A Study on the Surface Resistance

Rim, Chang-Soo*

1. Introduction

Evapotranspiration 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. Recent developments of evapotranspiration models indicate that vegetation and crop must take surface parameters into account. One of the method to estimate actual evapotranspiration considering surface parameters is Penman-Monteith equation proposed by Monteith (1964). Monteith discussed the concepts and relationships of aerodynamic and surface resistance in the evaporative process and incorporated them into the Penman combination equation (1948). He used a single "surface resistance" and an "aerodynamic resistance" to characterize the physiological and meteorological control of water loss from a plant community.

Surface resistance was calculated from the ratio of potential to actual evapotranspiration using Penman-Monteith equation, and potential evapotranspiration was calculated from Penman-Monteith equation, putting surface resistance equals zero. The relationship between surface resistance, r_s (in sec/m) and soil moisture at 5 cm, 20 cm and 60 cm depths from the ground surface was obtained. The daily variations of soil moisture at 5 cm, 20 cm and 60 cm depths from the ground surface indicate that the variation of soil moisture is not highly correlated with surface resistance. The study results also indicate that the correlation between soil moisture content and surface resistance decreases as thickness of soil increases. The diurnal variation of surface resistance is relatively less significant in the morning and relatively more significant in the afternoon.

2. Experimental Site

The site chosen for the experiment is the well-instrumented Lucky Hills experimental watershed operated by the Southwest Watershed Research Center of the U.S. Department of Agriculture's Agricultural Research Service (ARS). The region has 250-500 mm of annual precipitation with the majority falling during a "summer monsoon season" in July and August. Lucky Hills has an area of 8.09 ha, having smoother topography. The dominant vegetation type is shrub.

3. Measurements

Meteorological and flux data used in this study were collected over native rangeland

* Department of Civil and Environmental Engineering, Chungwoon University

shrub at Lucky Hills during the summer rainy period from July 17 through August 10, 1990. The data on the vertical distribution of soil moisture was collected by the ARS (Goodrich et al., 1994) using the time domain reflectometry (TDR) method at Lucky Hills 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 5 cm, 20 cm, and 60 cm depths 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 average of the TDR replications in each watershed was used to represent the soil water content.

4. Analyses and Results

4.1 The Penman-Monteith Equation

A fundamental extension of Penman's model was developed by Monteith (1964). The Penman-Monteith equation is a one-dimensional single-source model of the evapotranspiration process. He used a single "surface resistance" and an "aerodynamic resistance" to characterize the physiological and meteorological control of water loss from a plant community. Thus, he modified Penman's equation to obtain

$$AET = \frac{\Delta(R_n + G) + \gamma \cdot E_a}{\Delta + \gamma(1 + r_s / r_a)} \tag{1}$$

where AET is the actual evapotranspiration (mm/day); Δ is the slope gradient of saturation vapor pressure curve (mb/°C); R_n is the net radiation (mm/day); γ (=0.55 mb/°C) is the psychometric constant above mean sea level; G is the combination of heat flux at soil heat flux plate and thermal energy stored in the soil layer above the sensor (mm/day); E_a is an aerodynamic vapor transport term, mm/day. The E_a can be defined as :

$$E_a = \frac{\rho \cdot c_p(e_{sa} - e_a)}{\lambda \cdot \gamma \cdot r_a} \tag{2}$$

where ρ is the density of air (g/m^3); c_p is the specific heat of air (cal/g°C); e_{sa} is the mean saturation vapor pressure at air temperature at height 2 m above the ground (mb); e_a is the saturation vapor pressure at dew-point temperature measured at height 2m above the ground (mb); λ is the latent heat of vaporization (cal/g); γ is the psychrometric constant (mb/°C); r_s is the surface resistance (s/m); r_a is the aerodynamic resistance (s/m). The r_a can be defined for neutral buoyancy conditions as:

$$r_a = \frac{\left[\ln\left(\frac{z-d}{z_o}\right)\right]^2}{k^2 \cdot u_z} \tag{3}$$

where u_z is wind speed at height z, in m/s; k is the von Karman constant of proportionality (0.41); z is the wind, air temperature, and vapor pressure measurement height, in mm; z_o is the surface roughness parameter, in mm; and d is the zero plane displacement height within the vegetation (height where wind speed averages zero), in mm. In practice for a wide range of vegetation the value of d and z_0 are approximately given by eqs. (4) and (5), respectively (Oak, 1987).

$$d = 0.667h \tag{4}$$
$$z_o = 0.1h \tag{5}$$

where h is the vegetation height, in mm.

Eqs. (4) and (5) ignores the influences of shape and spacing of the elements. Therefore, PET (potential evapotranspiration) obtained from eq.(1) and PET obtained from Penman equation have been compared to determine d and z_0. For the purpose of the present study, constant values of d and z_0 have been used to obtain r_a, chosen to be representative of desert shrub condition for Lucky Hills watershed. Furthermore, for simplicity, stability effects are ignored here and turbulent transfer coefficients for heat, water vapor and momentum are assumed equal. Variables used for the surface conditions at Lucky Hills watershed are listed in Table 1.

Table 1. Surface conditions used at Lucky Hills watershed

z (mm)	h (mm)	d (mm)	z_0 (mm)
2,000	800	9.4	1.4

z : wind, air temperature, and vapor pressure measurement height
h : vegetation height
d : zero plane displacement height within the vegetation
z_0 : surface roughness parameter

Potential evapotranspiration equation (eq. 6) can be derived from eq. (1), using the relevant r_a and putting r_s=0

$$PET = \frac{\Delta(R_n + G) + \gamma \cdot E_a}{\Delta + \gamma} \tag{6}$$

From eq. (1) and (6) surface resistance can be obtained from (Monteith et al., 1965):

$$r_s = r_a(1 + \frac{\Delta}{\gamma})(\frac{PET}{AET} - 1) \tag{7}$$

where Δ is the slope gradient of saturation vapor pressure curve (mb/°C); γ (=0.55 mb/°C) is the psychometric constant above mean sea level. Eq. (7) allows retrospective evaluation of r_s from previously determined AET values. These may then be used to assign signature values for surfaces or to derive predictive procedures to allow AET to be evaluated from eq. (1). In this study AET is estimated from energy balance approach and PET is calculated from eq. (6).

4.2 Daily variation of surface resistance as a function of soil moisture

Figure 1 shows the daily variation of surface resistance, rainfall, AET, PET, and soil moisture at 3 different depths (5 cm, 20 cm and 60 cm) during the study period. On July 17 (DOY 198), surface resistance, actual evapotranspiration, and potential evapotranspiration were

361 sec/m, 3.86 mm, and 5.45 mm, respectively. On July 18 (DOY 199), there was 2.50 mm of

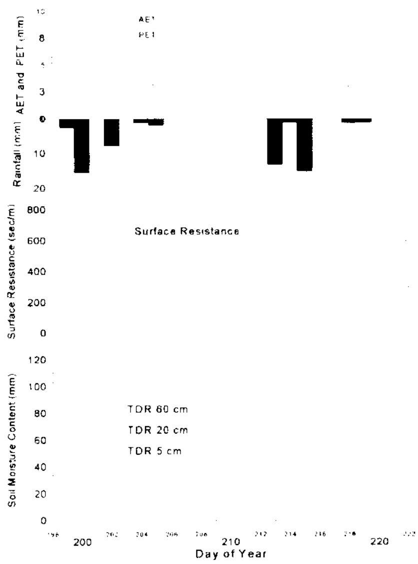
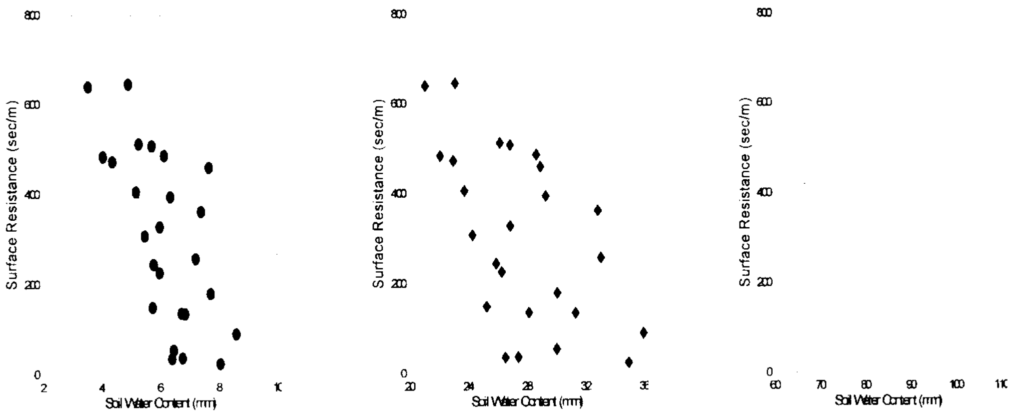


Fig. 1. Daily variation of surface resistance, rainfall, AET, PET, and soil moisture contents at 3 different depths (5 cm, 20 cm and 60 cm).

rainfall. The following day, there was a 15.45 mm of rainfall. Surface resistance value immediately fell to 23 sec/m on DOY 201. During this day of lower surface resistance, energy balance results show that 5.88 mm of water evapotranspirated. The period of low surface resistance corresponded to the period during which soil is wet. There was a rainfall until DOY 205. Following this the soil moisture was depleted until DOY 211. On DOY 211, surface resistance and actual evapotranspiration were 484 sec/m and 3.13 mm, respectively. The variation of soil moisture content from DOY 200 to DOY 211 showed some decreasing trend.

Another rainfall event occurred on DOY 213, and continued until DOY 219. The surface resistance was 36 sec/m with 4.26 mm of actual evapotranspiration on DOY 214, and at the end of the study period (DOY 222) the surface resistance was 645 sec/m with 3.36 mm of actual evapotranspiration. The surface resistance was low when there was high soil moisture content, and the surface resistance was high when there was low soil moisture content. Based on the study results, it can be concluded that surface resistance is sensitive to the variation of soil moisture (therefore rainfall rate).

The relationships between surface resistance, r_s (in sec/m) and soil moisture at 5 cm, 20 cm, and 60 cm depths from the ground surface are shown in Figure 2. The average value of surface resistance during the study period is 302 sec/m. The daily values of soil moisture at 5 cm, 20 cm and 60 cm depths from the ground surface indicate that the daily variation of soil moisture is not highly correlated with surface resistance. The study results also indicated that the correlation between surface resistance and soil moisture content decreases as thickness of soil increases. This is probably because desert shrub in semiarid watershed is not active on transpiration.



(a) (b) (c)

Fig. 2. Daily variation of surface resistance as a function of soil moisture (a) at top 5 cm, (b) at top 20 cm, and (c) at top 60 cm depths from the ground surface.

4.3 Diurnal variation of surface resistance, aerodynamic resistance and actual evapotranspiration during the relatively wet and dry days

To study the effects of soil moisture on actual evapotranspiration, two days (DOY 203 and DOY 211) were chosen. DOY 203 represents the relatively wet day, and DOY 211 represents the relatively dry day. Figure 3 show the two progressive stages of drying. The figure show the diurnal variation of surface resistance, aerodynamic resistance, and actual evapotranspiration.

The r_a obtained from eq. (3) was used to find the diurnal variation of aerodynamic resistance as a function of wind speed and surface roughness. Aerodynamic resistance exhibited a less significant diurnal pattern, compared with surface resistance. Daytime values of r_a usually were between 141 and 437 during the DOY 203, and between 92 and 165 during the DOY 211.

The r_s obtained from eq. (7) was used to find the diurnal variation of surface resistance as a function of soil moisture. The diurnal variation of surface resistance is relatively less significant in the morning and relatively more significant in the afternoon. A clear response of the soil moisture change was observed eight days later (DOY 211), as in Fig. 3, with the maximum value of r_s being around 1253 sec/m.

5. Conclusions

Meteorological, flux and soil moisture data measured from small semiarid watershed during the summer rainy period were used to find the relationship between actual evapotranspiration and surface resistance as a function of soil moisture content measured at several different depths (5cm, 20cm and 60cm). The surface resistance obtained from Penman-Monteith equation suggested by Monteith (1964) was also used to find the diurnal variation of surface

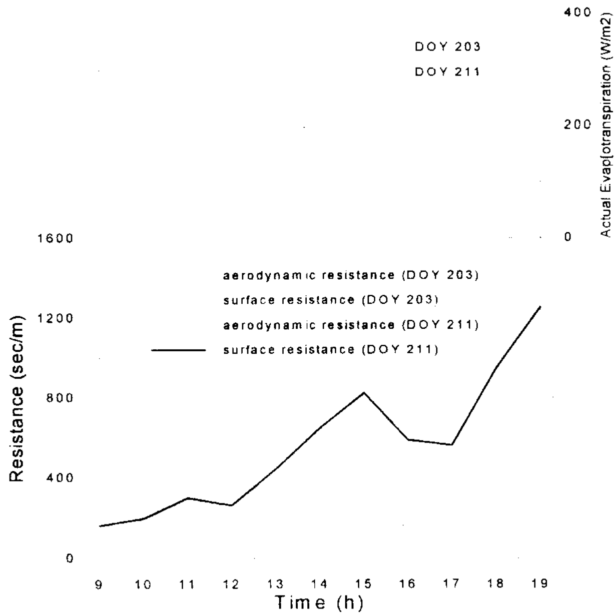


Fig. 3. Diurnal variation of the surface resistance, aerodynamic resistance and AET at Lucky Hills watershed, 1990.

resistance as a function of soil moisture. Furthermore, the effects of wind and surface roughness on actual evapotranspiration was examined using the concept of aerodynamic resistance.

The diurnal variation of surface resistance is relatively less significant in the morning and relatively more significant in the afternoon. Aerodynamic resistance exhibited a less significant diurnal pattern, compared with surface resistance. The daily variations of soil moisture at 5 cm, 20 cm and 60 cm depths from the ground surface indicate that the variation of soil moisture is not highly correlated with soil moisture (therefore rainfall rate). The study results also indicate that the correlation between soil moisture content and surface resistance decreases as thickness of soil increases. This is probably because desert shrub in semiarid watershed is not active on transpiration.

6. References

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