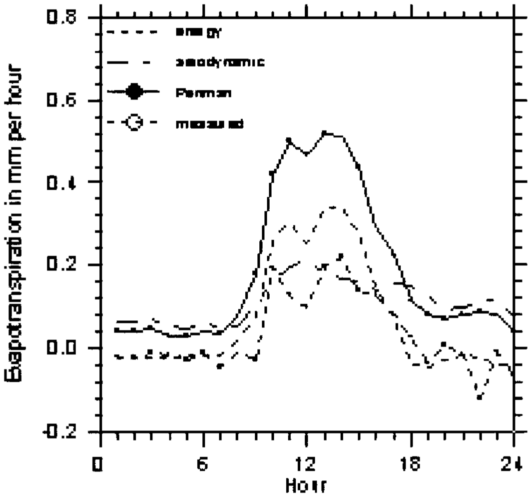
(a) wet soil (DOY92033)



(b) wet soil (DOY92034)

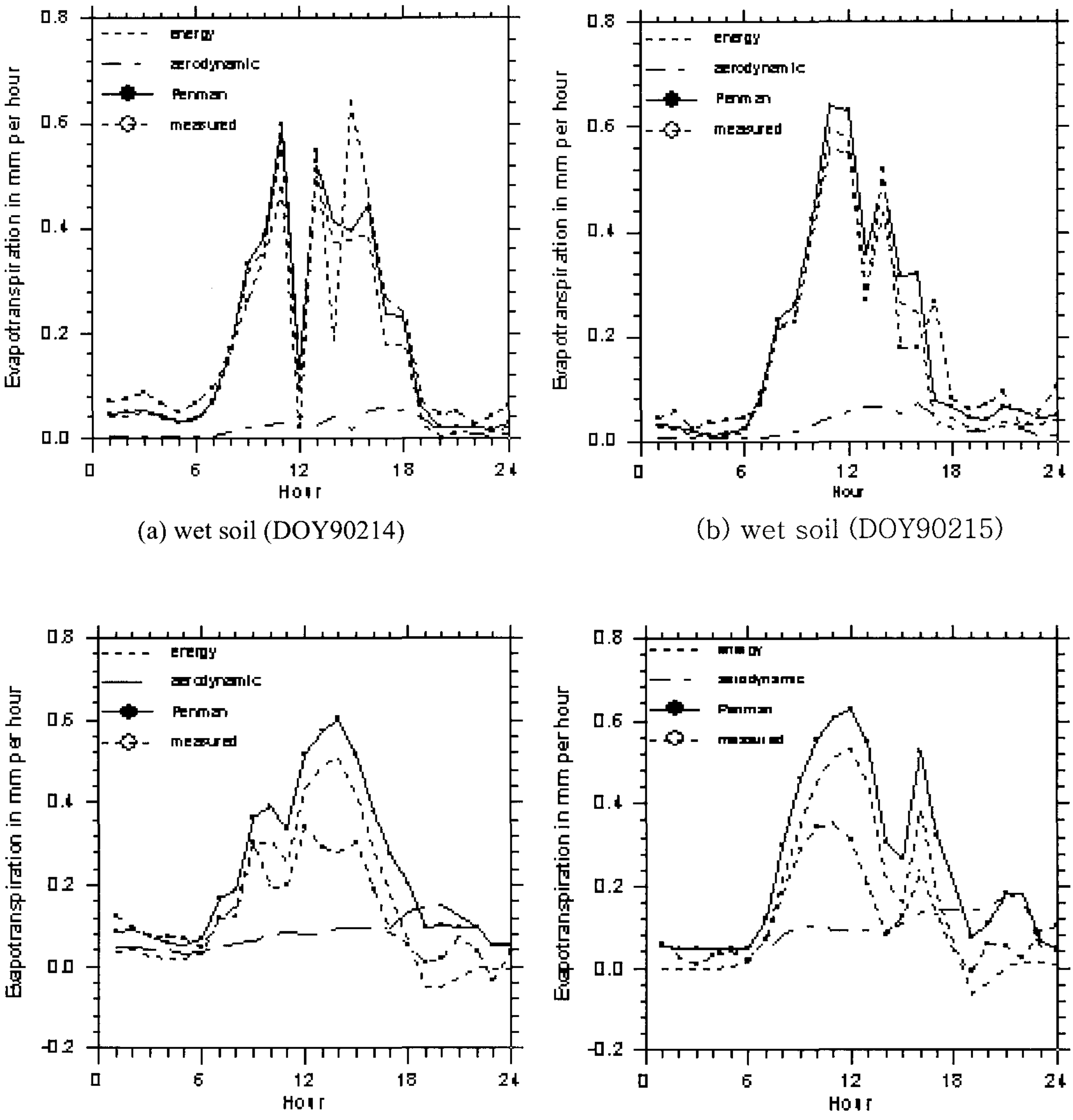


(c) dry soil (DOY92059)



(d) dry soil (DOY92060)

Fig. 4. A comparison of calculated versus measured values of the hourly evapotranspiration rate from shrub land at Lucky Hills (winter period)



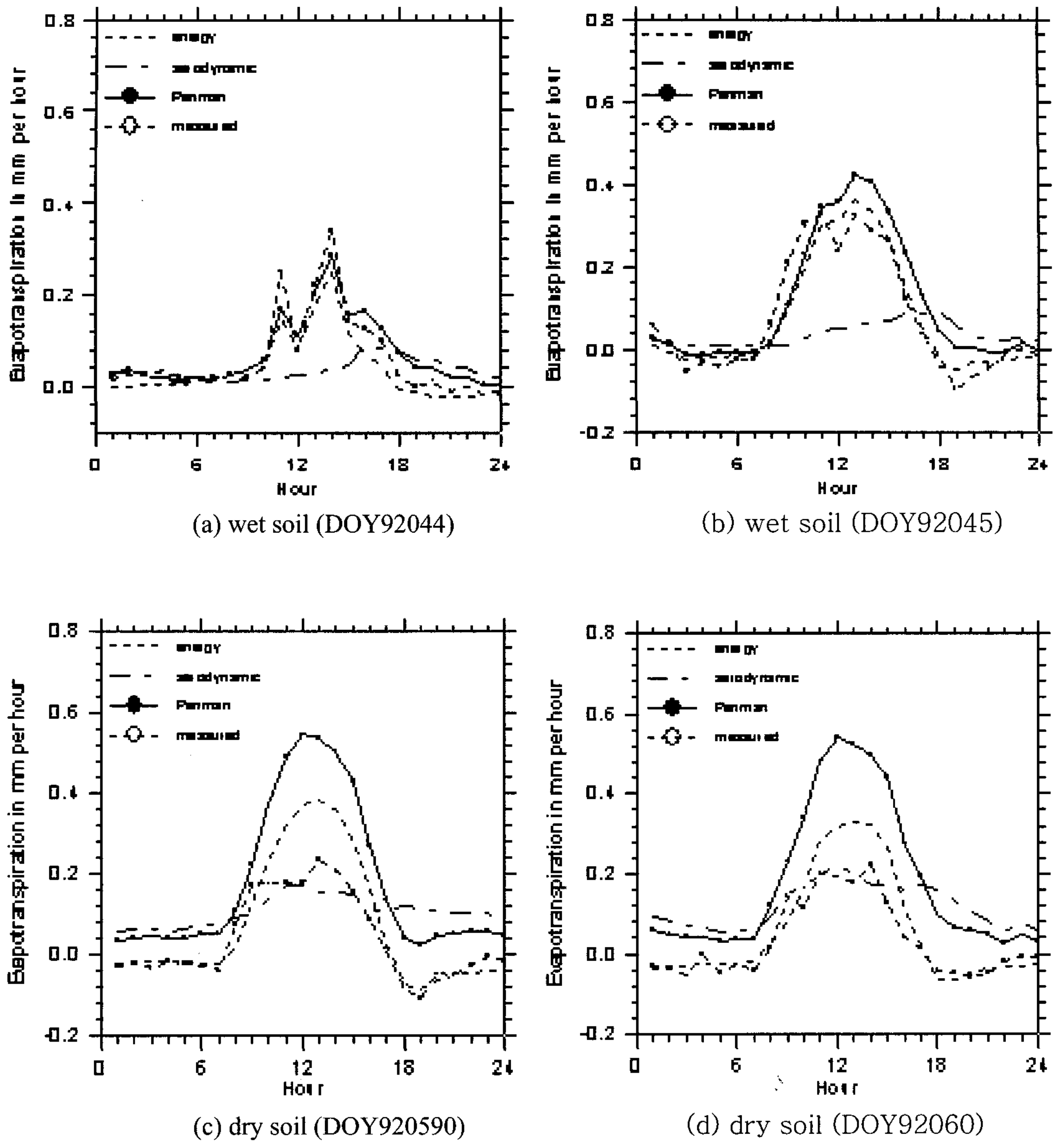
(a) wet soil (DOY90214)

(b) wet soil (DOY90215)

(c) dry soil (DOY90211)

(d) dry soil (DOY90212)

Fig. 5. A comparison of calculated versus measured values of the hourly evaporation rate from grass land (summer days)



(a) wet soil (DOY92044)   (b) wet soil (DOY92045)

(c) dry soil (DOY920590)   (d) dry soil (DOY92060)

Fig. 6. A comparison of calculated versus measured values of the hourly evaporation rate from grass land (winter days)

of Penman ET is much more significant compared with other variables. The net radiation is the driving factor for energy exchange because in most systems it represents the net energy available from sources and sinks

5. CONCLUSIONS

To study the effects of surface condition (soil water content) on estimates of ET, energy balance for 24-hour period of evaporating surfaces (grass land and shrub land) during the summer and winter days was examined. The study results indicate that the net radiation was not sensitive to a change in soil water content for both grass land and shrub land. This results may indicate that both the albedo and emissivity properties of the surface are not sensitive to the change of soil moisture availability. However, latent heat flux(QLE), sensible heat flux(Qh), and ground heat flux(Qg) were sensitive to variations in soil water content, with the Qh term being most sensitive. As the soil surface is wet, QLE increased; but Qh and Qg decreased. There was an especially strong relationship between QLE and Qh.

During the winter days at both watersheds, the aerodynamic term of Penman ET is much greater than that of energy term of Penman ET for dry soil condition because of vapor pressure deficit. It also indicates that energy is not much more important factor for ET estimation compared with wind speed during the days. On the other hand, the opposit phenomena appeared for wet soil condition. During the summer days at both watersheds, energy term is much more important factor for ET estimation compared with aerodynamic term during the period.

There were very similar variation patterns of hourly energy term for both wet and dry days showing the highest values at midday. This study results may indicate that the variation of Qn is not sensitive to the change of soil water content, and that both the albedo and emissivity properties of the surface are not sensitive to the change of soil moisture availability. On the other hand, hourly variation of aerodynamic term for both wet and dry days at both watersheds showed the highest values in the afternoon due to a strong wind. Therefore, in the estimation of ET using Penman model, the energy term has significant effect at midday, and the aerodynamic term has significant effect in the afternoon.

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