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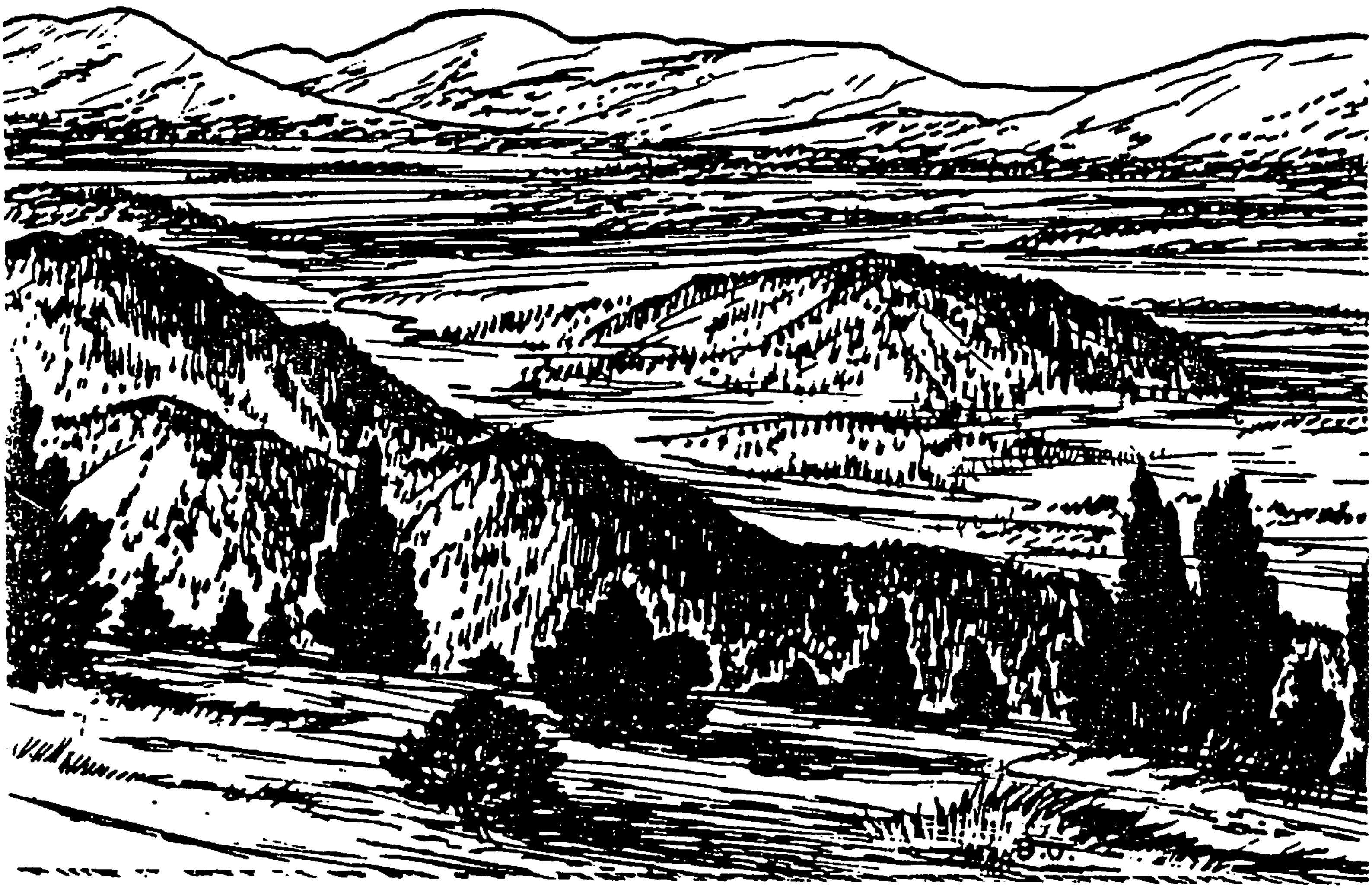

Proceedings—Pinyon-Juniper Conference

Reno, NV, January 13-16, 1986

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WATER BALANCE CALCULATIONS IN SOUTHWESTERN WOODLANDS

Leonard J. Lane and Fairley J. Barnes

ABSTRACT: Water balance calculations are required to compute individual components of the water budget or balance: precipitation, runoff, evapotranspiration, soil moisture recharge and depletion, and seepage below the root zone. Hydrologic models are used to make these calculations, and soil-water-plant relationships are used to identify gaps in knowledge and, thereby, to suggest methods of improving hydrologic models.

INTRODUCTION

Pinyon-juniper, an important type of southwestern woodland, occupies significant portions of several physiographic provinces (e.g., Hunt 1974). West and others (1975) state that almost three-fourths of the pinyon-juniper ecosystem type are found in the Basin and Range and Colorado Plateau provinces. This means the ecosystem type is especially important in Arizona, New Mexico, Nevada, Utah and Colorado.

The pinyon-juniper type generally occupies an elevation, temperature, and precipitation zone between the more arid desert shrub and chaparral, and more mesic ponderosa pine forests at higher elevations (Dortignac 1960). In discussing water yield, Dortignac (1960) described the pinyon-juniper type as having structure and hydrologic characteristics intermediate between grass lands and forests. Mean annual precipitation for this vegetation type was characterized as usually varying from about 300 to 450 mm. The corresponding approximate elevation zones were described (e.g., Dortignac 1960, p. 19) as follows: Arizona 1370 to 1980 m, New Mexico and Utah 1520 to 2130 m, and Colorado 1830 to 2440 m. Mean annual temperatures vary from about 4°C to over 18°C, depending upon latitude and elevation. West and others (1975) plotted climatic diagrams (using monthly mean precipitation and temperature data) for 15 stations. These diagrams illustrate the relationships between seasonal temperature and precipitation, and suggest periods of soil moisture recharge (when mean monthly temperature is less than mean monthly precipitation) and periods of soil moisture depletion (when mean monthly temperature is greater than mean monthly precipitation). While such diagrams suggest soil moisture recharge and depletion, they are not water balance calculations.

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A purpose of this paper is to illustrate the use of hydrologic models to calculate a water balance to quantify the various components: precipitation, evapotranspiration, runoff, percolation below the root zone, and changes in soil moisture storage. These calculations illustrate the water balance on a stand or watershed scale. A second purpose of the paper is to use a simple diffusion model of the woodland canopy to simulate soil-water-plant relationships over smaller spatial scales, and over diurnal cycles. Analyses on these space and time scales are used to illustrate gaps in knowledge limiting the development of more comprehensive water balance calculation methods and improved hydrologic models.

WATER BALANCE CALCULATIONS

As water is often the limiting factor for plant growth and survival in arid and semiarid areas (e.g., Brown 1977) and for growth and productivity in semiarid and subhumid woodlands (e.g., Lieth and Whittaker 1975), water balance calculations are an essential part of soil-water-plant relationship studies in the pinyon-juniper type. Plant water use as the transpiration fraction of the evapotranspiration (ET) component affects the water balance and soil moisture content and, thereby, infiltration and runoff. As discussed below, soil moisture status often limits the rate of ET, so that consideration of a water balance or budget necessarily involves feedback mechanisms (e.g., Veihmeyer and Hendrickson 1955).

With the assumptions of no net subsurface water movement in the horizontal direction, and a limited rooting depth well above the permanent water table, then the discrete form of the water balance equation for a unit area of land surface can be written (e.g., Lane and Stone 1983) as:

$$\frac{\Delta S}{\Delta t} = P - Q - ET - L \tag{1}$$

where: S = soil water content (mm representing units of volume per unit area),
Δt = time period for the calculations (hr, day, month, etc.),
P = depth of precipitation for the time interval (mm/Δt),
Q = runoff volume (mm/Δt),
ET = combined evaporation and transpiration for the time interval (mm/Δt), and
L = percolation below the root zone for the time interval (mm/Δt).

Positive values of $\Delta S/\Delta t$ represent soil moisture recharge, while negative values represent soil moisture depletion. If precipitation is considered uncontrolled climatic input to the system, then equation 1 shows that all other components of the water balance are interrelated, and are functions of precipitation.

Runoff occurs as the result of precipitation exceeding the rate of water infiltrating into the soil. The rate of infiltration during a rainfall event depends upon rainfall rate, amount, and time distribution during the storm event. It also depends upon antecedent soil moisture, and thus upon all other terms in equation 1. Soil characteristics, including texture, porosity, water content, hydraulic conductivity, structure, depth, and surface features affect infiltration, as does land use, condition, and management. Vegetation type and conditions affect infiltration, and thus runoff, through a wide variety of complex interactions. Runoff is estimated from precipitation data using a variety of techniques, including indices, regression equations, daily rainfall-runoff equations, and infiltration equations. Key sources describing methods of predicting infiltration and runoff are "Rangeland Hydrology" (Branson and others 1981) and "Hydrologic Modeling of Small Watersheds" (Haan and others 1982).

The rate of ET, in equation 1, depends upon the potential evapotranspiration rate, upon soil texture and surface characteristics, and upon vegetation characteristics (e.g., leaf area index, rooting depth, etc.) when soil moisture is nonlimiting. When water is limiting, it depends upon the same factors as well as soil water content. Hanson (1973) summarized several relationships (e.g., Veihmeyer and Hendrickson 1955; Thornthwaite and Mather 1955) between the ratio of actual evapotranspiration (AET) and potential evapotranspiration (PET) as soil moisture ranges between field capacity and the permanent wilting point. These relationships can be summarized in equation form as

$$AET = \begin{cases} PET & SM > SM_1 \\ f(SM,\ PET) & WP \lesssim SM \leq SM_1 \\ 0 & SM \lesssim WP \end{cases} \qquad (2)$$

where SM_1 is a soil water content between field capacity (FC) and wilting point (WP). The function f controls the ratio of AET to PET when soil moisture is between WP and SM_1, and is also a function of the plants' physiological response to water stress. Basic source material on ET processes is given in the references cited earlier, i.e., "Rangeland Hydrology" and "Hydrologic Modeling of Small Watersheds," as well as in "Primary Productivity of the Biosphere" (Lieth and Whittaker 1975).

The rate of percolation or seepage below the root zone, L in equation 1, is determined by many of the same factors determining infiltration rates into the soil. The movement of water in the liquid phase in soil can be described by combining the continuity of mass equation with a flow rate equation called Darcy's equation. With this description, the flow rate of water through the soil is determined by the hydraulic gradient and the hydraulic conductivity. Soil characteristics, such as texture, structure, porosity, and antecedent water content, in large part determine hydraulic gradient and the hydraulic conductivity. Because percolation below the root zone can result in return flow or base flow in intermittent and perennial streams, L, in equation 1, is often included in the runoff term when water balance calculations are made on an annual or monthly basis. Key sources describing percolation include those cited earlier in the discussion of infiltration, and others, such as Hillel (1971), Todd (1959), Brooks and Corey (1964), and Rawls and others (1982).

Examples of the Water Balance on an Annual Basis

The Beaver Creek watersheds are located in the plateau climatic region of Arizona, and are subject to two distinct precipitation seasons (Baker 1982). The winter precipitation season is from October through April, and the summer precipitation season is mainly in July through September, with May and June as dry months. Four intergrading vegetation types found on the Beaver Creek Watershed (Baker 1982) are: semidesert, Utah juniper (*Juniperus osteosperma* (Torr.) Little), alligator juniper (*Juniperus deppeana* Steud.), and ponderosa pine (*Pinus ponderosa* Laws.). Components of the water balance for the three woodlands are given in table 1 (adapted from Baker 1982, and Campbell and Ryan 1982).

The data in table 1 suggest the following approximate values for an annual water balance. Runoff as a percent of precipitation is 6% for the Utah juniper watersheds, 22% for the alligator juniper watersheds, and 22% for the ponderosa pine watersheds. This means that evapotranspiration varied from 94% of annual precipitation on the Utah juniper watershed to 78% on the alligator juniper and ponderosa pine watersheds.

Dortignac (1960) tabulated precipitation and runoff data for 10 years from three experimental watersheds near Santa Fe, NM, for 6 to 20 years of data from 9 watersheds at Mexican Springs, NM, and for 2 years of data from six experimental watersheds at Beaver Creek, AZ. These data suggested that annual runoff amounts to about 2 to 4% of annual precipitation on the New Mexico watersheds and from 5 to 7% on the Beaver Creek juniper watersheds. However, the data in table 1 would suggest that annual runoff amounts to about 6 to 22% of annual precipitation on the juniper watersheds on Beaver Creek. This difference (6 to 22% as opposed to 5 to 7%) illustrates the value of a 23-year record (table 1 1958-1980) over a 2-year record in estimating mean annual values of components of the water balance. Interpretations of the data shown in table 1 also suggest the importance of seasonal distribution of precipitation (winter and summer at Beaver Creek and predominately summer in New Mexico, e.g., see figure 2 on p. 23 of Dortignac 1960), and of soil types and textures (predominately sandy and loamy soils on the New Mexico watersheds and clay soils at Beaver Creek).

Examples of the Water Balance on a Monthly Basis

A simple monthly water balance model based on equation 1 was developed to illustrate monthly

Table 1.--Components of the annual water balance for watersheds in three vegetation types on the Beaver Creek Watershed in Arizona. Data base is 1958-1980

Vegetation Type	Approximate Elevation (m)	Mean Precipitation[1]	Annual Values in mm Runoff[2]	Evapotranspiration[3]
Utah Juniper	1500	441.	27.	414.
Alligator Juniper	1900	553.	121.	432.
Ponderosa Pine	2250	634.	141.	493.

[1]Precipitation data from table 1 of Campbell and Ryan (1982).
[2]Runoff data from table 1 of Baker (1982), and assumed to include L in equation 1.
[3]Calculated as the difference between precipitation and runoff.

water balance calculations. Equation 2 was used for the AET calculation, with PET calculated from mean monthly temperature (e.g., see Bailey 1981), and runoff calculated using a modification of the USDA Soil Conservation Service procedure. This simple model needs prior calibration using measured monthly runoff or output of a more realistic water balance model such as the CREAMS model (Knisel 1980). However, once the monthly water balance model is calibrated, it can be used to predict components of the water balance for various combinations of monthly temperature and precipitation.

Seven sites, selected for illustration of monthly water balance calculations, are listed in table 2. Rock Valley, NV was selected as a climatic extreme for a predominately winter precipitation site, and because water balance calculations have been made there on a daily basis (e.g., Lane and others 1984), Holbrook, AZ was selected as a climatic extreme for a predominately summer precipitation site. Both sites are too arid to support woodland vegetation, but were selected to illustrate differences in seasonal precipitation patterns reflected in the monthly water balance. The Kingman, AZ site was selected as a winter precipitation site, with precipitation just under amounts sufficient to support a pinyon-juniper woodland. The three Beaver Creek, AZ sites represent average climatic and hydrologic conditions from several experimental watersheds (e.g., see Baker 1982). However, it should be noted that the clay-type soils found on the Beaver Creek watersheds have lower infiltration rates, and thus produce relatively more runoff than would occur at the other sites (all other conditions being equal) shown in table 2. The Los Alamos, NM site was selected as a summer precipitation site at the upper limit (with respect to precipitation) of the pinyon-juniper site, and because water balance calculations also have been made there using the CREAMS model (e.g., Lane 1984).

Results of monthly water balance calculations, for the seven sites described in table 2, are summarized in table 3. The calculated ET and runoff values shown in table 3 were made using the simple monthly water balance model described earlier. As such, the values represent approximate monthly means estimated using mean monthly precipitation and temperature. The resulting monthly ET and runoff estimates have less variability than if they were means estimated by summing the results of monthly values estimated using 20 years of monthly precipitation and temperature data.

For example, based on 20-year means for monthly precipitation and temperature, the monthly water balance model predicts no runoff for the months of January-June and November-December at Los Alamos, NM. However, application of the CREAMS model, using daily rainfall amounts (individual values, not means) for the same 20-year period of record and the same soil conditions, suggests that runoff occurred at least once during every month of the year (Lane 1984; table XV, p. 38). The reason for these differences (and a major weakness in using long-term means in calculating a water balance) is illustrated by the variations in April precipitation at Los Alamos over the 20-year period from 1951 -1970. The mean April precipitation was 20.3 mm, with a standard deviation of 19 mm and a range of 0 to 60.5 mm. It is quite likely, for example, as suggested by the CREAMS model, that runoff occurred during the April period, with 60.5 mm of precipitation. In spite of these shortcomings in the monthly water balance model, it did produce much of the information present in the CREAMS model estimates of mean monthly runoff.

The results of monthly water balance model estimates of mean monthly runoff (from table 3) and average measured values for Beaver Creek, AZ were also compared. In each case, the monthly water balance model improved the estimates of mean monthly runoff over those obtained using precipitation alone. Precipitation alone explained from 17 to 30% of the variance in mean monthly runoff, while the monthly water balance model explained from about 33 to 53 %. Therefore, the runoff estimates shown in table 3 should be interpreted as approximate values suggesting generalized seasonal patterns.

Much less observed data are available to judge the validity of the ET estimates shown in table 3. Lane and others (1984) found that the CREAMS daily water balance model explained some 90% of the variance in mean monthly soil moisture for Rock Valley, NV, and for bare soil and vegetated lysimeters at Los

Table 2.--Location and mean annual precipitation and temperature for seven sites in Arizona, Nevada, and New Mexico

Station Name	Location: Latitude N Deg - Min	Location: Longitude W Deg - Min	Elevation (m)	Mean Precip (mm)	Annual Temp. (C°)	Comments
Rock Valley, NV	36° 40'	116° 05'	1020	161	17	Northern Mojave Desert. Example of climatic extreme for winter precipitation.[1]
Holbrook, AZ	34° 54'	110° 10'	1545	187	13	Summer precipitation site below the pinyon-juniper type.
Kingman, AZ	35° 11'	114° 03'	1024	239	16	Winter precipitation site just below pinyon-juniper type[2].
Beaver Creek, AZ[3]						
Utah Juniper	34° 35'-34° 50'	111° 35'-111° 45'	1500	441	14	Lower pinyon-juniper type.
Alligator Juniper	34° 35'-34° 50'	111° 25'-111° 45'	1900	553	10	Mid pinyon-juniper type.
Ponderosa Pine	34° 40'-34° 55'	111° 20'-111° 45'	2250	634	7	Upper to above pinyon-juniper type for winter precipitation.
Los Alamos, NM	35° 53'	106° 19'	2250	468	9	Upper to above pinyon-juniper type for summer precipitation.

[1]Precipitation distributed over the entire year, but winter season precipitation dominates the water balance. The opposite is true for summer precipitation sites.
[2]"Below pinyon-juniper type" refers to elevation and/or mean annual precipitation below or lower than found at pinyon-juniper sites. The opposite is true for "above pinyon-juniper type."
[3]Approximate range in latitude and longitude, but approximate mean elevation for gaging sites.

Table 3.--Observed monthly precipitation and monthly water balance model[1] estimates of evapotranspiration and runoff for the seven sites shown in table 2

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual[2]
						Precipitation in mm							
Rock Valley, NV	15.5	34.5	22.4	5.8	5.8	5.1	9.9	10.2	13.7	13.0	18.9	16.0	161.
Holbrook AZ	10.7	9.7	11.7	8.9	6.6	6.4	27.4	43.2	21.8	18.5	10.4	11.9	187.
Kingman, AZ	25.9	26.9	26.9	19.6	5.1	3.6	19.8	34.8	17.5	15.7	16.8	25.9	239.
Beaver Creek, AZ													
Utah Juniper	40.4	46.5	52.1	27.7	9.4	4.6	38.1	54.1	47.5	40.6	35.3	44.7	441.
Alligator Juniper	57.2	58.9	65.0	32.5	17.5	8.4	47.2	60.2	52.6	47.0	46.2	60.7	553.
Ponderosa Pine	64.3	68.6	78.0	39.1	19.6	10.2	57.7	64.5	53.3	47.2	61.0	70.4	634.
Los Alamos, NM	18.8	18.5	23.9	20.3	28.2	33.0	85.1	116.3	37.1	41.2	19.3	26.4	468.
						Evapotranspiration in mm							
Rock Valley, NV	13.5	25.1	25.4	16.0	11.2	8.1	9.7	9.9	11.7	10.9	8.6	10.9	161.
Holbrook, AZ	9.4	10.7	12.4	12.2	9.9	8.4	23.4	36.8	23.9	17.5	10.9	9.4	185.
Kingman, AZ	23.4	26.9	27.7	24.1	11.7	6.4	16.8	29.2	19.8	15.5	15.0	20.3	237.
Beaver Creek, AZ													
Utah Juniper	32.3	40.4	48.3	41.1	25.4	13.7	32.3	45.5	42.9	35.3	29.2	31.0	417.
Alligator Juniper	35.1	41.1	47.8	42.7	32.8	20.3	35.8	44.5	41.1	34.5	30.7	33.3	440.
Ponderosa Pine	35.1	42.3	50.3	49.8	45.2	38.1	46.7	47.2	41.1	34.0	31.5	32.5	494.

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Table 3.--(Continued)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual[2]
	Evapotranspiration in mm												
Los Alamos, NM	18.0	20.3	24.6	26.9	32.5	37.8	67.3	90.2	51.6	37.8	23.1	20.1	451.
	Runoff in mm												
Rock Valley, NV	0	0.3	0	0	0	0	0	0	0	0	0	0	0.3
Holbrook, AZ	0	0	0	0	0	0	0.2	1.8	T	0	0	0	2.0
Kingman, AZ	0.2	0.3	0.3	0	0	0	0	0.8	0	0	0	0.2	1.7
Beaver Creek, AZ													
Utah Juniper	2.3	3.5	4.6	0.4	0	0	1.1	3.7	2.6	1.7	1.1	2.8	23.8
Alligator Juniper	14.6	15.6	17.7	5.0	0.8	0	7.3	11.6	9.4	8.1	8.5	14.8	113.3
Ponderosa Pine	16.6	18.8	22.7	7.5	1.4	0	10.6	13.1	9.6	8.0	13.3	17.9	139.5
Los Alamos, NM	0	0	0	0	0	0	5.2	12.0	0.1	0.2	0	0	17.4

[1]Monthly estimates based on long-term mean monthly precipitation and temperature, and a standard 1-m deep soil profile with site-specific estimates of soil water retention properties.
[2]Annual totals may differ from sum of monthly values due to roundoff errors.

Alamos, NM. The monthly water balance model was fitted to monthly ET estimates and estimates from the CREAMS model for vegetated lysimeters at Los Alamos, NM. The monthly water balance model explained about 60% of the variance in monthly ET values. Although these comparisons were based on only 2 years of data from lysimeters, they are probably indicative of the relative precision of ET and runoff estimates--i.e., estimation errors in ET are larger than those in runoff, but proportionally are less, because runoff is a smaller component of the water balance.

A final illustration of the degree to which a simple monthly water balance model can be used to estimate seasonal distribution of water balance components in pinyon-juniper woodlands is shown in figure 1. The data in figure 1 represent averages for both the Utah and alligator juniper sites at Beaver Creek, AZ. The upper portion of figure 1 shows the monthly distribution of measured precipitation and estimated ET. These data suggest soil moisture recharge ($P > ET$) during the months of January - March and July - December, and soil moisture depletion ($P < ET$) during April - June. The resulting profile-average soil moisture estimates are shown in the lower portion of figure 1. Average measured runoff and average estimated runoff are shown in the central portion of figure 1. Although the annual runoff volumes are comparable, the estimated monthly values are low in the winter and spring (February through April), and high during the summer (July through September), and approximately equal to the measured values in January, May, and October through December. However, with the exception of the high runoff estimates in July and August, the seasonal pattern of estimated runoff agrees with the measured seasonal pattern of runoff. This would suggest that the seasonal patterns of ET and soil moisture estimates are approximately correct for the Beaver Creek watersheds. More accurate estimates might result from application of a daily water balance model such as described earlier. The next section describes a more physiologically based approach.

SOIL-WATER-PLANT RELATIONSHIPS

The use of a simple water balance model has shown that there are large variations in yearly ET over a wide geographic range of woodland sites. However, the method used did not differentiate between different vegetation types or between vegetation densities. On a local scale, different vegetation types grown under the same climatic conditions can have wide variation in seasonal ET due to species differences in canopy resistance (a function of leaf area index, LAI, and stomatal resistance, R_s) and phenology (Nulsen 1984; Stewart 1984). As soil moisture, S, decreases, not only is the threshold at which stomata close widely variable, but the dynamics of stomatal closure has been shown to vary among species (Schulze and Hall 1982). This means that the relationships shown in equation 2 are approximate and dynamic through the growing season. Consequently, several authors have emphasized the need to include physiological responses in models designed to simulate ET from native plant communities (Denmead 1984; Kowalik and Eckersten 1984).

A simple diffusion model has been used to simulate ET from forest communities (Tan and others 1978; Sammis and Gay 1979; Running 1984). Based on the Penman-Monteith equation, the model assumes that leaf temperature is not significantly different from air temperature, and that the air in the substomatal spaces is saturated, thus allowing the atmospheric demand to be approximated by the ambient vapor pressure deficit (VPD).

Transpiration (E, in units $g\ cm^{-2}\ s^{-1}$) is calculated as,

$$E = R\ Cp(LAI)(VPD)/(L\ \gamma\ R_s) \quad (3)$$

where R is the density of moist air (1.2×10^{-3} g/cm^3); Cp is the specific heat of moist air (1.01 $J^{-1}\ {}^\circ C^{-1}$); L is the latent heat of vaporization of H_2O(2450J/g); γ is the psychrometric constant (0.066 kPa/°C); LAI is the leaf area index (m^2/m^2); VPD is vapor pressure deficit (kPa); R_s is stomatal resistance to water vapor diffusion (s/cm), and $R_s = 1/G$ where G is stomatal conductance. VPD was calculated according to Campbell (1977).

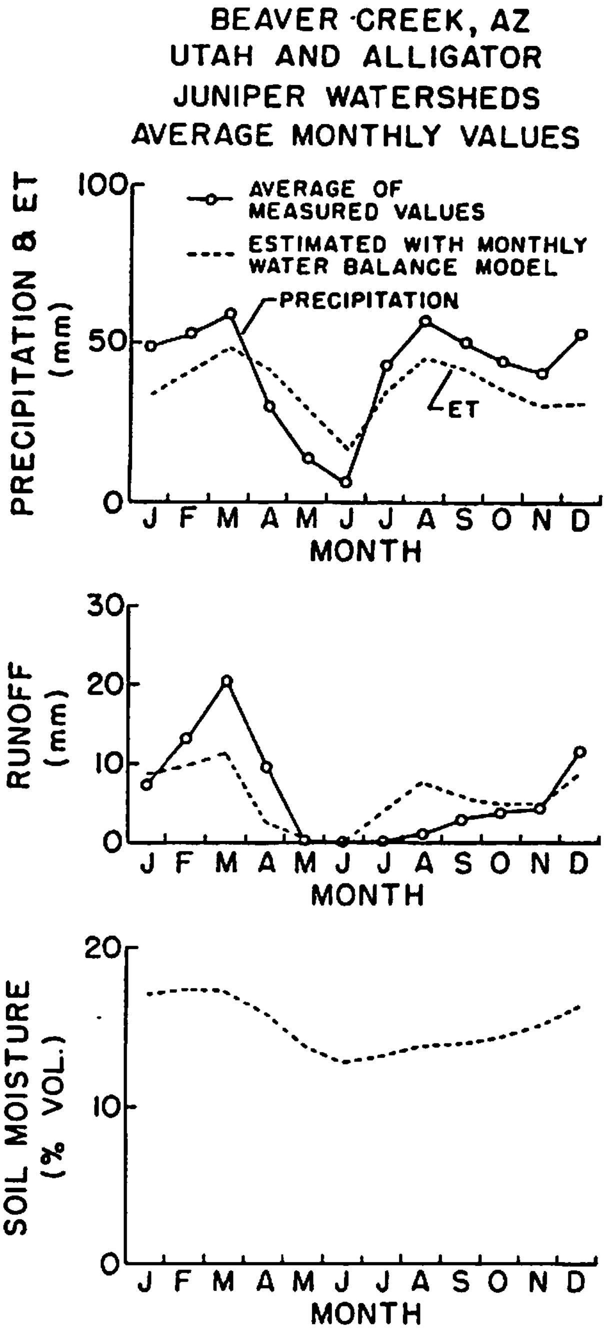

Figure 1.--Illustration of measured and estimated mean monthly water balance components for the Utah and alligator juniper watersheds at Beaver Creek, AZ.

Application of the Canopy Diffusion Model

A study of the physiological ecology of one-seed juniper (Juniperus monosperma) and pinyon (Pinus edulis) in the Los Alamos, NM region (Barnes 1986) has yielded sufficient data to begin to build a model of canopy transpiration rates of pinyon-juniper woodland. Data include measurements (every 2 to 4 weeks from April to October, 1982) of predawn leaf water potentials (LWP) of dominant species across a series of six woodland sites, two in each of three habitat types, as well as laboratory data on the stomatal responses of pinyon and juniper to light, temperature, and water stress. Meteorological data from Los Alamos weather stations (within 12 km of each field site) have also been used. Calculations of daily stand transpiration form the basis for estimating stand transpirational water losses throughout the year. Three of the 6 sites were chosen to illustrate, in tabular form, scenarios typical of the range of pinyon-juniper woodland in the Los Alamos area. The 3 sites differed in physical characteristics, species composition, and seasonal water stress (table 4), and are typical of the range of pinyon-juniper woodland types in the area. Foliage biomass per unit ground area for each site was estimated using the frequency distributions of diameter at base (DAB) size classes of the trees on each study plot. These data were used as input to the regression equations of Miller and others (1981) to express the relationship between DAB and total foliage biomass of singleleaf pinyon (P. monophylla) and Utah juniper (J. osteosperma). Leaf area indices were then estimated using specific leaf mass values for each species (Barnes 1986).

Statistical analysis of the gas exchange measurements on intact juveniles of each species (details in Barnes 1986) showed that stomatal conductance (G) and LWP have a highly significant exponential relationship. There were significant differences ($P < 0.05$) between stomatal responses of the two species. Within the group of junipers studied, there were significant differences ($P < 0.001$) between individuals collected from the xeric (site 2) and mesic (site 6) ends of the habitat continuum. The field LWP data at each site, and the regression relationships (table 5), were used to estimate the depression in monthly maximum G due to water stress of pinyons and junipers on all sites. For the winter and early spring months, when no LWP field data were available (November through April), it was assumed that the LWP was -1.2 MPa for pinyons and -1.0 MPa for junipers.

Daily maximum transpiration was calculated (equation 3) under conditions of maximum daily atmospheric demand using 1982 monthly means of daily maximum temperatures and relative humidity at 1400 h from both the Los Alamos National Laboratory main weather station at elevation 2250 m (LA), and a subsidiary station at elevation 1950 m (WR). The LA data were used to estimate transpiration for sites 5 and 6; the WR data were used for sites 1 and 2, and an average of the two meteorological data sets was used for the intermediate sites 3 and 4 estimates. Daily total stand transpiration (ST) was estimated using a sine function factor calculated for the 15th day of each month, as described by Jackson and others (1983).

The model predicted a reduction in stand transpiration (ST) during June and July at all sites, the reduction being least at site 1, which was the lowest elevation site. This pattern of reduced summer ST was not predicted by the water balance model for

Table 4.--Stand characteristics and seasonal mean minimum predawn leaf water potentials (LWP) of 3 intensive study sites in northern New Mexico

Site	Elevation	Slope	Aspect	Leaf Area Index			Minimum LWP (MPa)	
				pinyon	juniper	total	pinyon	juniper
	(m)	%						
2	1950	19	ESE	0.41	1.31	1.72	-2.26	-3.39
4	2011	5	SSW	1.92	0.76	2.58	-1.91	-2.32
6	2072	27	NNE	3.07	0.70	3.77	-2.03	-3.57

Table 5.--Relationships between stomatal conductance, G(mol m^{-2} s^{-1}), and predawn leaf water potential, LWP(MPa), using the model $\ln G = B_0 + B_1(LWP)$

Species/habitat	B_0	B_1	r^2
pinyon (1-6)*	-2.284	1.644	0.58
juniper (3,4)	-2.136	0.711	0.85
juniper/xeric (1,2)	-1.829	0.808	0.89
juniper/mesic (5,6)	-2.237	0.679	0.84

*Sites for which the parameters were used to calculate stand transpiration.

the Los Alamos area (fig. 2), although this discrepancy is, in large part, the result of mean precipitation data being used for the water balance model and 1982 data for the diffusion model. In 1982, June was particularly dry, followed by large storms in July, which may have generated higher than average amounts of runoff. Yearly stand transpirational water loss was highest at the lowest elevation site 1 (360 mm), lowest at site 5 (69 mm), and intermediate at the remaining sites (site 2, 203 mm; site 3, 165 mm; site 4, 170 mm; site 6, 216 mm) (fig. 2). These values are all considerably below the 451 mm for total ET predicted by the water balance model simulation using the LA weather station data (20 year means). We expected the ST estimates to be below total ET, since ST includes neither interception losses nor soil evaporation. However, yearly ST varied from 15 to 80% of yearly precipitation, a very wide range.

The differences among the 3 sites are probably due to many factors. Given the extremely localized nature of high intensity summer thunderstorms in the Southwest, the actual precipitation at each site may be considerably different from that received at the nearby weather stations. In addition, the slope and aspect of the sites are quite varied, which would have significant effects on runoff and soil evaporation. Finally, cover of vegetation, bed rock, and litter varies among the sites, all of which affect interception, infiltration, and runoff. There are also numerous physiological factors which could account for the wide range of ST predicted. The influence of relative humidity on stomatal conductance of pinyons and junipers has not been studied, and was not included in the diffusion model. Since high VPD can directly affect stomatal closure (Kaufman 1976; Running 1984), the actual stand transpiration rates may be significantly different from those reported here, especially in the drier months, when VPD is high and LWP is low. It is also likely that the two species have uniquely

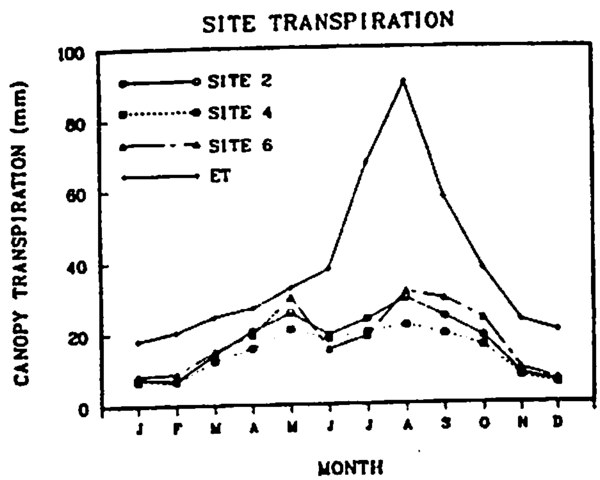

Figure 2.--Monthly stand transpiration estimated using the canopy diffusion model for sites 2, 4 and 6, and monthly ET estimated using the water balance model.

different stomatal responses to decreasing VPD, as noted by Turner and others (1984) and Johnson and Ferrell (1983), for other woody species. The simplification of using monthly means of temperature and RH may have resulted in erroneous estimates of ST if the relationships between stomatal conductance and these factors proved to be nonlinear. Again, this suggests that calculations on a daily basis are required for improvements over monthly calculations described earlier.

Although these results demonstrate the need for additional physiological data on the two species, particularly under field conditions where acclimation to seasonal climatic changes may be quite pronounced, there is strong evidence for the dependence of stand ET on species composition. The high ST at site 2 (205 mm/yr) is due in part to the higher evaporative demand at lower elevation, but primarily to the fact that the vegetative cover at that site is largely juniper, which has higher conductance than pinyon at high water availability, and greater drought resistance in that the stomata remain open to much lower LWP than in pinyon. At sites 4 and 6, which are dominated by pinyon, junipers contribute as much, or more, to transpirational water losses than the pinyons.

Several authors have noted a correlation between LAI and site water balance (Grier and Running 1977; Gholz 1982), and the water balance models in use generally assume some direct linear relationship between stand LAI and ET. In diffusion model estimates, there was no correlation between total LAI and ST, but very good correlation between LAI of each species and the transpirational losses attributable to the species (fig. 3). The large difference in the slopes of the species plots is the result of the unique physiological characteristics of the two species.

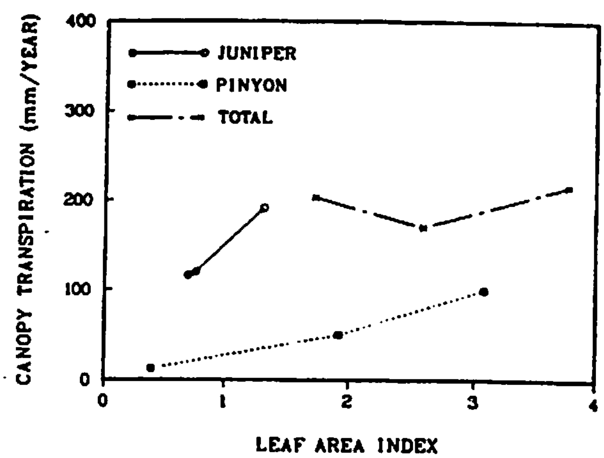

Figure 3.--Relationship between estimated canopy transpiration and leaf area index for each species and for the total stand.

CONCLUSIONS

Monthly water balance models of the type used here require calibration, and reproduce seasonal trends in components of the water balance in only an approximate manner, as shown in figure 1. It is apparent that the diffusion model alone is insufficient to predict site water balance, and must be linked with a hydrologic model capable of modeling runoff, infiltration, and soil water storage over a variety of soils and topographies. Hydrologic models, incorporating a plant physiological component, are rarely used; firstly, because of the limited data on native species, and secondly, because they require a detailed and continuous meteorological data base for each site (Denmead 1984; Running 1984). While current hydrologic models provide us with an assessment of water balance across broad geographic or climatic gradients, a more detailed model, incorporating species composition and specific physiological characteristics, may be needed to describe water balance on a more local scale, and over shorter time periods.

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