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Estimating Soil Moisture in Small Watersheds, Using a Water Balance Approach

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Soil moisture content was estimated daily by a energy balance and water budget (*EBWB*) analysis of two small subwatersheds in the Walnut Gulch Experimental Watershed near Tombstone, Arizona. One watershed was 8.1 ha and covered with grass, and the other was 48.6 ha and covered with shrubs. The four-week experiment took place in July and August, during the summer rainy season that dominates the precipitation pattern of southern Arizona.

Mean daily soil moisture (*SM*, mm) was estimated by a water balance at each watershed, using precipitation (*P*), runoff (*RO*), and evapotranspiration (*ET*). Daily *ET* estimates were derived from an energy balance on each watershed, using measured net radiation (Q_n), soil heat flux (Q_g) and sensible heat flux (Q_h) to solve for latent energy (Q_{LE}, and hence *ET*) as a residual term. Next, independent estimates of watershed *SM* were obtained from Time Domain Reflectometry (*TDR*). The results of simple correlation analyses between the methods showed that the simple correlation coefficients for Lucky Hills and Kendall are 0.764 and 0.791 respectively. The agreement of the two sets of soil moisture measurements confirms that simple water and energy balance measurements can yield appropriate estimates of soil moisture in small watersheds.

Introduction

There are large areas of semiarid lands of gentle topography and moderate elevation (typically, about 1,400 to 1,800 m above mean sea level) in southern Arizona. They are used primarily as low quality grazing lands for cattle. Since vegetation in semiarid rangelands is sparse with respect to that of humid environments, the soil plays a major role in the water, energy and hydrologic balances (Kustas *et al.* 1991). In terms of the hydrologic cycle, the condition of the soil surface influences the magnitude of runoff. This is especially evident in semi-arid rangelands, where infiltration is often an important factor 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). Other 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 semiarid watershed areas. Lane *et al.* (1984) made water balance calculations for a unit area watershed in the northern Mojave desert, using modeled *ET* rates to estimate water use by perennial vegetation. These studies clearly document interest in developing estimates of soil moisture for a variety of reasons, with runoff generation being perhaps the most compelling. Even so, few studies have successfully defined each of the components that comprise the hydrologic cycle in semiarid watersheds.

The hydrologic cycle is usually studied in terms of water fluxes and the principle of conservation of mass. The major water fluxes are precipitation (*P*), runoff (*RO*), evapotranspiration (*ET*), and change in soil moisture storage (*S*). Water flux units will be mm d^{-1}. The *ET* term is measured in this analysis as a component of the surface energy balance with typical units of MJ $m^{-2}d^{-1}$, giving rise to the name "energy balance and water budget (*EBWB*) approach". Units used in the surface energy balance are interchangeable with those in the water balance, using the practical relation that the evaporation of 1 mm depth of water involves latent energy of vaporization which is approximately equal to 2.45 MJ m^{-2}.

The purpose of this study is to validate the *EBWB* approach to estimate daily soil moisture at the small watershed scale in southern Arizona's semiarid grazing lands. This method will be applied to two small watersheds. Soil moisture estimates determined by the balance approach will be compared to direct, independent measurements of soil moisture. The agreement of the two methods (or lack thereof) will confirm (or reject) applicability of the *EBWB* method for determining watershed scale soil moisture in the semiarid grazing country found in southern Arizona. The comparison is a valuable evaluation of agreement between current soil moisture measuring systems, and *EBWB* methods when applied to small watersheds. Since this balance method has a sound theoretical basis, it should be applicable to other areas of similar environment.

The Walnut Gulch Experimental Watershed

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 Ser-

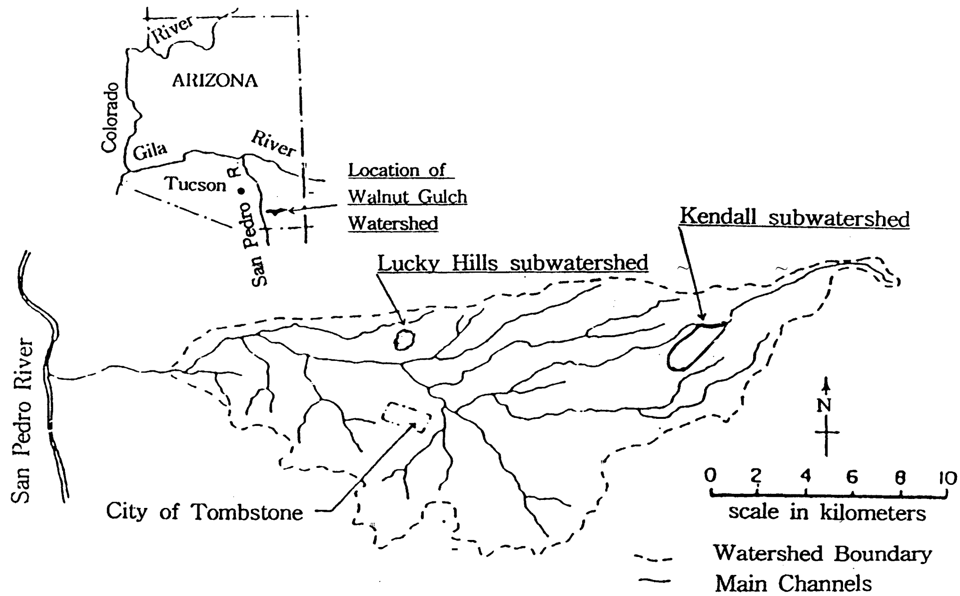

Fig.1. USDA-ARS Walnut Gulch experimental watershed location map.

vice (ARS). Renard *et al.* (1993) have summarized ARS research and facilities at Walnut Gulch. The watershed is located in southeastern Arizona about 120 km southeast of Tucson, Arizona (Fig. 1). It is about 150 km^2 in area, and elevation ranges from about 1,300 m above mean sea level at the outlet in the west, up to a maximum of about 1,800 m in the eastern highlands. The city of Tombstone, Arizona, is located near the center of the watershed, at an elevation of 1,405 m.

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 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 northwest portion of the

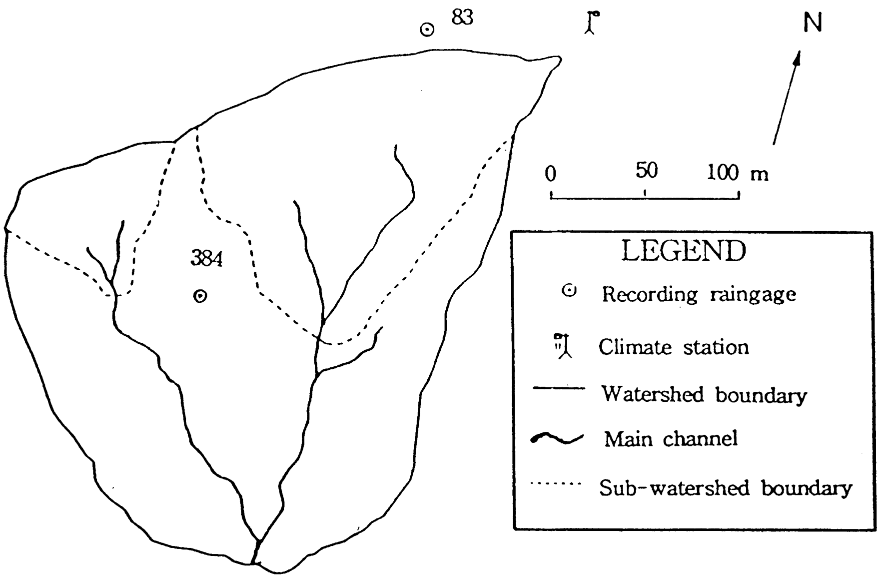

Fig.2. The locations of measurement stations at Lucky Hills watershed.

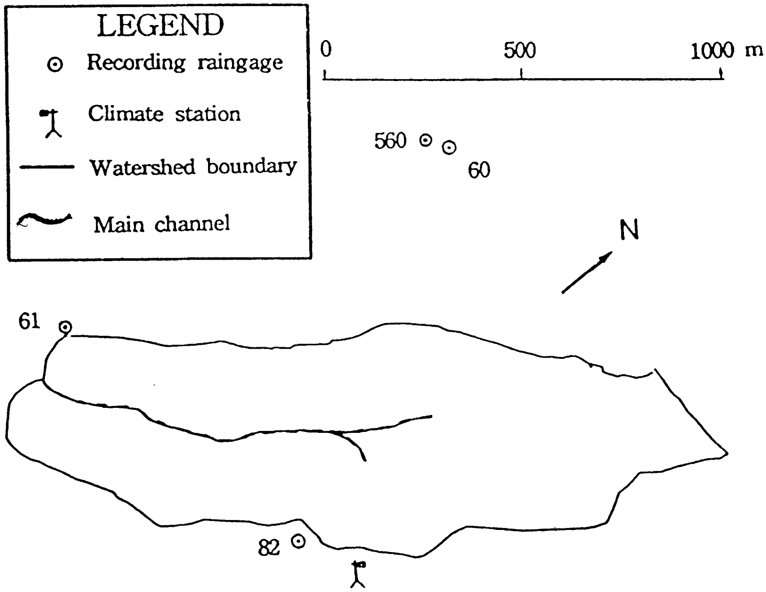

Fig.3. The locations of measurement stations at Kendall watershed.

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. Figs. 2 and 3 show the locations of measurement stations at Lucky Hills and Kendall respectively. Raingages 83 and 384 are located on or adjacent to Lucky Hills. Raingages 60, 61, 560 and 82 are located on or near Kendall watershed.

Soil characteristics at the two sites differ somewhat. 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.

The water balance data used in this analysis were collected by the Agricultural Research Service in their continuing study of rainfall-runoff relationships at Walnut Gulch. Runoff (RO, mm d^{-1}) was measured at the outlets of the Lucky Hills and Kendall subwatersheds by a calibrated Smith supercritical flume (Smith *et. al.* 1981) and precipitation (P, mm d^{-1}) was measured with 2 or more standard recording raingages. Flow duration ranges from minutes to hours, rather than days or more. Runoff in the summer rainy season is more variable than precipitation in the study area, and stream channels are normally dry, with runoff on only a few afternoons and evenings, and always in association with convective rainstorms. 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 appears to be more affected by rainfall variability than does the larger Walnut Gulch watershed, because runoff per unit area decreases with increasing watershed size. The total amount of channel loss from Lucky Hills or Kendall subwatershed becomes less significant compared with that of Walnut Gulch watershed during the rainy period. That is mainly because these two sites have rather small drainage areas.

Methods

The basic water balance observations in this analysis were augmented by specialized energy balance measurements at Lucky Hills and Kendall subwatersheds during the 4-week period July 17-August 15, 1990, in the midst of the summer rainy season. For convenience, we express dates such as July 17, 1990, as day of year DOY 198. The energy balance data were collected as part of the Monsoon 90 experiment (Kustas *et al.* 1991). The flux components of the energy balance were measured successfully from DOY 198 through 227 at Lucky Hills watershed, and from DOY 202 through DOY 221 at Kendall watershed. In addition, mean daily soil moisture was measured at both subwatersheds from DOY 198 through 227. Thus the components of the water balance and the energy balance can be combined to yield an estimate of mean daily soil moisture, and this estimate can be compared with direct measurements of mean daily soil moisture.

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 (Q_n, net exchange of allwave radiation), ground heat flux (Q_g, thermal storage rate, primarily in the ground), sensible heat flux (Q_h, thermal convective exchange between the earth and atmosphere), and latent heat flux (Q_{LE}, 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 $MJm^{-2}d^{-1}$). Energy totals can be expressed as the depth of water containing equivalent latent energy. The surface energy balance equation is

$$Q_n + Q_g + Q_h + Q_{LE} = 0 \tag{1}$$

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).

Net Radiation and Soil Heat Flux

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

Soil heat flux (Q_g) is the heat flux (Q_{gh}) detected by a REBS soil heat flux plate at 5 cm depth, plus any change in thermal energy (Q_{gs}) stored in the soil layer between the heat flux plate and the surface. 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 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 Q_{gs}. Therefore,

$$Q_{gs} = 0.01 \Delta T_s C_s \Delta z / \Delta t \qquad (2)$$

where C_s is volumetric heat capacity of the soil (= 1.5MJ m^{-3} K^{-1}); ΔT_s is the soil temperature difference between T_{si} and T_{si-1}, in °C; 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 (= 3,600 s); and Δz is the thickness of soil layer (= 5 cm).

Sensible Heat Flux

Sensible heat flux (Q_h) in this analysis was measured with the eddy covariance (*EC*) method during the Monsoon 90 experiment (Kustas, *et al.* 1991). Values of Q_h were calculated from covariance of vertical wind (w, m s^{-1}), and air temperature (T_a, °C); both were measured at 9 m above ground level and both were sampled at 4 Hz over periods of 20 min. The flux was calculated using standard formulation, as

$$Q_h = -\rho_a c_p \overline{w'T'_a} \qquad (3)$$

where ρ_a is air density (kg m^{-3}), c_p is specific heat of air (J kg^{-1} K^{-1}), primes denote deviations from period means, and the overbar denotes a period mean of the product (w'T_a') (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 T_a. 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 as much as 150 m away in the upwind direction.

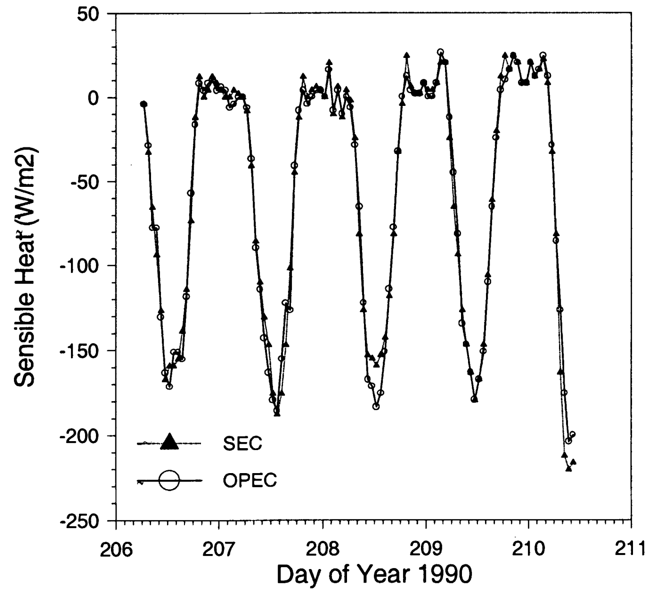

Fig.4. Comparison of OPEC sensible heat and SEC sensible heat at Walnut Gulch.

The effect of atmospheric stability on the OPEC estimates of Q_h must also be taken into account. Blanford and Gay (1992) developed stability corrections for the OPEC sensible heat, based upon theoretical and experimental grounds. 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 empirical comparisons between propeller-based EC and sonic-based EC.

The question to be answered at this point is whether or not Q_h from a simple OPEC system satisfactorily duplicates Q_h 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. 4. It is evident that Q_h from OPEC at Walnut Gulch is in excellent agreement with Q_h from SEC. Regressing SEC sensible heat against OPEC sensible heat confirms the agreement that is obvious in Fig. 4. 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 R^2=0.981. This comparison provices conclusive envidence that the OPEC and SEC sensors in Fig. 4 are measuring the same sensible heat flux.

Latent Heat Flux and Evapotranspiration

Latent heat (Q_{LE}) is the most troublesome energy flux to measure. Bowen ratio systems and lysimeters are often used for tests, calibration, and operational measurements of Q_{LE}. Latent heat can also be measured directly by EC systems by correlating fluctuations in vertical wind (w, m s^{-1}) with fluctuations in water vapor density (q, g m^{-3}). In principle, the addition of a single, fast-response hygrometer is all that is needed to add latent heat flux to the EC system that is already being used to measure sensible heat. The measurement is similar to that for Q_h, in that $Q_{LE} = L(\overline{w'q'})$ where L (MJ kg^{-1}) is latent heat of vaporization. However, present hygrometers are not completely satisfactory. They consume substantially more power, and are affected by presence of water during rain, the buildup of dust when dry, and electronic drift at any time. EC estimates of latent heat require additional real time corrections for air properties, which generates need for a substantial increase in computation capacity and increased technical support. Fortunately, it is possible to monitor the performance of EC systems if both Q_h and Q_{LE} are measured, since conservation of energy considerations dictate that $Q_n + Q_g$ must equal $-(Q_h+Q_{LE})$, with fluxes moving toward the exchange surface having positive polarity. Failure of the turbulent fluxes to "close" the energy balance equation signifies erroneous measurements in one or more of the fluxes. Unfortunately, closure errors with eddy covariance flux estimates are almost always associated with underestimates of Q_{LE} that typically range from 10 to 30 per cent.

EC closure problems are illustrated by Dugas *et al.* (1991), who compared mean flux measurements from three SEC systems during daylight with means from four Bowen ratio systems in irrigated alfalfa in Arizona. He reported that mean Q_h from three SEC systems agreed well with that from four Bowen ratio systems. However, Q_{LE} was substantially underestimated by SEC instruments. Kizer *et al.* (1988) measured alfalfa Q_h and Q_{LE} with eddy correlation. They then calculated alfalfa latent energy as a residual in the surface energy balance; we will distinguish residual latent energy with a "prime" (*i.e.*, Q_{LE}') to distinguish it from directly-measured Q_{LE}. Thus $Q_{LE}' = -(Q_n + Q_g + Q_h)$, with fluxes moving to the surface having positive polarity. Kizer considered residual Q_{LE}' to be correct, and reported that EC-measured Q_{LE} from alfalfa was only 81 per cent of the residual alfalfa Q_{LE}'. Acceptance of this evidence for the validity of residual Q_{LE}' makes it possible to use the simplified OPEC system.

Comments on Measurement Quality

The calibration in Fig. 4 confirms that an OPEC system can yield the same Q_h values as a SEC system. Some calibration results are available to help define errors in OPEC estimates of Q_{LE}' (and hence *ET*). Stannard *et al.* (1994) evaluated the performance of the OPEC systems during the summer rainy season at Walnut Gulch with the aid of a "roving" portable sonic eddy correlation (SEC) system that measured both Q_h and Q_{LE}. The relation between hourly, daytime values of SEC Q_{LE}

(Wm^{-2}) and OPEC residual Q_{LE}' was $Q_{LE} = 0.98Q_{LE}' - 21.5$, with s.d. = ±16.4 or about 10%. Similar periodic comparisons of net radiometers Q_{n1} and Q_{n2} at Lucky Hills yielded a relationship Q_{n1} (W m^{-2}) = $1.02Q_{n2} - 6.0$, with s.d. = ±12.3. They also pointed out the possibility of errors in the estimate of Q_{LE}' when the larger, watershed scale area sampled by 9 m high sensors is non-homogenous. These values suggest that mean daily latent energy at Lucky Hills is probably measured within 10 to 20%. There have also been several long-term tests of OPEC measurements.

Gay *et al.* (1996b) measured *ET* with OPEC systems above a Scots pine forest in southwestern Germany for 5.5 months during the summer half-year in 1991. The forest *ET* total was 328 mm by the OPEC system, and 358 mm by a water balance, or 343 mm ± 5 per cent. Amiro and Wuschke (1987) used the original single propeller system to measure Q_h, and then determined Q_{LE}' as a residual in the surface energy balance. They concluded that their mean weekly OPEC *ET* for red pine in Saskatchewan through the summer season was within about ± 10 per cent, based upon errors associated with the instruments, and comparisons between the flux measurements and the catchment water balance. Finally, acceptance or rejection of the eddy covariance/energy balance estimate of Q_{LE} eventually depends upon the success of the *EBWB* method in adequately matching direct measurements of soil moisture. Thus our Walnut Gulch Watershed analysis uses a water balance and direct measurements of soil moisture to test the assumption that $Q_{LE} = Q_{LE}'$.

Time Domain Reflectrometry

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.

Results and Discussion

There were significant effects of precipitation and runoff pattern on soil water content estimation during study period on each watershed. The rainfall pattern during the summer rainy period 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 are 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

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

where P is the net daily precipitation (mm/day); ET is the net daily evapotranspiration (mm/day); RO 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 (P, ET and RO) at Lucky Hills and Kendall watersheds.

The daily soil water content estimated from the *EBWB* approach at Lucky Hills and Kendall watersheds during the summer rainy period is shown in Figs. 5 and 6. The flux components of the energy balance were measured successfully in 1990 from DOY 198 through 227 at Lucky Hills watershed, and from DOY 202 through DOY 221 at Kendall watershed. In addition, mean daily soil moisture was measured in 1990 at both subwatersheds from DOY 198 through 227. Thus, the components of the water balance and the energy balance can be combined to yield an estimate of mean daily soil moisture, and this estimate can be compared with direct measurements of mean daily soil moisture. The 1990 *TDR* measurements of soil water on DOY 198 and DOY 207 defined the initial soil water content for Lucky Hills and Kendall watersheds, respectively.

The results at Lucky Hills are illustrated in Fig. 5, and it is evident that the soil moisture estimates from the two methods are in reasonable agreement. Soil moisture from the *EBWB* analysis ranged from 61 to 108 mm, while the *TDR* measurements ranged from 79 to 106 mm. The ET rates at Lucky Hills ranged from 2 to 6 mm d^{-1}. Fig. 6 shows that conditions at Kendall Watershed were drier, and agreement was better. Soil moisture from the *EBWB* method ranged from 76 to 104 mm, while the *TDR* measurements ranged from 80 to 99 mm. Daily ET at Kendall varied from 2.4 to 4.4 mm d^{-1}. The total rainfall, evapotranspiration, and runoff at Lucky Hills was 122, 112, and 26 mm respectively. Totals at Kendall were 47, 70, and 2 mm, respectively. Considering that the amount of rainfall is less than sum of evapotranspiration and runoff in each subwatershed during the study period, soil water having existed in the root zone of each subwatershed was obviously evaporated or transpired. Therefore, based on the results of *EBWB* analysis, soil water of 16 mm and 25 mm was lost due to evapotranspiration from the root zone of Lucky Hills and Kendall subwatersheds respectively.

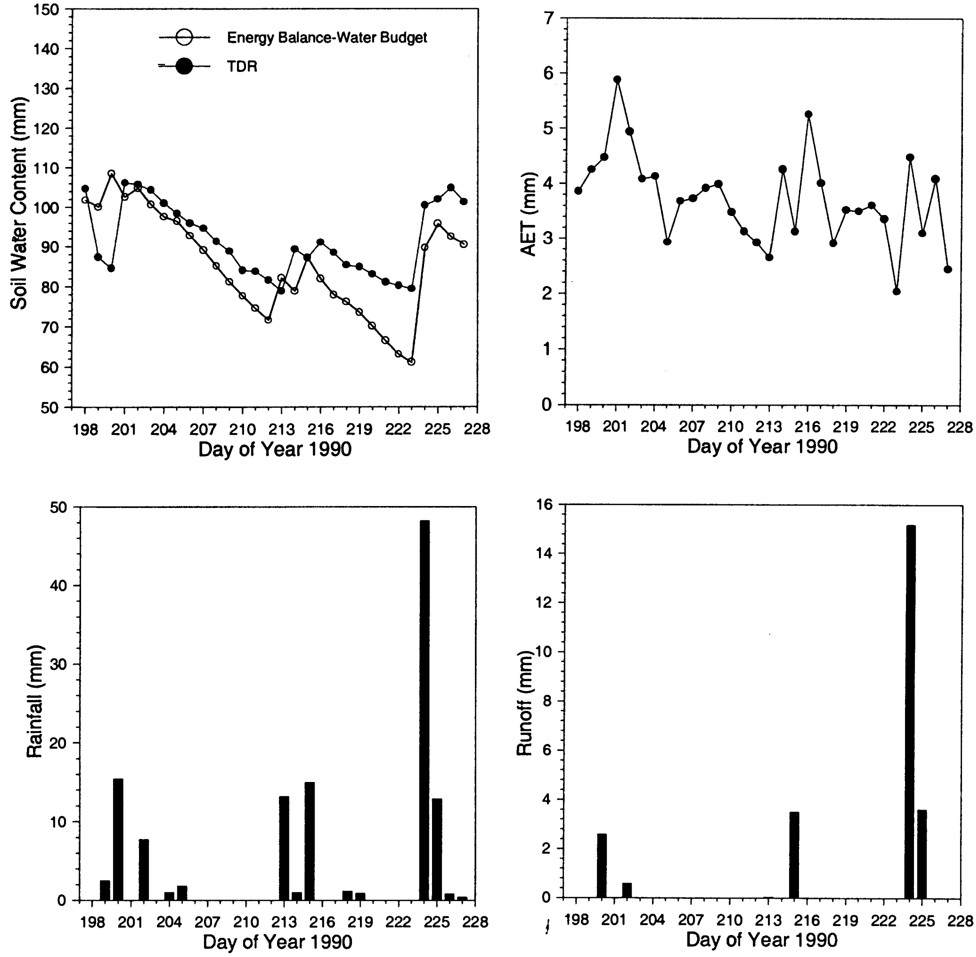

Fig.5. Water balance during the summer rainy period (1990) at Lucky Hills watershed.

The groundwater occurs only at substantial depth in this basically semi-arid region, and thus the surface hydrology is effectively disconnected from the aquifer. Therefore, soil moisture content change is just 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. Eq.(4) shows how the water storage in the watershed is dependent upon the water input which is usually mainly precipitation (*P*), and the water output via evapotranspiration (*ET*) and runoff (*RO*). However, the daily processes of *P*, *ET* and *RO* are fundamentally different in nature. *P* 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

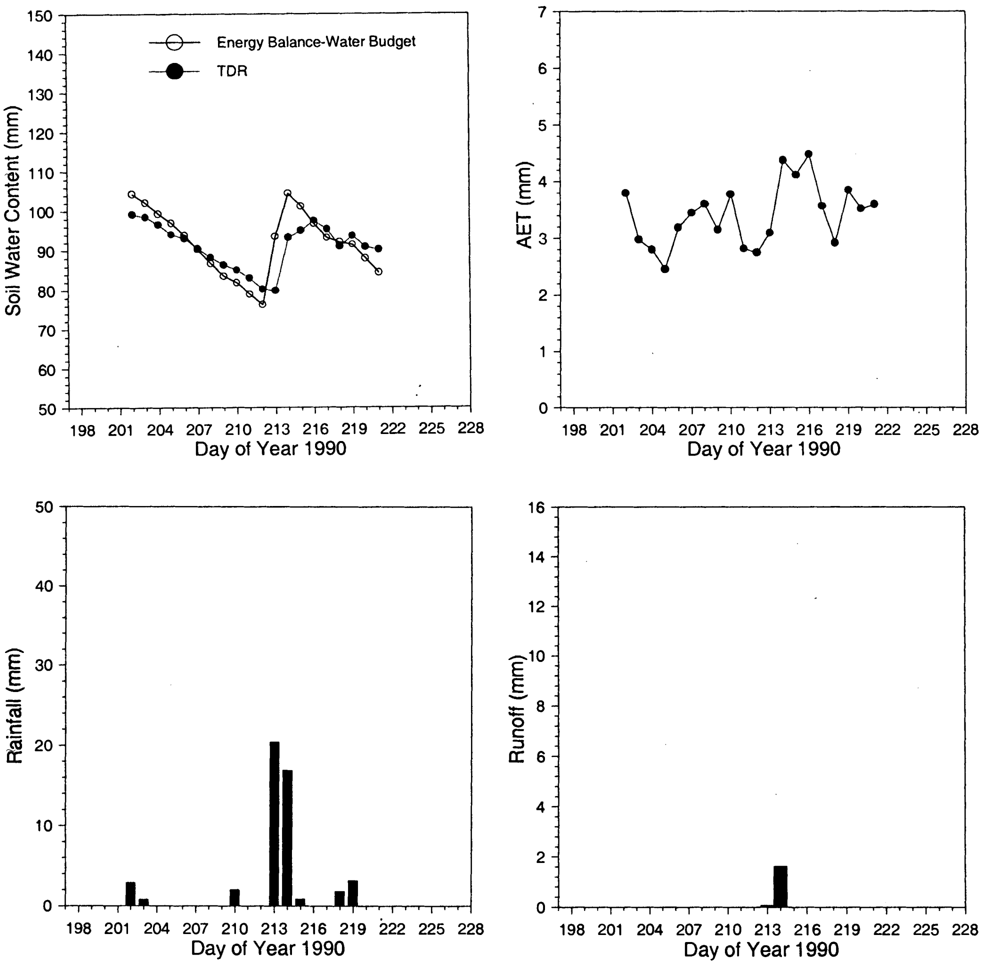

Fig.6. Water balance during the summer rainy period (1990) at Kendall watershed.

the soil moisture is being almost continually depleted by evapotranspiration. In this circumstance Eq.(4) can effectively be reduced to

$$\Delta SM \cong - ET \tag{5}$$

Therefore, unlike the annual situation where net water storage is not important, on the short time-scale Δ *SM* may be very important. The results in Figs. 5 and 6 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 levels of available energy create 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 mois-

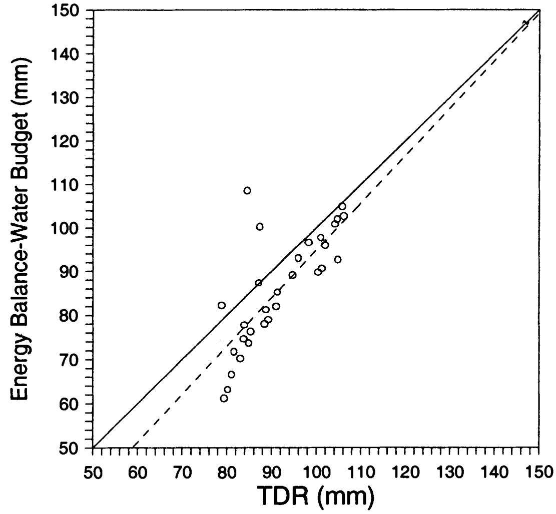

Fig.7. Comparing daily soil moisture from the *EBWB* with *TDR* measurements at Lucky Hills during the summer rainy period (1990).

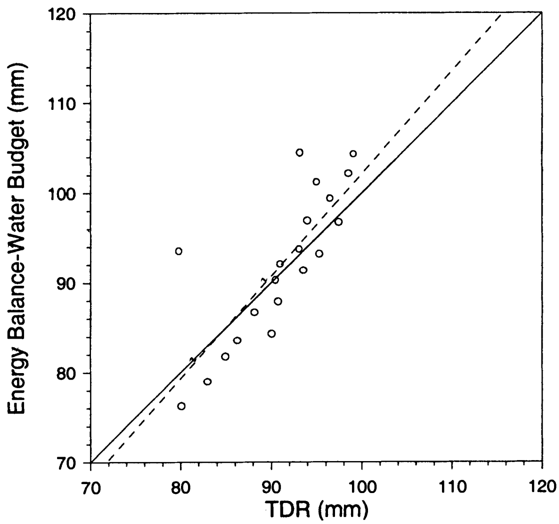

Fig.8. Comparing daily soil moisture from the *EBWB* with *TDR* measurements at Kendall during the summer rainy period (1990).

ture decreases. Therefore, dry surface soils evaporate less, and the surface air becomes drier. From Figs. 5 and 6, it is evident that the decrease of soil water content estimated with *EBWB* during dry periods is steeper than that of measured with *TDR*. On the other hand, the *EBWB* method increases more than the *TDR* method during rainy period. So the *EBWB* method predicts soil water contents that agree on a long-term average –during the summer rainy period –with the *TDR* method. Considering an extended dry period only, the *EBWB* method seems to underestimate the soil water content.

The water balance estimates of soil water were compared with measured soil water content (*TDR*) during the study period. The degree of similarity between the two methods of measuring soil water content (*EBWB* and *TDR*) was described by determining the correlations between the methods at Lucky Hills and Kendall watersheds during the summer rainy period (Figs. 7 and 8). The simple correlation analysis between the methods was accomplished. The simple correlation coefficients for Lucky Hills and Kendall are 0.764 and 0.791 respectively. The test results showed that P values for Lucky Hills and Kendall are 0.000, which indicate that the correlation between the methods is statistically significant.

Conclusions

To validate the *EBWB* approach to estimate daily soil moisture at the small watershed scale in semiarid grazing lands, soil moisture content was estimated daily by energy and water balance analysis of two small subwatersheds in the Walnut Gulch Experimental Watershed near Tombstone, Arizona. The first step was to derive mean daily changes in soil moisture (*SM*) from a water balance at each watershed, using daily totals of precipitation (*P*), runoff (*RO*), and evapotranspiration (*ET*). *ET* estimates were derived from measured daily totals of net radiation (Q_n), soil heat flux (Q_g) and sensible heat flux (Q_h) at an energy balance site on each watershed. The next step developed an independent set of daily soil moisture estimates from measurements with Time Domain Reflectometry (*TDR*). The *TDR* measurements were accepted as the ground-truth standard. Finally, comparison of the two sets of soil moisture measurements provides valuable information on possibilities to define soil moisture at the watershed scale using *EBWB* approach.

The degree of similarity between the two methods of measuring soil water content (*EBWB* and *TDR*) was described by determining the correlation between the methods at Lucky Hills and Kendall watersheds during the summer rainy period. The simple correlation analysis indicates that the correlation between the methods is statistically significant. However, the comparison of time series plots show that the decrease of soil water content estimated with *EBWB* during dry periods is steeper than that of measured with *TDR*. On the other hand, the *EBWB* method increases more than the *TDR* method during rainy period. So the *EBWB* method predicts soil water contents that agree on a long-term average –during the summer rainy period – with the *TDR* method. Considering an extended dry period only, the *EBWB* method seems to underestimate the soil water content.

Acknowledgement

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