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Data Sets and Related Information Used for Estimating Regional Ground-Water Evapotranspiration in Eastern Nevada

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Estimating Discharge of Shallow Groundwater by Transpiration From Greasewood in the Northern Great Basin

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Evapotranspiration from bare soil and phreatophytes is a principal mechanism of groundwater discharge in arid and semiarid regions of the midwestern and western United States including the Great Basin. The imbalance between independent estimates of groundwater recharge from precipitation and of groundwater discharge based on estimates of groundwater evapotranspiration leads to large uncertainties in groundwater budgets. Few studies have addressed this problem. Energy budget micrometeorological field studies were conducted in a stand of sparse-canopy greasewood growing in an area of shallow groundwater in the western Great Basin during the summer of 1989. The data were used to calculate above-canopy fluxes of sensible and latent heat using the energy budget-Bowen ratio method. The calculated energy budget fluxes were used, with soil surface and plant canopy temperature measurements, to calibrate and apply a two-component, energy-combination model that partitions the energy and heat fluxes between bare soil and the canopy. This permitted the separation of evaporation from the soil and transpiration from greasewood. The calibrated model was used to estimate daily transpiration of groundwater by greasewood growing in an area with a depth to water of about 2 m. The daily rate of groundwater discharge by transpiration during July and August was estimated to be 2.4 mm. A period of 100 days for groundwater discharge at this rate was assumed to estimate an annual discharge of groundwater of 24 cm at the study site.

INTRODUCTION

Evapotranspiration from bare soil and phreatophytes is a principal mechanism of groundwater discharge in arid and semiarid regions of the Midwestern and western United States. Uncertainty in the estimates of groundwater consumption by phreatophytes in these areas leads to major uncertainty in water budgets, especially groundwater budgets. A number of studies have been conducted to evaluate evapotranspiration by phreatophytes in the western and southwestern United States, including studies by *Lee* [19121, *White* [1932], *Gatewood et al*. [1950], *Robinson* [1970], *Gay* [1979], and *Weeks et al*. [1987], to name only a few. However, few studies have been conducted to determine evapotranspiration rates of the most important phreatophyte in the Great Basin, greasewood, and only two previous investigations have addressed the issue of groundwater consumption by greasewood [*White*, 1932; *Robinson*, 1970]. The present study attempts to quantify the annual transpiration of groundwater by greasewood in the northern Great basin, but not for other important phreatophytes elsewhere in the western United States.

White [1932] presented data from which several estimates were made of the annual discharge of groundwater by greasewood (*Sarcobatus vermiculatis*), the dominant phreatophyte in the northern Great Basin. He concluded that the annual evapotranspiration of groundwater by greasewood was about 6 cm yr^{-1} in areas with a depth to groundwater of 0-2.4 m, and about 5 cm yr^{-1} in areas with a depth to groundwater of 2.4-9 m. These values were based on estimates of the volume of aquifer dewatered as calculated from daily groundwater fluctuations believed caused by greasewood transpiration. Daily water level fluctuations were on the order of 1.5 to 3.0 cm, and the annual decline was from 33.5 to 45.5 cm. It is now believed that the discharge of groundwater was underestimated by considering only the volume of aquifer dewatered; the volume of water moving laterally and vertically through the aquifer in response to increased groundwater gradients was not considered.

Robinson [1970] conducted studies of evapotranspiration by greasewood and rabbitbrush near Winnemucca, Nevada. He concluded, based on evapotranspiration tank experiment data, that consumption of groundwater by greasewood ranged from about 18 cm yr^{-1} to about 24 cm yr^{-1}. Rabbitbrush, during the same experiment, transpired about 32 cm yr^{-1}.

Published groundwater budget studies in the western Great Basin, beginning with *Piper et al.* [1939] and extending through *Van Denburgh and Rush* [1974] (Table 1), have used annual groundwater discharge rates for greasewood ranging from 0.9 to 24.5 cm for areas with depths to groundwater ranging from 0.3 to 18 m and plant densities variously described as sparse, low, and moderate. The most commonly used annual evapotranspiration rates are 6-9 cm. All of the studies have cited *White* [1932] as a source of information for the rate used.

More recent studies by *Carman* [1993] in western Nevada, by *Duell* [1988] in the Owens Valley of California, and by *Malek et al*. [1990] in the eastern Great Basin in Utah have suggested significantly higher evapotranspiration rates for greasewood. Only the study by *Malek et al*. [1990] attempted to estimate the rate of groundwater discharge. Their results are ambiguous and appear not to have been corrected for precipitation (evaporation from bare soil) and changes in soil moisture during the measurement period.

Attempts to determine groundwater discharge by greasewood and other phreatophytes in the northern Great Basin and other semiarid areas are complicated by the sparseness of the vegetation, both in distribution and in canopy structure. Lysimeters are considered to provide the most accurate and reliable measurements of evapotranspiration.

TABLE 1. Estimated Annual Rates of Evapotranspiration of Groundwater by Greasewood in the Western Great Basin

Reference	Locale	DTW, m	Density, %	Rate, cm/year
Piper et al. [1939]	Hamey Basin, Oregon	?	?	9.0
Maxey and Eakin [1949]	White River Valley, Nevada	?	?	24.4
Eakin et al. [1951]	Goshute Valley, Nevada	<7.6	sparse	0.9
Eakin and Maxey [1951]	Ruby Valley, Nevada	1.5-3	moderate	9.0
Zones [1961]	Crescent Valley, Nevada	2.4-6	15	4.6
Everett and Rush [1964]	Smith Creek Valley, Nevada	3-12	20-30	6.0
Glancy and Rush [1968]	Smoke Creek Desert, Nevada	6-15	?	6.0
Van Denburgh and Rush [1974]	Railroad Valley, Nevada	9-15	moderate	3.0

DTW, depth to water below land surface.

Evapotranspiration tank experiments, such as those conducted by *Lee* [1912], *White* [1932], *Gatewood et al.* [1950], and *Robinson* [1970] can provide accurate measurements of groundwater consumption by evapotranspiration. However, both approaches are difficult to apply in remote rangeland areas and both require disturbing existing rangeland plants for transplantation into the lysimeter or evapotranspiration tank; this disturbance causes unknown changes in plant growth response for an unknown period of time. Ultimately, both methods provide a measure of total evapotranspiration and cannot differentiate easily between evaporation from bare soil and transpiration by the plants.

To better quantify the discharge of groundwater by greasewood in the Great Basin, detailed energy budget field studies were conducted in 1989 in central Nevada. Micrometeorological studies that measure above-canopy fluxes of latent and sensible heat suffer from the same problem of distinguishing between evaporation and transpiration as do lysimeter or tank experiments. The present study, which is based on micrometeorological methods, measured several variables not commonly measured, namely, soil surface and plant canopy temperatures, that were used to help separate evaporation from transpiration. The energy budget dat were used to calculate above-canopy fluxes of vapor and heat using the Bowen ratio method [*Tanner*, 1960]. The data and calculated energy budget fluxes, together with soil surface and canopy temperatures, were used to calibrate and apply a theoretically based energy-combination model [*Shuttleworth and Gurney*, 1990] that partitions available energy between the canopy and soil for sparse-canopy conditions. This permitted the separation of soil evaporation and plant transpiration.

TWO-COMPONENT ENERGY-COMBINATION MODEL

Micrometeorological and other methods of measuring above-canopy fluxes of sensible and latent heat include fluxes from both the canopy and underlying bare soil. In semiarid and arid rangeland phreatophyte areas, most or all of the latent heat flux comes from the canopy while most or all of the sensible heat flux comes from the bare soil. This is not true following precipitation, when large latent heat fluxes originate from the bare soil. Significant sensible heat flux may originate from the canopy when the plants become stressed because of inadequate water supply.

It is necessary to determine the energy budget for each source, soil surface, and canopy to better understand the significance and magnitude of evaporation from the bare soil and transpiration by the plants. The energy budget for the soil is given by

$$Rn_s = \lambda E_s + H_s + G_s \quad (1)$$

(symbols used in the following equations are defined in the notation list at the end of the appendix) and for the canopy by

$$Rn_c = \lambda E_c + H_c. \quad (2)$$

The solution of these equations requires a partitioning of net radiation between the soil and canopy. The present analysis uses the simplest approach for estimating these values of net radiation by assuming that the total net radiation can be partitioned between the soil and canopy using a Beer's law relation given by

$$Rn_s = Rn \exp(-\alpha LAI) \quad (3)$$

for the soil, and

$$Rn_c = Rn[1 - \exp(-\alpha LAI)] \quad (4)$$

for the canopy. Following *Choudhury and Montheith* [1988], the value of α was estimated by assuming a spherical leaf distribution exposed at a solar altitude θ, giving $\alpha = 0.5 \operatorname{cosec} \theta$.

Solving the energy budget equations (1) and (2) for the soil and canopy requires a method for determining the sensible and latent heat fluxes from each source. *Shuttleworth and Wallace* [1985] proposed a one-dimensional, two-component energy combination model for sparse-canopy conditions using various resistance terms to calculate these fluxes. The resistance formulation for sparse-canopy conditions was modified by *Shuttleworth and Gurney* [1990] and by *Shuttleworth* [1991]. The model uses a within-canopy air flow and reference height to allow energy transfer among the soil, canopy, within-canopy atmosphere, and above-canopy atmosphere. Concepts and assumptions used in developing the model are fully discussed in the above cited articles and the reader is referred to them for more detailed discussion of the equations, their theoretical basis, and their derivation. The principal equations needed to solve the energy budget are summarized below.

The following equations, modified from *Shuttleworth and Gurney* [1990], describe the fluxes of sensible heat

$$H_s = \frac{\rho c_p (T_s - T_0)}{r_{as}} \quad (5)$$

$$H_c = \frac{\rho c_p (T_c - T_0)}{r_{ac}} \quad (6)$$

and the fluxes of latent heat as

$$\lambda E_s = \frac{\rho c_p \left(e_*(T_s) - e_0\right)}{\gamma \left(r_{as} + r_{ss}\right)} \quad (7)$$

$$\lambda E_c = \frac{\rho c_p \left(e_*(T_c) - e_0\right)}{\gamma \left(r_{ac} + r_{sc}\right)}. \quad (8)$$

Equations for the resistance terms and other supporting equations are given in the appendix.

Lafleur and Rouse [1990] obtained good agreement between measured fluxes at a high-latitude wet sedge meadow site and estimated fluxes derived with the original energycombination model [*Shuttleworth and Wallace*, 1985]. Less satisfactory results were obtained by *Ham and Heilman* [1991], who applied the original model to sparse-canopy cotton. They concluded that the results of their study suggested that quantifying energy flux using bulk aerodynamic resistances, in combination with standard meteorological data, is not feasible. More recently, however, *Nichols* [1992] demonstrated the general applicability of the modified energy-combination model [*Shuttleworth and Gurney*, 1990; *Shuttleworth*, 1991] to sparse-canopy rangeland vegetation. This study is an extension of the earlier study by *Nichols* [1992] and focuses on partitioning the energy budget to obtain an estimate of the transpiration of groundwater.

METHODS AND DATA

Energy budget-Bowen ratio data were collected in Smith Creek Valley (39º19'N, 117º30'W) from late May to early September 1989 to characterize the energy budget for sparse greasewood growing in areas where the water table is less than 2 m below land surface. Smith Creek Valley is in west-central Nevada, about 196 km east of Carson City and about 41 km southwest of Austin, Nevada. The valley is a semiarid hydrologically closed basin encompassing about 1500 km^2 with a large playa covering about 50 km^2. The playa is at an altitude of about 1850 m; surrounding mountain ranges rise to 3000 m.

Recharge to the basin is derived from precipitation, largely snow, in the bounding mountains. There is no surfacewater discharge outside the basin. Groundwater discharge is by evapotranspiration by greasewood, rabbitbrush, and in some places sagebrush, which surround the central playa. Winter precipitation on the valley floor restores soil moisture that is evapotranspired during the spring and early summer. Summer precipitation on the valley floor is lost quickly by evaporation from bare soil with minor amounts being transpired.

The depth to groundwater at the study site was 1.40 m below land surface in late May. By mid-August, it had declined to 1.82 m below land surface.

Greasewood, and in places greasewood with rabbitbrush or rabbitbrush with sagebrush, occurs in a narrow band around the playa extending for about 600-750 m to as much as 1800 m from the playa. The greasewood shrubs at the study site have a crown height of about 0.75 m and a plant density of about 25%. Elsewhere in the basin, greasewood shrubs may be no more than about 0.4 m high; plant density may vary from about 10% to as much as about 35%. Rabbitbrush and sagebrush in shallow groundwater areas may be as large as 0.8 to 1.0 m high and have a density of up to 35%.

Data collected include incident and reflected short-wave radiation, incident and emitted long-wave radiation, air temperature and vapor pressure at two heights above the canopy, wind speed at two heights above the canopy, soil heat flux and soil temperature, soil surface temperature, and canopy temperature. Details of the equipment and techniques used to collect these data have been given by *Nichols* [1992]. Data were collected and averaged over 20 min time intervals.

The collected data were used to solve the energy budget equation using the Bowen ratio method [*Tanner*, 1960]. Net radiation flux and soil heat flux were derived or calculated directly from collected data. The Bowen ratio was calculated using the measured air temperature and vapor pressure gradients and was used to partition the remaining energy into fluxes of latent and sensible heat. The results obtained with the energy budget-Bowen ratio equation were then used to calibrate the *Shuttleworth and Gurney* [1990] energy-combination model for sparse canopy conditions so that the above-canopy sensible and latent heat fluxes could be partitioned between the bare soil and the canopy.

ANALYSIS

Two time intervals were selected for model calibration, July 23 to August 4, 1989, and September 1-6, 1989. These times were considered to have the most consecutive number of days with a good solution to the energy budget-Bowen ratio equation and therefore provided the best sensible and latent heat flux values with which to calibrate the energy-combination model. Inaccurate measurements of canopy temperature from May 25 to July 14 precluded using the energy-combination model for the days before July 15. The energy-combination model previously had been calibrated for the period July 23 to August 4 [*Nichols*, 1992]. Direct application of the model calibrated for July canopy conditions to the September data did not yield a satisfactory solution because of changes in LAI (leaf area index). The plant density at the study site is about 25%. In July, each shrub was still fully leafed, with a LAI of 4 (LAI varies from 0 to 4); this results in an equivalent LAI of 1 for the study site in July. By September, the each shrub had lost many leaves and had an estimated LAI (based partly on model calibration and partly on field observations) of about 3 for an equivalent LAI of 0.8. Canopy temperature measurements show that the leaf temperature gradually increased above air temperature from July to September, suggesting the plants were experiencing greater water stress as time passed. This was a significant change in canopy conditions and required a recalibration of the model to estimate new values for the attenuation coefficient for eddy diffusivity and the attenuation coefficient for wind speed that are used in calculating the resistance terms (equations (9) and (11)). Values for these variable are given in Table 2 for each time period. Soil conditions had not changed, and the influence of changes in canopy conditions resulted in minor changes to n. Canopy changes were significant and the change to n' was greater.

TABLE 2. Energy Combination Model Variables Used in This Study

	LAI	*n*	*n'*
July	1.0	3.8	0.6
September	0.8	3.6	1.1

It is important also to note that the variables *n* and *n*' will contain errors introduced by errors in data and errors in other estimated variables such as LAI, the source-height temperature, and variability in canopy height. The variable *n*' and the calculation of sensible and latent heat fluxes from the canopy is particularly sensitive to measurements of canopy temperature. Canopy temperature commonly is close to the air temperature and therefore close to the estimated within-canopy source height temperature. Small errors in measured canopy temperature lead to large errors in calculated sensible heat flux that in turn affect the calculation of latent heat flux. The canopy temperature used in this study was measured with an infrared thermometer that assumed a canopy emissivity of 0.98. Recent studies in Arizona suggest that the emissivity of desert shrubs may range from about 0.98 to about 0.995 (K. Humes, U.S. Department of Agriculture, written communication, 1992). *Hipps* [1989] reported a mean emissivity for *Artimesia tridentata* of 0.97. Correction of canopy temperatures for site specific shrub emissivity will lead to small changes in the calibrated value of *n*'.

It is not yet clear to what extent the values for *n* and *n'* given in Table 2 are transferrable to other sparse-canopy conditions. Research in progress suggests that these values may apply to similar stands of compact, stiff-limbed shrubs such as greasewood, sagebrush, saltbush, shadscale, and perhaps rabbitbrush. They may not apply to more wispy shrubs of the desert southwest such as creosote bush (creosote bush is not a phreatophyte). It also appears that once the model has been calibrated for a site for several of the seasons (spring, summer, fall) for a given year and the relation developed between LAI and *n* and *n'*, it may not be necessary to recalibrate for succeeding years if a value for LAI is determined. Nevertheless, values given in Table 2 should be considered as applicable to the central Nevada site and the transferability to other sparse-canopy sites is not known.

Once calibrated, the energy-combination model was used to calculate fluxes of sensible and latent heat from the soil and the canopy from July 15 to September 7, 1989. The three variables LAI, *n*, and *n'* were assumed to vary linearly with time, and were calculated in the model as a function of the calendar day number (January 1 is day 1 and December 31 is day 365 or 366). Fluxes were calculated with the model for the same 20-min intervals as the fluxes determined with the energy budget-Bowen ration method. The 20-min values calculated with the energy-combination model were averaged to calculate a daily average for all fluxes. The daily values for latent heat flux (Figure 1) were converted to mm of water. For the central Nevada study site, transpiration of groundwater ranged from about 3.5 mm d^{-1} in mid-July to about 1.0 mm d^{-1} in early September. The high rates in late July (Figure 1) reflect the effects of summer convective storm precipitation. These values were corrected to compensate for summer precipitation (discussed below). The daily values were averaged over the 55-day period to calculate a mean daily average that was assumed to be equal to the mean daily average rate for groundwater discharge by greasewood in areas where the depth to groundwater is about 2 m. At the central Nevada study site this rate is 2.4 mm d^{-1}.

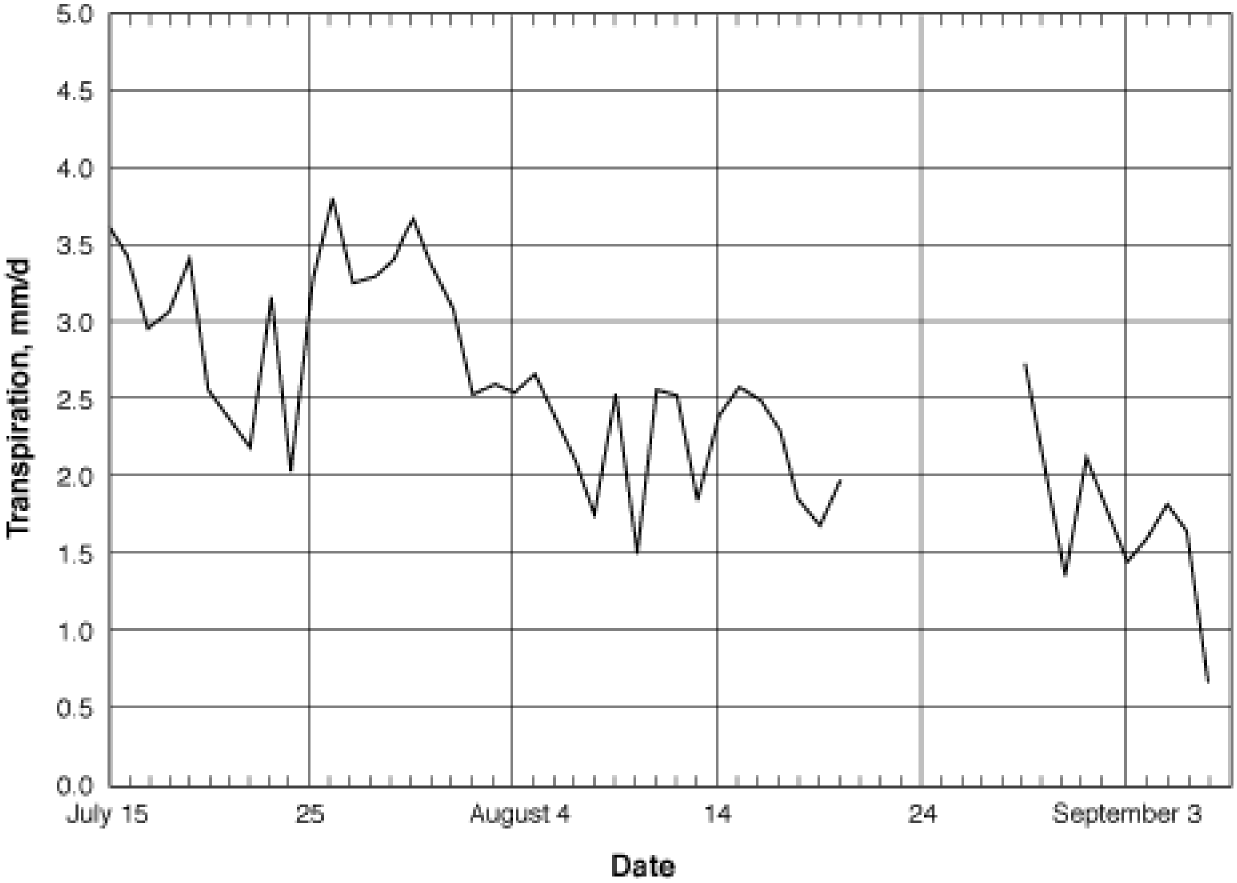

Fig. 1. Estimated daily transpiration of groundwater by greasewood July 15 to August 7, 1989.

The model also provided an estimate of evaporation from bare soil. This ranged from as much as 2.1 mm d^{-1} following summer convective storm precipitation to a minimum of about 0. 2 mm d^{-1} in late August. The average estimated soil evaporation was about 0.6 mm d^{-1}. Total estimated soil evaporation for the 55 days from July 15 to September 7 was 3.3 cm. Excluding days when soil evaporation is affected by precipitation, the energy combination model consistently predicted soil evaporation during the morning hours. This suggests that there also is groundwater discharge by evaporation from the water table at the study site (discussed below). The mean daily rate of discharge, corrected for summer precipitation is about 0.25 mm d^{-1}.

Estimated daily transpiration shown in Figure 1 obviously is not constant, but decreases from mid-July to early September. It finally will go to zero sometime in late September or October. The decrease is a function partly of the decrease in net radiation, and therefore a decrease in available energy to drive the energy budget. It also is a function of a decrease in shrub LAI as the shrubs dropped leaves to survive during the periods of high temperatures and increased water stress. For some types of detailed studies, it may be more appropriate or desirable to develop a functional relation between transpiration and time to reflect this decrease in rate. That was not done in this study for several reasons. First, the intent of this investigation was to develop an estimate of annual groundwater discharge by greasewood that might be compared to previous estimates made by *White* [1932] and *Robinson* [1970] and that might prove useful in reconnaissance groundwater studies. Second, and perhaps more important, there was no way, with the data available, to determine the time when groundwater consumption becomes the dominant component of transpiration (compared to soil moisture from winter and spring precipitation) and consequently no way to determine a functional relation for transpiration before the mid-July time period for which data were available. The problem then remains to convert the estimated mean daily rate of groundwater discharge by transpiration into an annual total.

DISCUSSION

Little information is available on the length of the growing season for greasewood, and no estimates are available on the length of the growing season during which greasewood uses predominantly groundwater. *White* [1932] did not address the growing season issue. Groundwater hydrographs published by *White* [1932] for areas of greasewood show water level decline beginning in mid to late April and continuing until early September or early October, although he also reports evapotranspiration by greasewood in October. The hydrographs suggest that the use of groundwater by greasewood extends from about mid to late May until middle or late September and implies a growing season of about 165 days at the latitude of Milford, Utah (38º25'N).

Robinson [1970] discusses factors affecting greasewood growth in the Winnemucca, Nevada area (41ºN). He [*Robinson*, 1970, p. 25] suggests that the growing season for greasewood in this area is determined by spring and fall threshold temperatures of -2.2ºC. During the mid-1960s, when the study was conducted, the number of days between the last -2.2ºC in the spring and the first day in the fall varied from about 120 days to about 190 days; the latest date in the spring ranged from April 20 to June 3 and the earliest date in the fall ranged from September 14 to October 24.

The summer of 1989, during which the data for this study were collected, was the third summer of an extended drought in western and central Nevada. A Bureau of Land Management fire-weather monitoring station about 8 km southwest of the study recorded 6.6 cm of precipitation from January 1 to July 1, 1989, nearly all of which had occurred by June 11. An additional 1.7 cm was recorded from July 1 to September 1. Above-canopy energy budget fluxes were calculated using the Bowen ratio method for 19 days of good micrometeorological data at the study site between May 25 and July 4. The average calculated evapotranspiration for these days was 2.5 mm d^{-1} . If this rate is applied for all of May and the first 20 days of June, then total evapotranspiration at the study site was 12.5 cm, enough to account for nearly twice the precipitation since January 1.

Similar, though less lengthy, field studies were conducted in Smith Creek Valley during the summers of 1987 and 1988. Soil moisture measurements that were made at the beginning and end of these studies together with measurements that were made at the beginning and during the study in 1989 suggest no significant change in shallow (0-10 cm) soil moisture from one year to the next. Measurements in September 1987, May 1988, September 1988, May 1989, and September 1989 all yielded a shallow soil moisture content of 0.08% by volume. This suggests that little winter precipitation occurred at the site and that whatever shallow soil moisture did accumulate over the winter months had evaporated or had been transpired early in the summer.

Observed evapotranspiration rates in 1989 reached a maximum at the Smith Creek Valley study site in early June, several weeks before summer solstice when net radiation reaches a maximum. If there had been abundant soil moisture or if the greasewood had been able to transpire groundwater at a rate high enough to support the biomass established by early June, then the transpiration rate should have continued to increase, as net radiation increased, until June 21 (summer solstice). That this did not happen is interpreted to indicate that both bare soil evaporation and shrub transpiration had consumed all readily available winter-accumulated soil moisture, and that the greasewood shrubs were beginning, in mid-June, to transpire groundwater.

Given the probable complete consumption of winter precipitation by mid-June and the decreasing evapotranspiration rate beginning in early June, it is assumed that greasewood at the study site transpired groundwater at a decreasing rate from late June until mid to late September. For this analysis it has been assumed that the growing season in central and northern Nevada extends for 140 to 165 days and that the period dominated by groundwater use is about 100 days. During the first 40-65 days of the growing season it is assumed that the greasewood shrubs are using dominantly winter-accumulated soil moisture after which time they use groundwater except for short periods of time when summer convective storm precipitation provides small amounts of shallow soil moisture that is readily transpired within several days of the storm. The annual rate of groundwater discharge was therefore estimated to be about 24 cm yr^{-1} in areas of depth to groundwater of less than 2 m. This is comparable to the rates of 18 to 24 cm yr^{-1} estimated by *Robinson* [1970].

The estimated daily rate of groundwater discharge has been corrected for summer convective storm precipitation. These storms provided only small amounts of moisture during the summer of 1989 and the moisture did not penetrate more than several centimeters before being evapotranspired. Typically, following a convective storm the sensible heat flux from the canopy became negative, indicating that the shrubs were transpiring at a rate exceeding the net radiation to the canopy. This was interpreted to mean the shrubs were using the readily available shallow soil moisture in addition to whatever groundwater was being transpired.

Accordingly, the transpiration rate was reduced by the amount of estimated negative sensible heat flux. This may not have corrected for all the shallow soil moisture being used, but any additional error in estimated groundwater transpiration is believed to be small.

The annual discharge of groundwater by greasewood estimated by this study is significantly greater than that used in previous groundwater studies in the Great Basin, particularly in Nevada. The most commonly assumed rate of groundwater evapotranspiration has been from 6.0 to 9.0 cm yr^{-1}. It must be remembered however, that the previously used rates were for areas with depths to groundwater of as much as 12 m, while the rate estimated in the present study is for areas with a depth to groundwater of 2 m or less. Additional studies in progress suggest that the rate of groundwater discharge by phreatophytes (excluding salt grass and salt cedar) may range from a maximum of about 24.5 cm yr^{-1} in areas with a depth to water of about 1.5 m to a minimum of about 1.3 cm yr^{-1} in areas with a depth to water of about 12 m. The results of these studies are preliminary and remain to be verified by additional field data.

Finally, the observed constant soil moisture in the 0- to 10-cm depth zone is consistent with the model predictions of evaporation from the soil in the morning hours during July and August. The model results and field measurements suggest that capillary action moves groundwater from the water table to very shallow depths below the soil surface. This moisture moves into the surface soil during the night when surface temperatures are low and solar energy is not available to drive the energy budget process. Shortly after sunrise, the moisture begins to evaporate and by about noon a dry soil crust has formed and the physics of unsaturated flow precludes further evaporation. The modeled evaporation from bare soil was 3.3 cm. About 1.4 cm of this would be accounted for by the continual evaporation of groundwater at the rate of .25 mm d^{-1} over the 55 days of measurements. The remaining 1.9 cm of modeled evaporation is readily accounted for by the approximately 1.7 cm of precipitation that fell during July and August.

SUMMARY AND CONCLUSIONS

Above-canopy fluxes of sensible and latent heat calculated with the energy budget-Bowen ratio equation were used to calibrate a two-component energy-combination model [*Shuttleworth and Gurney*, 1990] for two periods at a field study site in central Nevada during the summer of 1989. The model partitions the energy between the soil and rangeland vegetation and was used to estimate the fluxes of sensible and latent heat from both the bare soil and the canopy for a period extending from July 15 to September 7.

The general applicability of the energy-combination model to sparse-canopy rangelands was demonstrated by Nichols [1992]. The extension of that analysis to a second time period at the same study site yields equally satisfactory results, but with different values for some of the site specific data, namely, LAI, *n*, and *n'*. It is not unreasonable to expect LAI to change as the summer progresses into fall. Canopy temperature measurements show that the leaf temperature gradually increased above air temperature from July to September, suggesting the plants were experiencing greater water stress as time passed. It is likely that the shrubs dropped leaves as stress increased in order to survive to the end of the growing season, and therefore that LAI decreased with time. The variables *n* and *n'* are related to canopy structure and architecture, so it is to be expected that these values will change in response to changes in leaf area. The exact relation among these variables is not known and many more field situations will need to be examined before defining that relation.

Groundwater discharge by transpiration from the canopy, which consists only of greasewood, was estimated to be about 2.4 mm d^{-1} for the 55 days from July 15 to September 7. This rate was converted into a mean annual rate of groundwater discharge for an estimated 100 days of the growing season when the greasewood was assumed to be transpiring only groundwater. The estimated rate is 24 cm yr^{-1} and applies to areas where the depth to groundwater is about 2 m.

This estimate of the annual groundwater discharge by greasewood is from 2.5 to 4 times greater than estimates commonly used in previous studies in the western Great Basin. It is comparable to the rate of from 18 to 24 cm reported by *Robinson* [1970]. Previous estimates, however, included areas where the depth to water was as much as 12 m below land surface; the present estimate is for areas where the depth to water is less than 2 m. Studies currently in progress suggest groundwater discharge rates ranging from about 24.5 cm yr^{-1} in areas with a depth to water of about 1.5 m to about 1.3 cm yr^{-1} in areas with a depth to water of 12 m. For the most part these rates are considerably greater than groundwater discharge rates used in previous studies and they have significant implications for groundwater budgets determined during these studies.

APPENDIX

Following are the equations for the resistance terms used to solve (5)-(8) together with supporting equations:

$$r_{as} = \frac{h\exp(n)}{nK_h}\left[\exp\{-nz_0'/h\} - \exp\{-nZ/h\}\right] \qquad (9)$$

$$r_{ac} = r_b / 2\ \mathrm{LAI} \qquad (10)$$

$$r_b = \frac{100}{n'}\left[\frac{(w/u_h)^{1/2}}{1-\exp(-n'/2)}\right] \qquad (11)$$

$$r_{sc} = \frac{(\rho c_p/\gamma)[e_*(T_c) - e_0]}{(Rn - Rn_s) - \rho c_p(T_c - T_0)/r_{ac}} - r_{ac} \qquad (12)$$

$$r_{ss} = \frac{(\rho C_p/\gamma)[e_*(T_s) - e_0]}{Rn_s - \rho c_p(T_s - T_0)/r_{as}} - r_{as} \qquad (13)$$

$$r_{aa} = \frac{1}{ku*}\left[\ln\frac{(z_R - d)}{h-d}\right] + \frac{h}{nK_h}\left[\exp\{n\ (1 - Z/h)\} - 1\right] \qquad (14)$$

The other variables are obtained from

$$e_0 = e_a + \gamma\left[r_{aa}(Rn/\rho c_p) - (T_0 - T_a)\right] \qquad (15)$$

$$K_h = ku*(h-d) \qquad (16)$$

$$u* = \frac{ku}{\ln[(z_R - d)/z_0]} \qquad (17)$$

$$u_h = \frac{u*}{k}\ln\left[\frac{z_h - d}{z_0}\right] - \psi_m \qquad (18)$$

$$z_0 = z_0' + 0.3h(0.07\,\mathrm{LAI})^{1/2} \quad \mathrm{for\ LAI} < 2.85 \qquad (19)$$

$$z_0 = 0.3h(1 - d/h) \quad \mathrm{for\ LAI} > 2.85 \qquad (20)$$

$$d = 1.1 h \ln\left[1 + (.07\,\mathrm{LAI})^{1/4}\right] \quad (21)$$

$$Z = Z_0 + D \quad (22)$$

where Z_0 and D are the preferred values of z_0 and d for LAI = 4.

NOTATION

c_p	specific heat of air at constant pressure, J kg^{-1} K^{-1}.
D	zero plane displacement height for full canopy, m.
d	zero plane displacement height for partial canopy, m.
E	evaporation.
e_0	vapor pressure at within-canopy source height, mbar.
e_a	vapor pressure at above-canopy reference height, mbar.
$e_*(T)$	saturated vapor pressure at temperature T ($T = T_a$, T_c, T_s), mbar.
G_s	soil heat flux, W m^{-2}
h	canopy height, m.
H, H_c, H_s	sensible heat flux above the canopy, from the canopy and from the soil, W m^{-2}
k	von Karman's constant, equal to 0.4, dimensionless.
K_h	eddy diffusion coefficient at the top of the canopy, m^2 s^{-1}.
LAI	leaf area index, dimensionless.
n	attenuation coefficient for eddy diffusivity, dimensionless.
n'	attenuation coefficient for wind speed, dimensionless.
r_{ac}	bulk boundary layer resistance of the canopy, s m^{-1}.
r_{as}	aerodynamic resistance between the soil and within-canopy source height, s m^{-1}.
r_b	mean boundary layer resistance per unit area of vegetation, s m^{-1}.
r_{sc}	bulk stomatal resistance of the canopy, s m^{-1}.
r_{ss}	surface resistance of the soil, s m^{-1}.
Rn	net radiation on both soil and canopy, W m^{-2}.
Rn_c, Rn_s	net radiation on the canopy, on the soil, W m^{-2}.
T_a	air temperature at above-canopy reference height, ^{o}C.
T_c	canopy temperature, ^{o}C.
T_s	soil surface temperature, ^{o}C.
T_0	air temperature at within-canopy source height, ^{o}C.
u	wind speed at above-canopy reference height, m s^{-1}.
u_h	wind speed at top of canopy, m s^{-1}.
$u*$	friction velocity, m s^{-1}.
w	leaf width, m.
z_h	height at top of canopy, m.

z_R	reference height above canopy, m.
z_0	roughness length for sparse canopy, m.
z'_0	roughness length for bare soil, m.
Z_0	roughness length for full canopy, m.
α	θ5 cosec
γ	psychrometric constant, mbar K^{-1}.
λE, λE_c, λE_s	latent heat flux above the canopy, from the canopy, from the soil, W m^{-2}.
ρ	density of air, kg m^{-3}.
Ψm	surface layer stability corrector for momentum, dimensionless.
θ	solar altitude, radians.

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