Comparison of Daily Soil Water Contents Obtained by Energy Balance–Water Budget Approach and TDR

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ABSTRACT : The daily soil water contents were obtained from the time domain reflectometry (TDR) method and energy balance-water budget approach with eddy correlation at the two small semiarid watersheds of Lucky Hills and Kendall during the summer rainy period. There was a comparison of daily soil water content measured and estimated from these two different approaches. The comparison is valuable to evaluate the accuracy of current soil water content measuring system using TDR and energy balance-water budget approach using eddy correlation method at a small watershed scale. The degree of similarity between the regressions of these two methods of measuring soil water content was explained by determining the correlations between these methods. Simple linear regression analyses showed that soil water content measured from TDR method was responsible for 58 % and 63 % of the variations estimated from energy balance-water budget approach with eddy correlation at Lucky Hills and Kendall, respectively. The scatter plots and the regression analyses revealed that two different approaches for soil water content measurement at a small watershed scale have no significant difference.

1. Introduction

The hydrologic cycle is studied primarily in terms of water fluxes and the principle of "conservation of mass" and is expressed as a water balance. Evapotranspiration (ET) which includes evaporation of precipitation from the plant surface and evaporation of moisture from the soil surface and from plants through transpiration is an important factor in the water balance. The hydrologic cycle can also be evaluated with respect to the surface energy balance, as the thermal energy from solar radiation is absorbed and transformed into either sensible or latent heat.

The selected experimental watersheds located in the southwest of the United State represent a typical semiarid land. Since the vegetation in semiarid rangelands is fairly sparse compared with humid regions, the soil plays a major role in the radiative and hydrologic balance (Kustus et al., 1991). In terms of the hydrologic cycle, the condition of the soil surface influences the mag-

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nitude of the runoff component. This is especially evident in semiarid and arid rangelands, where infiltration may be one of the most important factors in determining the amount of runoff (Keppel and Renard, 1962). Antecedent soil moisture is certainly an important factor in the amount of runoff at the watershed scale in this area (Hino et al., 1988 ; Loague and Freeze, 1985).

Many investigators (Kincaid et al., 1964 ; Osborn and Lane, 1969; Lane and Stone, 1983 ; Faures, 1990) have studied hydrologic systems using a water balance approach in arid watershed areas. Lane et al. (1984) studied water balance calculations for a unit area watershed in the northern Mojave desert. They used computed evapotranspiration rates to estimate water use by perennial vegetation.

The daily soil water contents were estimated from the energy balance-water budget approach with the eddy correlation at semiarid watersheds of Lucky Hills and Kendall during the summer rainy period. This daily estimated soil water contents were compared with the measured soil water contents using TDR at a watershed scale. The comparison is valuable to evaluate the accuracy of current soil water content measuring system using TDR and sensible heat flux measurement using eddy correlation method at a small watershed.

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 the southwestern Arizona about 120 km southeast of Tucson, Arizona (Fig. 1). The Walnut Gulch watershed encompasses the 150 km2. The region has 250-500 mm of annual precipitation with the majority falling during a "summer monsoon season" in July and August. The rainfall pattern during the summer rainy period is the airmass thunderstorms characterized by the extreme spatial variability with short duration and limited areal extent.

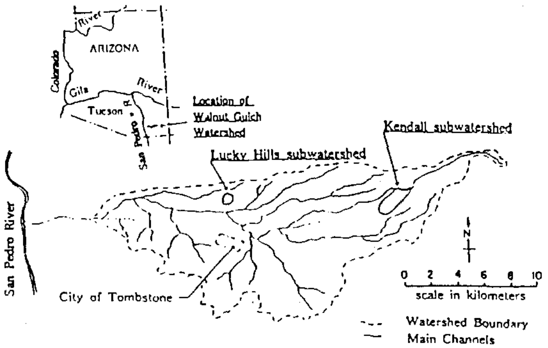

Fig. 1 USDA-ARS Walnut Gulch Experimental Watershed Location Map

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 (0.08 km^2) nestled in the western portion of the Walnut Gulch watershed, having smoother topography (Fig. 2). The dominant vegetation type is shrub. Raingages 83 and 384 are located on or near the Lucky Hills watershed.

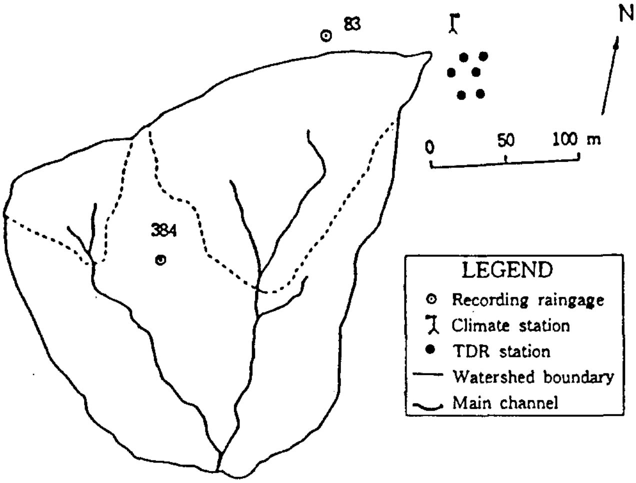

Fig. 2 Lucky Hills Watershed Map

The Kendall subwatershed has an area of 48.6 ha (0.48km^2) nestled in the eastern portion of the Walnut Gulch watershed (Fig. 3). It is typical of the southwestern rangeland where cattle graze on gentle hillslopes dominated by grass. Raingages 60, 61, 560 and 82 are located on or near the Kendall watershed.

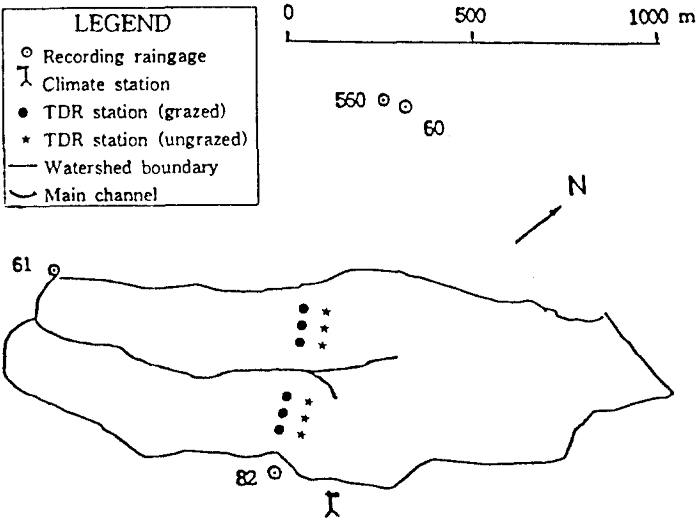

Fig. 3 Kendall Watershed Map

Runoff was measured at the outlets of the Lucky Hills and Kendall subwatersheds by a calibrated Smith supercritical flume (Smith et al., 1981). In the study area, 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 range from minutes to hours, rather than by days. The dominant factor in runoff variability at the small watersheds such as Lucky Hills and Kendall is rainfall variability (Renard et al., 1993). 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 the increasing watershed size. If only the Lucky Hills or Kendall watersheds are considered, channel losses are less significant because of the steep slopes and small drainage area of these two subwatersheds.

3. Method and Results

The flux data were measured from the Monsoon 90 experiment (Kustus et al., 1991). Flux 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.

The data on the vertical distribution of soil moisture were collected by ARS 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. 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). The 600 mm rooting depth is the same at both watersheds, but the water holding capacities differ. Available soil water content at Lucky Hills is about 65 mm, while the wilting point is 35 mm and the field capacity is about 100 mm. Available soil water content at Kendall is about 82 mm, while the wilting point is 76 mm and the field capacity is about 158 mm.

3.1 Flux Measurements

The flux data (net radiation(Q_n), sensible heat flux(Q_h) and ground heat flux(Q_g)) were measured during the study period (summer rainy period, 1990) at Lucky Hills and Kendall watersheds (Kustus et al., 1991). The latent heat flux (QLE) can be measured directly using a variety of methods. However, it has been recognized that it is more reliable to estimate long term latent heat flux from other more-easily measured fluxes (Q_n, Q_h and Q_g), based on the energy balance approach ($QLE = - Q_n - Q_h - Q_g$). The measurements of three basic fluxes (Q_n, Q_h and Q_g) are described below. All fluxes are averaged over 1-hour period in units of watts per square meter (W/m^2).

Net radiation (Q_n) was measured with a REBS Q*6 net radiometer at 2. 5 m above the ground level. Q_n is the driving factor for the energy exchange because in most systems 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 with 5 cm depth and thermal energy (Q_{gs}) stored in the soil layer above the sensor. 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 the 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 the 2.5 cm and 5 cm depths. The averaged ground temperature was used to obtain the Q_{gs}. Therefore,

$$Q_{gs} = 0.01 \Delta T_s C_s \Delta z / \Delta t \tag{1}$$

where C_s is 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 the summer of 1990. The EC values of Q_h were calculated from the air temperature, T_a, and the vertical wind speed, w, both measured at 9 m above the ground level and both sampled at 4 Hz over periods of 20 min. The flux was calculated as

$$Q_h = -\rho_a \cdot c_p \overline{w' T_a'} \tag{2}$$

is air density (kg/m^3), cp 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 [$\mathrm{cov}(w \cdot T_a)$] 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 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 (day time) periods, respectively.

For the verification of accuracy of the OPEC system, Blanford and Stannard (1991) compared theOPEC with SEC (a sonic eddy correlation system) at Walnut Gulch Experimental Watershed duringJuly 1990. In order to maintain a continuing evaluation of the performance of the Gill systems, two sites (rain gauge 40 and Lucky Hills) in Walnut Gulch watershed were visited with a more accurate roving system. The roving system measured latent and sensible energy directly by correlating vertical wind speed measured by a one-dimensional sonic anemometer with a krypton hygrometer and a 12.5μ fast-response thermocouple. The EC sensors were placed farther 9 m above the ground. The test results show that the coefficient of determination (r^2) between the sensible heat measured by the roving and Gill EC systems were 0.97 and 0.95 at rain gauge 40 site and at Lucky Hills site, 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 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.

3.2 Soil Moisture Measurements

The data on the vertical distributiiion of soil moisture was collected by the 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 representsthe 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.

3.3 Daily Soil Moisture Estimation

The daily soil water content was estimated from the energy balance-water budget approaches with eddy correlation at Lucky Hills and Kendall watersheds during the summer rainy period (Figs. 4 and 5). 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.

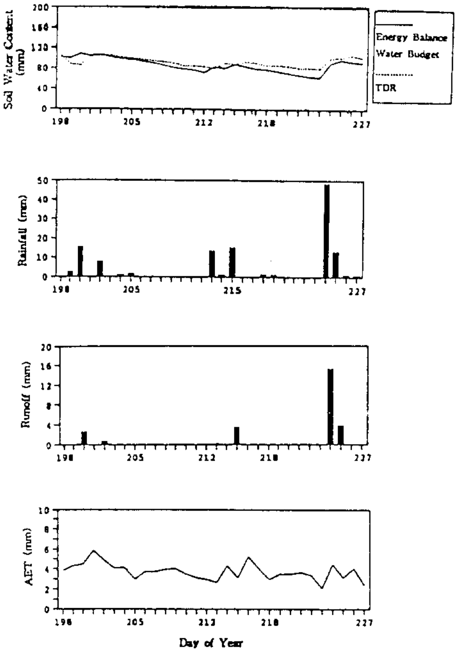

Fig. 4 Water Balance during the Summer Rainy Period(1990) at Lucky Hills Watershed

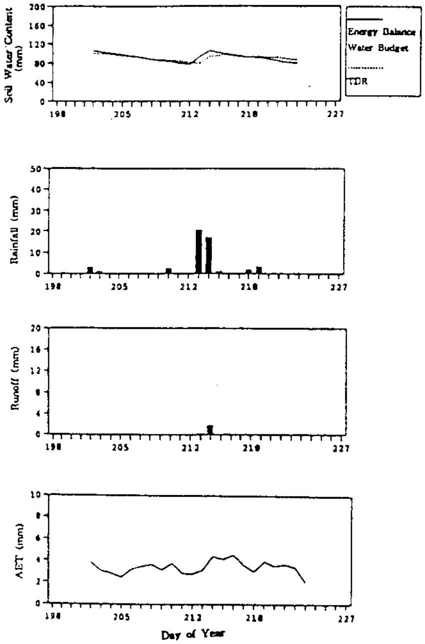

Fig. 5 Water Balance during the Summer Rainy Period(1990) at Kendall Watershed

There were significant effects of precipitation and runoff pattern on soil water content estimation during the study period on each watershed. The rainfall pattern during that time at Lucky Hills and Kendall watersheds is airmass thunderstorms characterized by extreme spatial variability with short duration and limited areal extent. Therefore, runoff was significant for a short time during the summer rainy period, and was almost proportional to rainfall intensity and duration.

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:

$$\Delta SM = \Delta P - \Delta ET - \Delta RO \tag{3}$$

where ΔP is the net daiy precipitation(mm/day) ; ΔET is the net daily evapotranspiration (mmday) ; ΔRO is the net daily runoff(mm/day) ; and ΔSM is the net change in soil moisture content(mm/day). However, the change of groundwater storage is not significantly affected by the net change in hydrologic variables (ΔP, ΔET and ΔRO) at Lucky Hills and Kendall watersheds. Theherefore, soil moisture content is just the residual of precipitation minus evapotranspiration and runoff. This is a reasonable approach, because the soil water condition on the watershed scale is not sufficiently homogeneous to be obtained by measurement at the one site.

Eq. (3) shows how the water storage in the watershed is dependent upon the water input which is usually precipitation (P), and the water output via evapotranspiration (ET) and runoff (RO). However, the daily processes of ΔP, ΔET and ΔRO are fundamentally different in nature. ΔP usually occurs in discrete, short-period bursts, whereas evaporation is a continuous and variable function. Thus, for example, during periods with no precipitation water input is zero but the soil moisture is almost continually depleted by evapotranspiration. In this circumstance Eq. (3) can effectively be reduced to :

$$\Delta SM = -\Delta ET \tag{4}$$

Therefore, unlike the annual situation where net water storage is not important, on the short time-scale ΔSM is very important.

3.4 Correlation between Measured and Estimated Soil Water Contents

The water balance estimates of soil water were compared with measured soil water content (TDR) during the study period. The estimated and measured soil water content showed a good agreement during the study period at Lucky Hills and Kendall watersheds. The study results (Figs. 4 through 7) show that the daily soil water content is closely related to the weather conditions in these watersheds. The available energy 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.

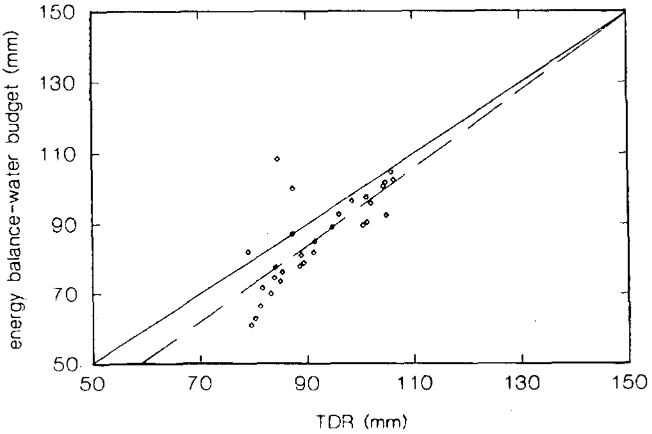

Fig. 6 Simple Linear Regression for Dailly Soil Moisture Measurement between the Energy Water Budget with Eddy Correlation and TDR at Lucky Hills Watershed during the Summer Rainy Period(1990)

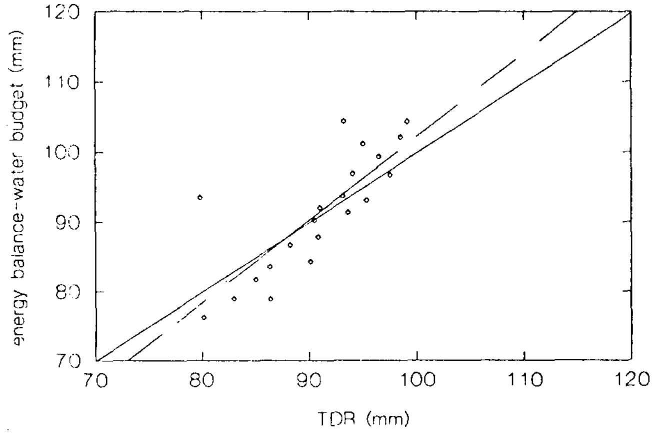

Fig. 7 Simple Linear Regression for Dailly Soil Moisture Measurement between the Energy Water Budget with Eddy Correlation and TDR at Kendall Watershed during the Summer Rainy Period(1990)

The degree of similarity between the regressions of the two methods of measuring soil water content (energy balance-water budget approach with eddy correlation and TDR) was explained by determining the correlations between these methods at Lucky Hills and Kendall watersheds during the summer rainy period (Table 1). Simple linear regression analyses showed that soil water contentmeasured from TDR method was responsible for 58 % and 63 % of the variations estimated from energy balance-water budget approach with eddy correlation at Lucky Hills and Kendall, respectively.

Table 1. Simple Linear Regressions between the Two Measurements of Daily Soil Water Contents at Lucky Hills and Kendall Watersheds during the Summer Rainy Period (1990).

No	Regression Equations	r^2	SEE	MSM_{EW}	MSM_{TDR}	n
1	$SM_{EW} = -14.058 + 1.089SM_{TDR}$	0.584	8.51	85.73	91.68	30
2	$SM_{EW} = -16.910 + 1.191SM_{TDR}$	0.630	5.34	91.28	90.81	21

(All the regressions are significant at $P<0.001$)
1) : Lucky Hills watershed
2) : Kendall watershed
SM_{EW} : daily soil water based on energy balance-water udget approach(mm)
SM_{TDR} : daily soil water based on TDR (mm)
MSM_{EW} : mean of SM_{EW} (mm)
MSM_{TDR} : mean of SM_{TDR} (mm)
n : sample size
r^2 : coefficient of simple determination
SEE : standard error of the regression(mm)

The standard error of estimate of the regression (SEE) for each method was also calculated. The SEE was 8.51 mm with mean SM of 85.73 at Lucky Hills (SEE = 9.9 % of mean SM), and 5.34 mm with mean SM of 91.28 mm at Kendall (SEE = 5.8 % of mean SM). The null hypothesis of no relationship between the daily soil water content estimated from energy balance-water budget and that measured from TDR was tested. The results rejected the null hypothesis of no relationship between these two methods at the 0.1 percent level of significance.

4. Conclusion

The degree of similarity between the regressions of two methods (energy balance-water budget approach with eddy correlation and TDR) of measuring soil water content was explained by determining the correlations between these methods. Simple linear regression analyses showed that the soil water content measured from TDR method was responsible for 58 % and 63 % of the variations estimated from energy balance-water budget approach with eddy correlation at Lucky Hills and Kendall, respectively. The scatter plots and the regression analyses revealed that two different aproaches for the soil water content measurement on a small watershed scale have no significant difference. The comparison tested the accuracy of current soil water content measuring system using TDR and energy balance-water budget approach using eddy correlation method on a small watershed scale.

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