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

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Groundwater discharge by phreatophyte shrubs in the Great Basin as related to depth to groundwater

William D. Nichols
Water Resources Division, U.S. Geological Survey, Carson City, Nevada

Abstract. An equation describing the mean daily discharge of groundwater by transpiration from phreatophyte shrubs as a function of plant density, leaf area index, and depth to groundwater was developed using an energy combination model calibrated with energy fluxes calculated from micrometeorological data. The energy combination model partitions the energy budget between the soil and canopy permitting plant transpiration to be separated from evaporation from the soil. The shrubs include greasewood, rabbitbrush, shadscale, and sagebrush. Converting a daily groundwater discharge rate calculated by the equation to an annual rate requires an estimate of the number of days the plants used only groundwater. Rates used during previous studies in the Great Basin range from 0.030 to 0.152 m yr^{-1}; rates calculated with the equation developed during this study range from 0.024 to 0.308 m yr^{-1} for the reported field conditions. Annual rates estimated in this study differ from the estimated annual rates used in previous studies by factors ranging from 0.8 to 5.0.

Introduction

Evapotranspiration is the principal, and in some areas the sole, mechanism of groundwater discharge in the Great Basin and can be a significant method of groundwater consumption in other areas of the arid and semiarid western United States. Estimates of groundwater discharge by phreatophyte transpiration have been based on results of a study by *White* [1932] and have been used to estimate groundwater budgets for much of the Great Basin. It is now recognized that the results of this study are based on a flawed analysis [*Nichols*, 1993]. Additionally, previous studies applied the results of *White* [1932] in a qualitative and inconsistent fashion. Given the increasing demand for water resources in the region and the need for better estimates of regional water budgets, it is essential to develop quantitative methods that can be applied systematically for estimating groundwater discharge by phreatophytes in the Great Basin and elsewhere in the arid and semiarid west. The present study extends earlier work [*Nichols*, 1993] and presents a physically based method for estimating groundwater discharge by transpiration from phreatophyte shrubs in the northern Great Basin as a function of depth to groundwater, plant density, and leaf area index.

Most closed basins and valleys of the Great Basin have a central bare playa, commonly underlain by a shallow water table (less than 2.5 m). Surrounding the playa are plants of the salt desert community, including iodine bush (*Allenrolfea occidentalis*, also called pickleweed), saltsage (*Atriplex tridentata*), and saltgrass (*Distichlis spicata* var. *stricta*). Iodine bush is reported to grow in areas with a depth to water of as much as 6 m [*Robinson*, 1958, p. 32]. Saltgrass, the most important phreatophyte in this zone, grows most commonly in areas where the depth to water is less than about 2.5 m but has been reported to grow in areas where the water table is as much as 3.6 m deep [*Blaney et al*., 1993, p. 50].

Next beyond this fringe of vegetation around the margin of the playa is the shadscale-greasewood plant community. Within this plant association are found not only greasewood (*Sarcobatus vermiculatis*) and shadscale (*Atriplex confertifolia*), but also saltbush (*Atriplex canescens*, also known as chamiso), spiny hopsage (*Grayia spinosa*), winterfat (*Ceratoides lanata*), and where soils and groundwater are less saline, rabbitbrush (*Chrycothammus nauseosus*) and big sagebrush (*Artemisia tridentata*). Of the plants that grow in the shadscale-greasewood zone, greasewood consumes the most groundwater. It covers about 4.8 million ha from Canada to Mexico but prefers the cold deserts north of 37°N [*Shreve*, 1942]. It is the principal phreatophyte, other than riparian, in the shadscale-greasewood zone of western Nevada [*Robertson*, 1983] and its range is more extensive than that of big sagebrush in western North America [*Robertson*, 1983]. It occurs in areas where depth to groundwater ranges from about 1.5 m to 11 m and perhaps to as much as 18 m [*Robinson*, 1958, p. 39]. *White* [1932, p. 33] noted that greasewood required at least 1 m of unsaturated soil most of the time. Saltbush is found where groundwater is from about 2.5 m to as much as 19 m below land surface [*Robinson*, 1958, p. 33]. Rabbitbrush grows in areas where the depth to groundwater is less than about 10.5 m. *Robinson* [1958, p. 34] suggests a maximum depth to water for rabbitbrush of 4.5 m, conventional wisdom has suggested a maximum depth of 8 m, and *Mower* and *Nace* [1957, p. 18] suggest a maximum depth of 10.5 m. Shadscale and spiny hopsage are not commonly included as phreatophytes but have been observed growing with greasewood in areas where the depth to water is at least 5 m and therefore are assumed to transpire groundwater at rates similar to those of greasewood. *White* [1932, p. 38] discusses the occurrence of shadscale with greasewood and rabbitbrush in areas of shallow groundwater but does not suggest a limiting depth to water. Big sagebrush has been observed in some basins of the Great Basin in association with rabbitbrush in areas where the water table is about 4 m below land surface, and in these circumstances it appears to be a phreatophyte as well, although *White* [1932, p. 43] assumed, on the basis of water-level fluctuations, that sagebrush used little or no groundwater even in areas of the Escalante Valley of Utah where the depth to water was less than 4.5 m. *Mozingo* [1987, p. 271] reports that sagebrush has a taproot that grows as deep as 4 m and commonly penetrates to the capillary zone just above the water table. Beyond the shadscale-greasewood zone, big sagebrush and other subspecies of sagebrush occur in areas where depths to water commonly exceed 20 m and their roots do not reach the water table. Only studies by *White* [1932] and *Robinson* [1970] have attempted to determine the evapotranspiration of groundwater by native shrubs of the cold desert of the Great Basin.

Energy budget field studies in stands of sparse-canopy phreatophytes, mainly greasewood, were conducted for the present investigation at seven sites in five basin in the northern Great Basin during the summers of 1988 through 1992. Using these data, plant density data, and estimated leaf area index (LAI) values collected during these field studies together with an energy combination model [*Shuttleworth and Gurney*, 1990; *Nichols*, 1992a; *Nichols*, 1993] that partitions energy between the soil and plant canopy, a relation has been developed for estimating groundwater discharge by evapotranspiration as a function of plant density, leaf area index, and depth to groundwater.

Previous Investigations

Among the earliest studies to measure the consumptive use of groundwater by evapotranspiration from native shrubs is that of *White* [1932], who conducted tank experiments to measure evapotranspiration from alfalfa, saltgrass, greasewood, and bare soil in 1926 and 1927 in the Escalante Valley near Milford, Utah. He also installed a number of small-diameter monitoring wells in areas of native vegetation underlain by shallow groundwater and measured small diurnal fluctuations of groundwater levels that were interpreted to be caused by the evapotranspiration of groundwater during the day. An expression was developed relating the discharge of groundwater to the specific yield of the water-bearing sediments and the 24-hour rate of water level change plus net water level change [*White*, 1932, p. 61]. A number of soil samples were taken to determine appropriate values of specific yield. The volume of groundwater discharged then was determined from the diurnal water level fluctuations. This volume was related to biomass production using data obtained from the tank experiments and was converted to areal estimates of groundwater discharge based, presumably, on areal estimates of plant canopy volume. *White* [1932, p. 86-87] concluded that in the Escalante Valley greasewood, rabbitbrush, and shadscale consumed about 0.045 m yr^{-1} in areas with a depth to groundwater of 2.4-9 m, and about 0.064 m yr^{-1} in areas with a depth to groundwater of less than 2.4 m. It is now recognized [*Nichols*, 1993] that these values are too small because of a misunderstanding in the assumptions in the original analysis made by *White* [1932]. Nevertheless, these values derived by *White* [1932] for groundwater consumption by greasewood and saltgrass provided the basis for estimates of groundwater discharge by investigators in Nevada from the 1940s to the present (Table 3).

Robinson [1970] conducted studies from 1963 to 1967 of groundwater evapotranspiration by woody phreatophytes in the Humboldt River Valley near Winnemucca, Nevada. Evapotranspiration tanks were planted with greasewood, rabbitbrush, willow, and wild rose. One tank contained bare soil. *Robinson* [1970, p. 31-32] concluded, on the basis of tank experiment data, that the consumption of groundwater by greasewood ranged from an average of about 0.18 m yr^{-1} to about 0.24 m yr^{-1} from 1963 to 1967. Rabbitbrush transpired an average of 0.324 m yr^{-1} from 1964 to 1967. These rates are considerably greater than the rates reported by *White* [1932] but are difficult to compare because of a lack of comparable canopy density and volume data for the two studies.

More recent studies of evapotranspiration by rangeland vegetation have used micrometeorological methods to measure total above-canopy fluxes of sensible and latent heat. *Malek et al.* [1990] measured evapotranspiration from the moist playa and playa margin of Pilot Valley, Utah. *Duell* [1990] conducted similar studies for a variety of desert shrub and grass communities growing in areas of shallow groundwater at a number of locations in Owens Valley, California. *Czarnecki* [1990] measured evapotranspiration at Franklin Lake Playa, Nevada, and *Weeks et al.* [1987] conducted studies of evapotranspiration by salt cedar, alkali sacaton, kochia, and grass in the Pecos River Valley between Acme and Artesia, New Mexico. Evapotranspiration rates determined by these studies are somewhat less useful in determining groundwater consumption by evapotranspiration because they include evapotranspiration of precipitation and soil moisture as well as evapotranspiration of groundwater.

Recently, *Nichols* [1992a] demonstrated the general applicability of an energy combination model [*Shuttleworth and Gurney*, 1990] for partitioning energy budgets, and hence evapotranspiration, between the soil and canopy of sparse-canopy rangeland vegetation. Using the results of an energy combination model calibrated for study sites underlain by shallow groundwater in west-central Nevada (sites 4 and 5, Figure 1 and Tables 1 and 2), *Nichols* [1992b, 1993] developed evapotranspiration rates for greasewood, rabbitbrush, and sagebrush ranging from 0.162 to 0.219 m yr^{-1}. These rates are closer to the rates suggested by *Robinson* [1970] than those suggested by *White* [1932], but still are difficult to compare because of uncertainty in the plant densities relevant to the earlier studies.

Data and Methods

Energy budget studies in stands of sparse-canopy phreatophytes were conducted at seven sites in five basins in the northern Great Basin during the summers of 1988 through 1992 (Figure 1 and Tables 2 and 3). Study sites were selected in each basin so that 95% of the shrubs were greasewood, or sagebrush and rabbitbrush in the case of site 5, and that similar plant density extended for at least 200 m in all directions from the instrument location. The data collected at these sites included incident and reflected shortwave radiation, incident and emitted longwave radiation, air temperature at two heights, dew point temperature at two heights, wind speed at two heights, soil heat flux, soil temperature in the interval between the surface and buried heat flux plate, soil surface temperature, and canopy temperature. Dew-point temperature was used to calculate vapor pressure. Values of net radiation, air temperature gradient, vapor pressure gradient, and soil heat flux were used to solve the energy budget, given by (symbols used in the following equations are given in the notation section)

$$Rn = \lambda E + H + G_s \tag{1}$$

using the Bowen ratio method [*Tanner*, 1960].

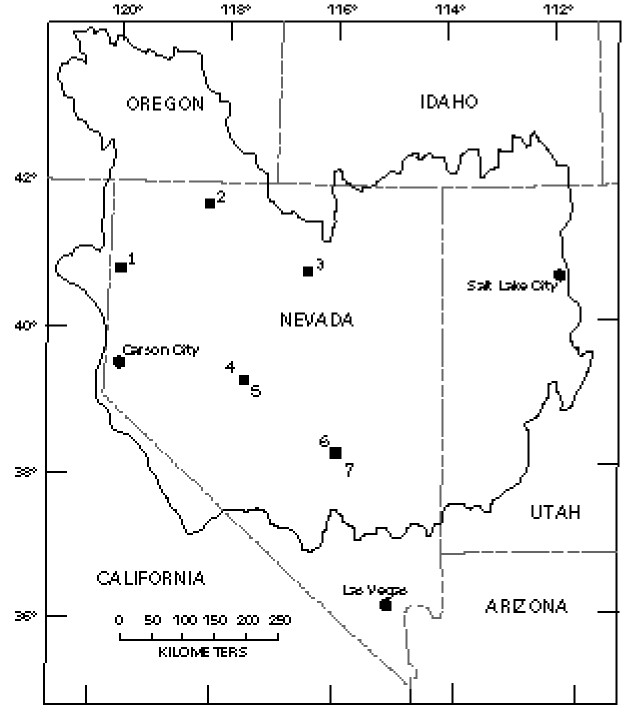

Figure 1. Location map of study area showing boundary of northern Great Basin Desert [after Trimble, 1989] and locations of field measurement sites. Numbers refer to site numbers in Tables 1 and 2.

Table 1. Field Study Site General Information

Site	Location	Latitude, °N	Longitude, °W	Altitude, m	Dates of Data Collection	
					Start	End
1	Smoke Creek Desert	40.5336	119.8178	1191.1	June 1991	Sept. 1991
2	Kings River Valley	41.5550	118.0847	1266.4	June 1991	July 1991
3	Boulder Flat	40.7556	116.4839	1415.2	July 1991 June 1992	Aug. 1991 Aug. 1993
4	Smith Creek Valley	39.3297	117.5125	1842.8	May 1989 May 1990	Sept. 1989 July 1990
5	Smith Creek Valley	39.3556	117.5000	1844.6	July 1988 May 1990	Jul y 1988 July 1990
6	Railroad Valley	38.5028	115.7694	1445.1	June 1992	...*
7	Railroad Valley	38.5028	115.7766	1453.9	June 1992	Sept. 1992

*Continuing as of August 1994.

Table 2. Depth to Groundwater and Canopy Information for Field Study Sites

Site	**Depth to Water, m**	**Vegetation**	**Canopy Height, m**	**Plant Density, d_p**	**LAI L_0**	**Equivalent Plant Density, d_e**
1	5.8*	greasewood, hopsage	0.50	0.23	3.3	0.19
2	4.9	greasewood, hopsage	0.75	0.25	3.2	0.20
3	5.5	greasewood, shadscale	0.60	0.23	3.9	0.22
4	1.7	greasewood	0.75	0.25	4.0	0.25
5	3.7	sagebrush, rabbitbrush	0.80	0.36	2.8	0.25
6	1.8	greasewood, shadscale	0.50	0.22	2.8	0.16
7	6.4	greasewood	0.65	0.13	1.8	0.06

LAI, leaf area index (estimated).
*Perched saturated zone at 2.74 m.

Table 3. Comparison of Estimated Annual Groundwater Discharge Rates for Phreatophyte Shrubs Used in Previous Studies and as Calculated With the Equations Developed by the Present Study

Depth to Water (Reported), m	Plant Density (Reported), %	Estimated Annual Rate, m yr-1			Factor by Which Estimated Rates Differ
		Previous Studies		This Study	
		Rate	Reference		
1.5	20	0.152	1	0.185	1.22
1.8	35	0.061	2	0.308	5.05
2.3	25	0.152	3	0.234	1.54
2.4	20	0.061	2	0.159	2.61
2.4	25	0.061	2	0.199	3.26
3.0	30	0.152	4	0.216	1.42
3.3	20	0.030	3	0.137	4.57
3.7	10	0.061	2	0.065	1.07
3.8	15	0.061	4	0.095	1.56
4.6	15	0.061	1	0.084	1.38
4.6	20	0.091	3	0.112	1.23
6.9	20	0.061	5	0.077	1.26
7.6	15	0.030	1	0.051	1.70
7.6	25	0.061	6	0.085	1.39
8.4	20	0.061	7	0.06	0.98
9.1	20	0.061	8	0.053	0.87
12.2	15	0.030	5	0.024	0.80

References are 1, *Eakin* [1960]; 2, *Everett and Rush* [1964]; 3, *Eakin et al.* [1967]; 4, *Rush and Kazmi* [1965]; 5, *Glancy* [1968]; 6, *Eakin* [1961]; 7, *Rush and Everett* [1966]; and 8, *van Denburgh and Rush* [1974].

Net radiation was calculated by summing the four measured components of the radiation budget. These components were measured with Eppley precision spectral pyranometers (PSP) and precision infrared radiometers (PIR) [*Fritschen* and *Gay*, 1979].

(The use of trade names is for identification only and does not constitute endorsement by the U.S. Geological Survey) The PIRs were equipped with thermistors to measure dome and case temperatures so that measured longwave radiation could be corrected for radiation generated by temperature gradients between the instrument dome and case. These corrections for net longwave radiation typically are on the order of about –8 to –12 W m^{-2} during midday hours and about +4 to +6 W m^{-2} at night.

Vapor pressure gradients were determined by measuring dew point temperatures at two heights using a Campbell Scientific, Inc. (CSI), single-cooled-mirror hygrometer. The measuring heights were 0.5 and 1.5 m above the top of the canopy (Table 2). Air is alternately drawn through intakes at each height and routed to the cooled mirror; a single pump aspirates the system. The system avoids problems of measuring vapor pressures that typically are associated with systematic sensor error by using a single sensor. However, operating limitations of the cooled mirror under conditions of high temperature and low humidity can lead to invalid dew point temperature determination and consequently invalid vapor pressures. These conditions occur when ambient temperature approaches 35°C and humidity drops below 10%. This is a common occurrence in central Nevada in July and August. Air temperature was measured at the same two heights using 76-µm-diameter unshielded, nonaspirated chromel-constantan thermocouples.

Soil heat flux was measured with two Radiation Energy Balance Systems heat flow transducers buried at a depth of 0.05m. Changes in soil temperature in the soil layer above each transducer was measured by four thermocouples wired in parallel to provide a spatially averaged soil temperature. Two of the four thermocouples were placed above each transducer, one at a depth of about 0.01m and one at a depth of about 0.03 m. The change in soil temperature measured by the thermocouple, together with periodically measured soil water content and soil bulk density and an estimated value for the specific heat of dry soil, were used to calculate changes in soil heat storage in the interval above the flux transducers. This heat storage was added to the flux measured by the transducer.

Soil heat flux can be a significant component of the energy budget in sparse-canopy rangelands. For field studies in 1988, 1989, and 1990, the two flux plates and thermocouple pairs were located so that one set of sensors would be in full sun at early morning and the other set would be in full sun at late afternoon. The rationale was that this might yield a general average value of soil heat flux throughout the day. Since 1990, both sets of sensors have been placed in full sun locations in order to measure the maximum soil heat flux throughout the day. This maximum value is then modified for the area of bare soil at each study site. Proper measurement of this quantity in sparse-canopy conditions is an area that requires further research.

Air and dew point temperatures were sampled at 1-s intervals and averaged over 20-min periods. Radiation, radiometer temperatures, soil heat flux, and soil temperatures were sampled at 10-s intervals and averaged over 20-min periods. Data were collected with CSI 21X microloggers.

Additional data were collected at each site for use in the energy combination model used to partition the energy budget between the soil and canopy. These data included soil surface temperature, canopy temperature, and wind speed. The soil and canopy temperatures were measured using Everest Interscience infrared (IR) sensors, model 110, 4000, or 4000A. The model 110 is a hand-held IR gun with a 3° field of view (FOV). The instrument was modified to operate continuously using an external 12-V battery. It was placed in a housing to protect it from precipitation and was mounted 1.0-1.25 m above the canopy. These instruments were used from 1988 to 1991 for canopy temperature measurements. Soil surface temperature was measured from 1988 to 1991 using the model 4000 IR sensor which has a 15° FOV. Temperatures measured with this model IR sensor must be corrected for temperature differences between the sensor and sensor housing. The sensor was mounted about 2 m above the soil surface and viewed an area of bare soil about 0.45 m in diameter; areas of bare soil at the study sites typically are as much as 3 m x 3 m. Both of these model sensors were replaced with the model 4000A in 1992. The model 4000A has a 4° FOV and is equipped with internal compensation for sensor-case temperature differences. The sensor for measuring soil temperature was mounted at a height of about 2 m above the soil, while the sensor for measuring canopy temperature was mounted from 0.1 to 0.2 m above the canopy. Care was taken so that the sensor did not shade the area of soil or canopy being monitored. Canopy temperatures obtained from a single shrub are believed to be generally representative of all shrub canopy temperatures in the vicinity. The canopy temperatures of other shrubs in the area of the fixed sensor were occasionally measured with a portable IR sensor (Everest Interscience, Inc., model 110) and found to be within a few tenths of a degree of the temperature measured by the fixed sensor.

Wind speed was measured using photo-chopper anemometers (R.M. Young, Inc.) with a threshold of 0.2 m s^{-1}. Measurements were made 0.5 and 1.5 m above the top of the canopy, the same heights as air and dew point temperature measurements. All of these sensors were sampled at 10-s intervals and averaged over 20-min periods. Data were collected with CSI 21X microloggers.

A number of problems were encountered during the course of the field studies. Data for some days for which measurements were made were rejected because of low humidity conditions that led to incorrect vapor pressure determinations. Data for other days were rejected because of the probable advection of heat or moisture which resulted in invalid Bowen ratios. These latter occurrences commonly were associated with wind speed above 4 or 5 m s^{-1}. Occasional sensor malfunction led to the loss of data for other days. It is estimated that about 20% of the data were rejected or lost for these reasons.

Small-diameter auger holes were drilled at each field site to measure the depth to ground water. The water level was measured continuously at the Boulder Flat site (site 3, Figure 1, Table 2); depth to water below land surface remained at about 5.5 m from early summer 1992 through the summer of 1993. The depth to water at site 4 in Smith Creek Valley (Figure 1, Table 2) was 1.4 m below land surface in May and 1.8 m below land surface in mid-August. Water levels at the other sites were measured late in the summer each year and are the approximate maximum depth to water at each site.

Analysis

The energy budget can be partitioned with an energy combination model [*Shuttleworth and Gurney*, 1990; *Nichols*, 1992a] between the soil and canopy; the budget for the soil surface is given by

$$Rn_s = \lambda E_s + H_s + G_s \tag{2}$$

And that for the canopy is given by

$$Rn_c = \lambda E_c + H_c \tag{3}$$

The equations of the energy combination model are not presented here. Concepts and assumptions used in developing the model are fully discussed in *Shuttleworth and Wallace* [1985] and *Shuttleworth and Gurney* [1990], and the reader is referred to them for more detailed discussion of the equations, their theoretical basis, and their derivation. They have been summarized by *Ham and Heilman* [1991] and *Nichols* [1992a] who also have demonstrated the applicability of the model to sparse-canopy rangeland vegetation. Two equations that are important in the calibration of the model, however, will de discussed. The first is the equation for aerodynamic resistance to sensible heat flux from the soil, which is given by

$$r_{as} = \frac{h \exp(n)}{nK_h}\left[\exp\left(-nz_0'/h\right) - \exp\left(-nZ/h\right)\right] \tag{4}$$

and the second is that for the canopy boundary layer resistance [*Choudhury and Monteith*, 1988] which is given by

$$r_{ac} = r_b/2\mathrm{LAI}$$

where

$$r_b = (100/n')\left\{\frac{\left(w/u_h\right)^{1/2}}{\left[1-\exp\left(-n'/2\right)\right]}\right\} \tag{5}$$

The parameters n and n' [*Nichols*, 1992a] used by these equations are related to canopy structure and architecture and are empirically derived. Measured values of sensible and latent heat fluxes are therefore required to calibrate the model and determine these parameters for a given site. The energy budget-Bowen ratio values represent total above-canopy fluxes so that

$$\begin{aligned} \lambda E_\beta &= \lambda E_s + \lambda E_c \\ H_\beta &= H_s + H_c \end{aligned} \tag{6}$$

To calibrate the model, data were selected for days when there was reasonable certainty that virtually all of the latent heat flux was coming from the canopy and all or most of the sensible heat flux was coming from the soil. Winter-accumulated soil moisture commonly appears to have been completely evapotranspired by early to mid-June. By late June it was necessary only to avoid periods following convective storm activity to find conditions of no significant latent heat flux from the soil. Experience has shown that summer precipitation evaporates from bare soil within 5 to 7 days following the precipitation. Consequently, selecting days when latent heat flux from the soil is nearly zero is fairly easy, and the soil energy budget is then given by

$$H_s = Rn_s - G_s \tag{7}$$

These values of sensible heat flux from bare soil are used together with wind speed data to estimate the soil surface resistance to sensible heat (equation (4)), r_{as} [*Nichols*, 1992a], and thus calibrate the soil part of the model.

The assumption regarding sensible heat flux from the canopy is not as readily met. Sensible heat from the canopy is a function of the difference between air temperature and canopy temperature. This temperature difference in turn is a function of plant transpiration which controls the temperature of the leaves; transpiration is controlled by the water available to the plant. In areas of very shallow groundwater, say 1-1.5 m, there is abundant water for transpiration, and leaf temperatures are close to air temperature (at the same time, evaporation of groundwater from bare soil in these same areas adds to the difficulties of estimating the soil energy budget). As the depth to groundwater increases, so does the difference between air temperature and canopy temperature. As the temperature difference increases, the sensible heat flux from the canopy increases and the assumption is not well met.

Nevertheless, under the dry soil conditions discussed above for sensible heat flux from the soil, the assumption that essentially all latent heat flux is from the canopy is met and

$$\lambda E_c = \lambda E_\beta \tag{8}$$

This value of λE was used to determine n' and to calibrate the model for latent heat flux from the canopy. Net radiation to the canopy in excess of calculated λE_c is sensible heat from the canopy and was added to the sensible heat flux calculated for the soil; these two values should equal the measured above-canopy sensible heat flux.

Once the model was calibrated for several days, it was used to predict the energy budget for several additional days with similar conditions. If the results of the predictions were satisfactory, then the model was used to predict the energy budgets for several days following precipitation. If these predictions were satisfactory, then the model was assumed to be calibrated for the conditions at the measurement site. If, on the other hand, the predicted energy budgets were not satisfactory, the calibration process was started anew using a different set of dry soil condition data. The calibration procedure was repeated for every 4-6 weeks of data available at a site. This was done because the parameters n and n' are unknown functions of canopy structure and architecture. The structure of rangeland plant stands may not change significantly from year to year, but the architecture of the canopy may change significantly over periods of several weeks as leaves are added or lost and as they change in length. Experience calibrating the model for several sites for periods from mid-June to early September suggests that LAI decreases with time, as might be expected as shrubs become stressed by heat and a prolonged period of surviving on groundwater alone. As LAI decreases, n appears to decrease as well, while n' appears to increase [*Nichols*, 1993].

Once the model had been calibrated for a site and the energy budget had been partitioned between the soil and canopy, the daily transpiration rate for the shrubs could be calculated. Model-derived transpiration rates for mid-July to early September were used to calculate a mean daily rate for the period when the shrubs were assumed to survive on groundwater. The mean daily rate was plotted as a function of the depth to groundwater, and an exponential curve of the form

$$ET_g = a_0 \exp(-kz_w) \tag{9}$$

was found to provide the best fit, where ET_g is groundwater discharge by greasewood, as well as sagebrush and rabbitbrush at site 5, and is in units of $L\ T^{-1}$, a_0 is in units of $L\ T^{-1}$, k is in units of L^{-1}, and z_w is the depth to groundwater and has units of L. It is believed that this equation describes the discharge of groundwater by any phreatophyte shrub species. The intercept of the equation, a_0, is a function of both plant density, d_p, and average leaf area index, L_0. The following coefficients (Figure 2) provided the best fit to the data with an $r^2 = 0.996$:

$$ET_g = (d_e)[0.0119 \exp(-0.165\ z_w)] \tag{10}$$

For z_w in meters and $d_e = 1.0$, for

$$d_e = d_p(L_0/4) \tag{11}$$

where d_e is a equivalent plant density, d_p is the actual plant density in decimal percent ranging from 0.0 to 1.0, and L_0 is the average leaf area index of the shrubs and has a value from 0 to 4. The actual plant density and average leaf area index were estimated visually at each study site. The initial estimates of leaf are index were whole integers (i.e. 1, 2, 3, or 4). These were modified during model calibration so that calculated transpiration matched observed evapotranspiration during extended dry periods when all evapotranspiration can be expected to be from the canopy. The process of model calibration has been discussed in detail by *Nichols* [1993]. In Figure 2, the curve and the data points for sites 4 and 5 are for an equivalent plant density, d_e, of 0.25. The data points for sites 1, 2, 3, 6, and 7 are daily rates that were adjusted from rates for equivalent plant densities ranging from 0.06 to 0.22 to be equal to the daily rate for an equivalent plant density of 0.25. The depth to groundwater at site 1 was 5.8 m (19 feet), but there is a perched saturated zone at 2.7 m (9 feet) and the modeled value of ET_g at that site is plotted for the shallower depth. The values labeled “H&P” are reported in the literature [*Harr and Price*, 1972]. Measured groundwater discharge by greasewood reported by *White* [1932] and *Robinson* [1970] could not be used because of uncertainty about the appropriate equivalent plant density for which the reported values applied. *Robinson* [1970] provides detailed measurements of plant density but no measurement or estimate of leaf area index. The family of curves of groundwater discharge for typical plant densities for greasewood, rabbitbrush, shadscale, and sagebrush in the Great Basin is shown in Figure 3.

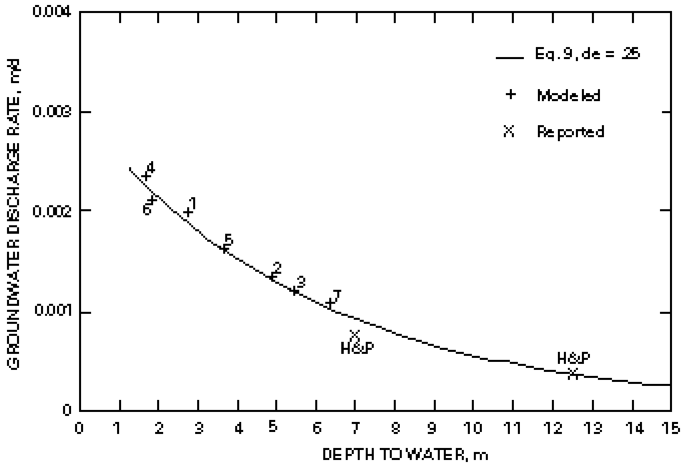

Figure 2. Mean daily groundwater discharge by phreatophyte shrubs by transpiration as a function of depth to groundwater for equivalent canopy density, de = 0.25. Numbers refer to measurement sites shown in Figure 1 and listed in Table 1. All sites are in Nevada. 1, Smoke Creek Desert; 2, Kings River Valley; 3, Boulder Flat, Humboldt River Valley; 4, 5, Smith Creek Valley; 7, 8, Railroad Valley. "H&P" refers to data from *Harr and Price* [1972].

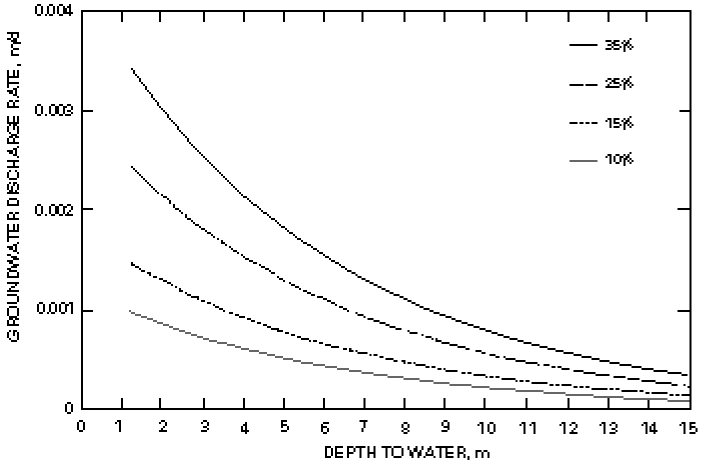

Figure 3. Mean daily discharge of groundwater by phreatophyte shrubs by transpiration as a function of depth to groundwater for equivalent canopy densities common in the northern Great Basin.

Discussion

Using (10) to estimate a value for mean daily groundwater discharge by evapotranspiration requires a good knowledge of plant density and leaf area index, and a good estimate of average depth to groundwater. For this study, values for equivalent plant density considered two factors. First, plant density was considered to be the ratio of the linear length of ground covered by plants to the total distance measured along transects of about 100 m. This value was modified for the estimated percent of the plant with leaves, or L_0, the leaf area index of the shrub converted to a fraction. As an example, site 6, located in Railroad Valley had a plant density of about 13% (0.13) and an estimated leaf area index of about 1.8 (1.8/4.0 = 0.45) for an equivalent plant density of about 6% (0.058).

Measured depth to groundwater may be misleading in some instances. At site 1, located in the Smoke Creek Desert, the depth to groundwater measured in a well drilled at the site was 5.8 m, but there was a perched saturated zone at a depth of 2.7m. Transpiration rates calculated with energy budget data and the energy combination model are consistent with this depth to groundwater. Consequently, application of (10) with the measured depth to groundwater of 5.9 m will result in a calculated groundwater discharge rate that is too low, 0.00115 m d^{-1} compared to 0.00189 m d^{-1} for a depth to water of 2.6 m.

Converting the estimated daily groundwater evapotranspiration rate into an annual rate is problematic. *Nichols* [1993] estimated annual groundwater discharge by evapotranspiration from greasewood in Smith Creek Valley in central Nevada based on an estimated 100-day period when the shrubs were assumed to subsist solely on groundwater. This interval will vary with latitude and annually and will depend on an early or late onset of spring and fall as well as the amount of winter-accumulated soil moisture and early spring precipitation. Field observations made in the spring and summer from 1989 through 1992 suggest that winter and spring precipitation is instrumental in determining the amount of biomass the shrubs produce by early summer. Plants use shallow soil moisture derived from winter and spring precipitation for vigorous early season growth, but they also require the nitrogen carried down by this precipitation from the land surface to the roots [*James and Jurinak,* 1978]. Without sufficient winter and spring precipitation to provide both shallow soil moisture and nitrogen, the shrubs are required to use groundwater earlier in the season and consequently produce less biomass. Maximum above-canopy evapotranspiration rates have been observed to occur in early to mid-June at sites in Smith Creek Valley and Smoke Creek Desert. These maxima occurred before summer solstice when net radiation is a maximum. This has been interpreted to indicate that the plants had consumed most of the winter and spring precipitation by this time and were beginning to use mostly groundwater. Observed evapotranspiration rates continued to decline, except for a few days following convective storm precipitation, into early September when field measurements were discontinued.

Robinson [1970] observed new leaves and buds on greasewood and rabbitbrush in early April but also noted that there was little groundwater consumption until June and that maximum groundwater discharge rates occurred in July and August. Groundwater discharge by evapotranspiration decreased rapidly in mid-September and had nearly ceased by mid-October. This is similar to the observations of *White* [1932]. Hydrographs of groundwater levels in greasewood areas [*White*, 1932, p.56] show only slight declines until early to mid May suggesting the shrubs were using little groundwater. Water levels stopped declining and began to recover by mid to late September.

On the other hand, there may be years when soil moisture from abundant winter and spring precipitation or from an unusual storm may provide sufficient water for the shrubs to subsist through much or all of a growing season with little consumption of groundwater. Shrubs growing in areas where groundwater levels have been lowered by groundwater pumping may be able to continue to grow for several years by reducing biomass produced each year. It is probable, however, that there is some level of reduced biomass below which most of these shrubs will not survive.

Summary and Conclusions

An equation describing the mean daily discharge of groundwater by evapotranspiration from phreatophyte shrubs, including greasewood, rabbitbrush, shadscale, and sagebrush as a function of equivalent plant density and depth to groundwater was developed using an energy combination model that was calibrated with energy fluxes calculated from micrometeorological data. The energy combination model [*Shuttleworth and Gurney*, 1990] partitions the energy budget between the soil and canopy, permitting plant transpiration to be separated from evaporation from the soil. Converting daily groundwater discharge rates calculated by the equation to an annual rate requires an estimate of the number of days the plants used only groundwater. Account must be made for evaporation and transpiration of winter and spring precipitation.

It is difficult to make generalizations about daily and annual groundwater discharge rates based on the equation presented because of the combination of factors controlling the rates. Comparisons can be made, however, between rates used during previous studies in the Great Basin, which are based on the results of the study by *White* [1932] and rates calculated with (10) for the reported field conditions. These comparisons are given in Table 3. Annual estimated groundwater evapotranspiration rates used in previous groundwater budget studies range from 0.030 to 0.152 m yr^{-1}; rates calculated with (10) range from 0.024 to 0.308 m yr^{-1} using the reported conditions given in Table 3 and assuming a 100-day groundwater evapotranspiration period. The annual rates estimated during this study differ from the estimated annual rates used in previous studies by a factor ranging from 0.8 to 5.0 (Table 3).

The higher annual rates of groundwater discharge estimated by (10) presented in this report would seem to imply that annual discharge of groundwater by transpiration may be as much as 5 times greater than estimated in previous studies. This, in turn, would appear to suggest that estimated groundwater recharge is as much as 5 times greater than was previously estimated. This is not the case, however, because of the inconsistent manner in which the previously estimated rates have been applied and because previous estimates of the area to which such rates apply may be in error. For instance, *Everett and Rush* [1964] estimated an annual groundwater transpiration rate of 0.06 m yr^{-1} from 89 km^2 of greasewood and rabbitbrush in Smith Creek Valley, Nevada. Detailed field mapping by *Hines* [1992] demonstrated that the area covered by these phreatophytes was actually about 49.2 km^2. Using rates estimated by (10), together with the area reported by *Hines* [1992], the annual groundwater discharge was estimated to be about 14.7 x 10^6 m^3 [*Nichols*, 1992b]. This is in contrast to the estimated discharge of 8 x 10^6 m^3 made by *Everett and Rush* [1964] and compares favorably with their estimated annual recharge of 14.8 x 10^6 m^3. Caution must be exercised in using groundwater discharge rates estimated by (10) with reported areas covered by phreatophytes.

Notation

d_e	equivalent plant density, dimensionless.
d_p	actual plant density, dimensionless.
ET_g	evapotranspiration of groundwater by phreatophyte shrubs, m d^{-1}.
G, 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, from the soil, respectively W m^{-2}.
H_β	above-canopy sensible heat flux calculated with the Bowen ratio, W m^{-2}.
K_h	eddy diffusion coefficient at the top of the canopy, m^{2}s^{-1}.
LAI	leaf area index, dimensionless.
L_0	average leaf area index of shrubs, 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}.
Rn	net radiation on both soil and canopy, W m^{-2}.
Rn_c, Rn_s	net radiation on the canopy and on the soil, W m^{-2}.
u_h	wind speed at top of canopy, m s^{-1}.
w	leaf width, m.
z_0'	roughness length for bare soil, m.
z_w	depth to groundwater, m
Z	preferred roughness length for LAI = 4, m.
$\lambda E, \lambda E_c, \lambda E_s$	latent heat flux above the canopy, from the canopy, from the soil, W m^{-2}.
λE_β	above-canopy latent heat flux calculated from Bowen ratio, W m^{-2}.

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W. D. Nichols, Water Resources Division, U.S. Geological Survey, 333 West Nye Lane, Carson City, NV 89706.

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