Water Balance Calculations and Net Production of Perennial Vegetation in the Northern Mojave Desert

L.J. LANE, E.M. ROMNEY, AND T.E. HAKONSON

Abstract

Measurements obtained between 1968 and 1976 indicate the influence of climatic factors and soil characteristics upon soil moisture and production of perennial vegetation in the northern Mojave Desert. Seasonal distribution patterns of precipitation are shown to have a strong effect on plant-available soil moisture, and these patterns are, in turn, reflected in net production of perennial vegetation. Available climatic data and soil characteristics were used as input to a continuous simulation model to calculate the water balance for a unit area watershed. Computed and measured soil moisture agreed quite well over a range of values from close to the wilting point to near field capacity. We used computed evapotranspiration rates to estimate water use by perennial vegetation. Computed water use was multiplied by a water use efficiency factor to estimate net production of perennial vegetation. Estimated net production exhibited year-to-year variability comparable with measured values, and agreed quite closely with available observations. This paper briefly describes soil-water-plant relationships in the northern Mojave Desert and illustrates an application of a continuous simulation model to predict soil moisture and net production of perennial vegetation. Based on our analysis, the simulation model would appear to have potential for estimating the water balance and above ground net primary production on arid and semiarid rangelands.

Of the extensive areas of the world classified as rangeland, some 80% is within arid and semiarid zones (Branson et al. 1981), where precipitation is generally less than potential evapotranspiration. Under these conditions, water availability is the most important environmental factor controlling survival and production of range plants (Brown 1977). Many of these arid and semiarid rangelands are closely associated, both climatically and geographically, with the major deserts of the world. Logan (1968) discusses climates and distribution of deserts, and Johnson (1968) describes the Mojave Desert, which, for the most part, is located in California and southern Nevada. Walter and Stadelmann (1974) describe water relations of desert plants.

Range plants in arid and semiarid regions are very often subject to stress because of water deficits. As extreme conditions producing water stress are characteristic of desert areas, knowledge of soil-water-plant relationships in the Mojave Desert should aid our understanding of these relationships. Moreover, if these desert relationships are compared with similar relationships on less arid rangelands, then our understanding of, and ability to manage, rangelands can be extended over wider climatic and geographic regions. Toward this end, we have examined soil-water-plant relationships at a site called Rock Valley in the northern Mojave Desert.

A most important need in understanding soil-water-plant relationships is the development of simplified, yet physically based, procedures to predict the water balance. For a given period of time, we can write a water balance equation for the soil profile to the plant rooting depth as

$$\frac{dS}{dt} = P - Q - ET - L \qquad (1)$$

where

S = soil water or soil moisture (L^3),
t = time (T),
P = precipitation (L^3),
Q = net runoff from the area (L^3),
ET = combined evaporation and plant transpiration (L^3), and
L = seepage or percolation below the root zone (L^3).

Terms in the right hand side of equation (1) have units of volume (length cubed, or L^3) per unit time which result in terms of flux (L^3/T). However, volume units are usually expressed in length measures as a volume per unit area. Thus, terms in equation (1) are usually expressed in mm or inches per hour, day, month or year. If precipitation is considered an uncontrolled climatic input, then equation (1) shows that all other components of the water balance are interrelated, and are functions of precipitation. Because the relationships summarized by equation 1 determine the rate of plant transpiration available for plant survival and growth, the water balance equation is essential in soil-water-plant relationships studies. Since water is often the limiting factor for range plants, water balance calculations are necessary to assess water use, and from this and plant growth models or water use efficiency factors, net production of vegetation.

Wight and Hanks (1981) characterized past attempts to predict range herbage production as primarily relying on statistical relationships between vegetation production and precipitation, soil moisture, and climatic variables. They also describe the more recent use of water-balance and climate models to predict evapotranspiration on rangelands, but stated that although their potential for predicting forage production has been recognized, it has not been fully utilized. Wight and Hanks (1981) then reported the development and application of a simple water-balance climate model to predict annual herbage production on native grasslands in Montana and North Dakota. A mathematical model was used to predict the ratio of actual to potential transpiration, which was then equated to the ratio of actual to potential (water nonlimiting) site forage yield. Their yield equation was

Authors are hydrologist, USDA-ARS, Southwest Rangeland Watershed Research Center, 2000 East Allen Road, Tucson, Ariz. 85719; biologist, UCLA Laboratory of Biomedical and Environmental Sciences, 900 Veteran Ave., Los Angeles, Calif. 90024; and staff member, Environmental Science Group, Los Alamos National Laboratory, MSK-495, PO Box 1663, Los Alamos, N. Mex. 87545.

Much of the research reported in this paper was conducted while the senior author was a visiting staff member at the Los Alamos National Laboratory in Los Alamos, N. Mex. Research at Los Alamos was supported by the U.S. Department of Energy through Contract No. W-7405-ENG.36. Data from the lysimeters at Los Alamos were collected under the U.S. Department of Energy's National Low Level Waste Management Program, and data from the Nevada Test Site were collected by the UCLA Laboratory of Biomedical and Environmental Sciences under AEC Contract AT(04-1)GEN-12, and as a part of the International Biological Program/ Desert Biome (National Science Foundation Grant BG32139).

This report is a contribution from the USDA-ARS, the University of California at Los Angeles Laboratory of Biomedical and Environmental Sciences, and the Los Alamos National Laboratory.

Manuscript received February 28, 1983.

$$Y = Y_p(T/T_p) \quad (2)$$

where

Y = actual site yield (kg/ha),
Y_p = potential site yield (kg/ha),
T = actual transpiration (mm), and
T_p = potential transpiration (mm).

Variables used in equation (2) were for the growing season until the time of peak standing crop. The advantage of equation (2) is that, since T cannot exceed T_p, then the actual forage yield, Y, cannot exceed the site potential yield. In addition, potential transpiration rates vary throughout the growing season, and site potential yield can reflect situations where plant nutrient availability is the limiting factor. A disadvantage is that site potential yield, Y_p, was estimated from herbage yield data on a site specific basis, and no general guidelines were given to estimate site potential yield at other locations. An alternative formulation for equation (2) is

$$Y = K_e T \quad (3)$$

where:

Y = actual site yield (kg/ha),
K_e = water use efficiency factor in kg of dry matter production per kg of water use, and
T = actual transpiration (kg/ha).

As in equation (2), actual transpiration, T, in equation (3) cannot exceed potential transpiration. Advantages of equation (3) include the facts that values of K_e can be estimated from greenhouse and field plot studies and can vary through the growing season to reflect phenology. A disadvantage is that, in general, it is not known how water use efficiency factors, derived under controlled conditions, apply to field conditions where water stress, competition, spatial variability in soil characteristics, and related factors might affect water use efficiency. Water use efficiency factors might not predict vegetation production as accurately at specific sites as can be done with equation (2). However, for this particular application, we feel that water use efficiency factors have an advantage over site potential estimates in that they are more amenable to estimation using short-term greenhouse and field plot studies, they are less site specific, and they appear to give reasonable results for the first-order approximation.

This paper briefly describes soil-water-plant relationships in the northern Mojave Desert, illustrates an application of a continuous simulation model to predict a water balance, and illustrates application of equation (3) to predict the annual dry weight increment in above-ground standing crop which is hereafter called above ground net primary production, or simply net production.

Brief Overview of the Hydrologic Model

Several procedures, or models, are available to estimate infiltration, runoff, erosion, and sediment yield. Knisel (1980a) summarized several of these models and described the hydrology, erosion, and chemistry components used in each. In 1978, the U.S. Department of Agriculture (USDA) recognized the need to develop mathematical models to evaluate nonpoint source pollution from agricultural lands. The resulting model, CREAMS, for Chemicals, Runoff, and Erosion from Agricultural Management Systems, is described in a recent USDA Conservation Research Report (Knisel 1980b).

Because the CREAMS model was developed for applications using the then existing, but state-of-the-art, technology, we feel that it has applications in rangeland areas. Although management options and land uses are different under cultivated agriculture and rangelands, many of the physical processes are similar, and the water balance equation remains valid. Although the CREAMS model has components for hydrology, erosion, and chemistry, our discussions herein are limited to the hydrologic component.

The hydrologic component consists of two options. The first, a daily rainfall model, is based on the Soil Conservation Service runoff equation (USDA, SCS 1972), and the second, an infiltration model, is based on the Green and Ampt infiltration equation (Green and Ampt 1911). These models are described in detail by Smith and Williams (1980). The soil profile, from the surface to the plant rooting depth, is represented by up to 7 layers, each with a representative depth, or thickness, and a water storage capacity. Other parameters used to describe the soil profile include the minimum saturated hydraulic conductivity and water retention characteristics, such as the volumetric water content at saturation, field capacity, and the wilting point. The evapotranspiration calculations are based on a method developed by Ritchie (1972), and include potential evapotranspiration estimates based on mean daily temperature and solar radiation, soil evaporation estimates based on a soil evaporation parameter, and plant transpiration based on a seasonal leaf area index. The evapotranspiration model includes procedures to reduce evaporation and transpiration when soil moisture is limiting. Flow through the soil profile is computed using a soil storage-routing technique based on the depth of the soil profile, the existing soil water content, and the saturated hydraulic conductivity. Percolation below the root zone is computed when soil moisture is in excess of field capacity, and the rate of percolation is dependent upon the saturated hydraulic conductivity and the amount soil moisture exceeds field capacity. Soil water storage in each soil layer is subject to evapotranspiration losses based on the rooting depth, soil water content, water use rate in the surface layer, and the distribution of roots in each soil layer. Computation of the water balance is on a daily time step.

In summary, the hydrologic model predicts runoff and infiltration and maintains a water balance by simulating evaporation, plant transpiration, and percolation below the root zone. Results of model testing and validation for runoff, evapotranspiration, and percolation on agricultural watersheds are summarized by Smith and Williams (1980). Applications of the model under arid and semiarid rangeland conditions are discussed by Lane and Nyhan (1981) and Hakonson et al. (1982).

Parameter Estimation and Field Data

Conservation Research Report No. 26 (The CREAMS Model Documentation, Knisel 1980b) contains a User Manual which describes parameter estimation techniques. Except as noted below, all parameters were estimated using the User Manual for the CREAMS model. Kleinkopf et al. (1980) presented photosynthesis-soil moisture data which showed desert shrubs in the Mojave Desert extracting soil water at soil water potentials as low as −50 bars. The CREAMS User Manual suggests use of the wilting point estimate at −15 bars, whereas we estimated the wilting point water content at near the air-dry soil water content. Although the Rock Valley site is over 100 km from Las Vegas, Nev., we used monthly solar radiation data from Las Vegas, Nev. The User Manual recommended value of the soil evaporation parameter was reduced by 15% to partially reflect the mulching effect of desert pavement. Leaf area index estimates for perennial desert vegetation were not available in the User Manual, so a seasonal leaf area index curve was estimated from leaf mass-leaf area and standing biomass data presented by Kleinkopf et al. (1980) and Romney et al. (1973). However, these data were taken at peak standing crop during the spring growing season, so our seasonal leaf area index estimates are tentative. Additional data, over an entire season, will improve the quality of our preliminary estimates. However, our estimates do include observed dates of leaf emergence and dormancy from phenological data reported by Ackerman et al. (1980).

Field data were collected from Rock Valley on the Nevada Test Site in the northern Mojave Desert. Detailed site descriptions are provided by Romney et al. (1973) and by International Biological Program Reports after 1972 (e.g., Turner, 1973 and subsequent reports). Available data in Rock Valley included soils data from 13 sampling sites and vegetation data from 8 vegetation quadrats 2 × 50 m in size. Abiotic data (rainfall, air, and soil temperature, and soil moisture data at depths of 15 and 35 cm below the soil surface) were collected at a central location. Rainfall data were collected for every storm, and the other data were taken approximately twice a month for 9 years (1968 through 1976). Soil moisture data were available for 5 years (1968 through 1972), and net production data, for perennial vegetation, were available for 7 years (1968, and 1971 through 1976). Vegetation data were used to characterize the 8 sites, and average net production data were taken each season on the perennial vegetation. Vegetation data were tabulated for a number of species (Romney et al. 1973). These data are summarized in Table 1. Notice that the 4 dominant species *(A. dumosa, G. spinosa, L. tridentata,* and *L. andersonii)* account for 74% of the total vegetative cover and 82% of the total standing crop. Moreover, for the data shown in Table 1, there is a strong correlation (r=0.94) between percent cover and standing crop.

Table 1. Characteristics of perennial vegetation for selected species. Data represent average values over eight sampling sites (Romney et al. 1973).

Species name	Percent cover	Standing crop (kg/ha)
Ambrosia dumosa	3.7	254.
Ephedra nevadensis	1.7	114.
Grayia spinosa	4.3	493.
Krameria parvifolia	2.3	93.
Larrea tridentata	5.4	656.
Lycium andersonii	5.2	604.
Lycium pallidum	1.9	117.
Other species	0.7	109.
Total	25.2	2440.

Characteristics of the soil from samples taken in 72 soil profiles were presented by Romney et al. (1973), and these data are summarized in Table 2. Soil profiles were obtained at 13 sites, and represented areas under the shrub canopy and in the bare areas between shrub clumps. The composite soil characteristics shown in the last column of Table 2 represent the area-weighted values used to describe the soil profile in the CREAMS Model.

Precipitation, temperature, and soil moisture for the Rock Valley site are summarized in Table 3. Although these monthly means are based on only 5 years of data, some seasonal trends are apparent. On the average, the months of November through January represent soil moisture recharge; the months of March through May represent soil moisture depletion; and soil moisture in the remaining months of the year is generally limited. Plant available soil moisture peaks in February–March, and is lowest in June–July. There appears to be a slight increase in plant available soil moisture in July–September, reflecting the occurrence of summer thunderstorms.

Results and Discussion

Field data analyzed in this paper include water balance calculations using data from lysimeters at Los Alamos, N.Mex., (Hakonson et al. 1982), evapotranspiration-net production data from the south Tunisian steppe (Floret et al. 1982), and the data from Rock Valley, Nev. (Romney et al. 1973). The data from Rock Valley form the basis of this paper, and the data from New Mexico and Tunisia are used to supplement the discussions of model applicability and water use efficiency.

Table 3. Selected climatic data for the Rock Valley, Nevada site. Data represent average values of a five-year period, 1968-1972 (Romney et al. 1973).

Month	Precipitation (mm)	Mean temperature (°C)	Average soil moisture at 15 and 35 cm (% by volume)
Jan.	16.3	6.1	11.4
Feb.	31.8	9.4	12.6
March	17.8	12.2	12.6
April	2.5	15.0	9.4
May	4.6	20.0	6.3
June	8.4	25.0	4.7
July	10.4	29.4	4.9
Aug.	17.5	29.4	5.6
Sept.	13.7	25.6	5.6
Oct.	10.2	17.8	5.1
Nov.	11.7	11.1	7.4
Dec.	20.1	5.0	8.6
Annual	165.	17.	7.8

The CREAMS model was used to compute evapotranspiration and soil moisture in two 90-cm diameter by 150-cm deep lysimeters at Los Alamos. One lysimeter had a bare-soil surface, and one was vegetated. Both lysimeters were subjected to rainfall and supplemental irrigation. Soil moisture was measured with a neutron probe approximately twice a week from July through December, 1981. Model parameters were estimated using procedures described in the CREAMS User Manual (Knisel 1980b).

Figure 1 shows components of the water balance for the bare plot, and similar data for the vegetated plot are shown in Figure 2. Only the points in these figures represent data; the lines connecting the points are to identify the data points and to suggest monthly trends. In general, computed monthly evaporation from the bare soil plot was less than the water application rate, suggesting an increase in soil moisture storage in the 150-cm soil profile (upper portion of Fig. 1). In fact, soil moisture increased during the experiment, and the model simulated a similar trend (lower portion of Fig. 1). In general, computed monthly evapotranspiration from the vegetated plot exceeded water application rates (upper portion of Fig. 2), and this was reflected in the measured and computed soil moisture (lower portion of Fig. 2).

Figure 3 shows components of the mean monthly water balance for the Rock Valley site for 1968–1972. Notice that the periods

Table 2. Summary of soil characteristics for the Rock Valley, Nevada site. Data represent mean values from 13 locations and 72 soil profiles (Romney et al. 1973).

Variable	Shrub cover Mean	Shrub cover Range	Bare soil Mean	Bare soil Range	Composite[1]
Depth (cm)	65.	33. - 110.	64.	28. - 106.	64.
Porosity (%)	33.0	26.4 - 43.9	34.5	20.9 - 41.8	34.
Soil moisture % by volume					
-1/3 Bar	14.1	9.6 - 18.9	16.4	9.8 - 26.0	16.
-15 Bar	7.1	5.5 - 9.8	6.9	5.2 - 10.0	7.
Percent cover					
Vegetation	—	—	—	—	25.
Rock & gravel	—	—	60.	5 - 70	45 - 60
Surface texture	—	Sand to loamy sand	—	Sand to loam	Loamy sand to gravelly, sandy loam.

[1]Area weighted composite based on a mean crown cover of 25%.

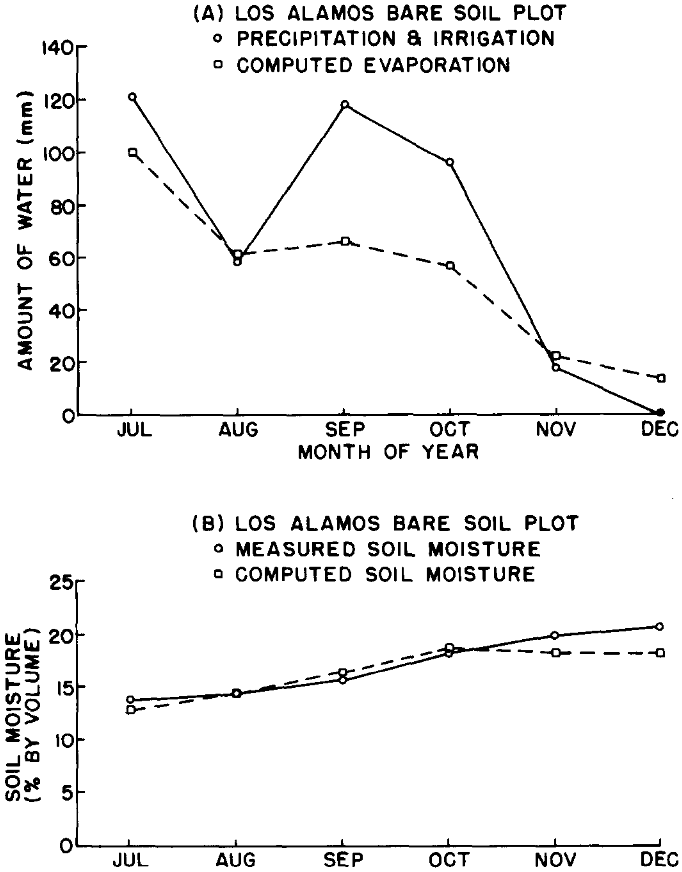

Fig. 1. *Components of the monthly water balance for Los Alamos, bare soil plot, 1981.*

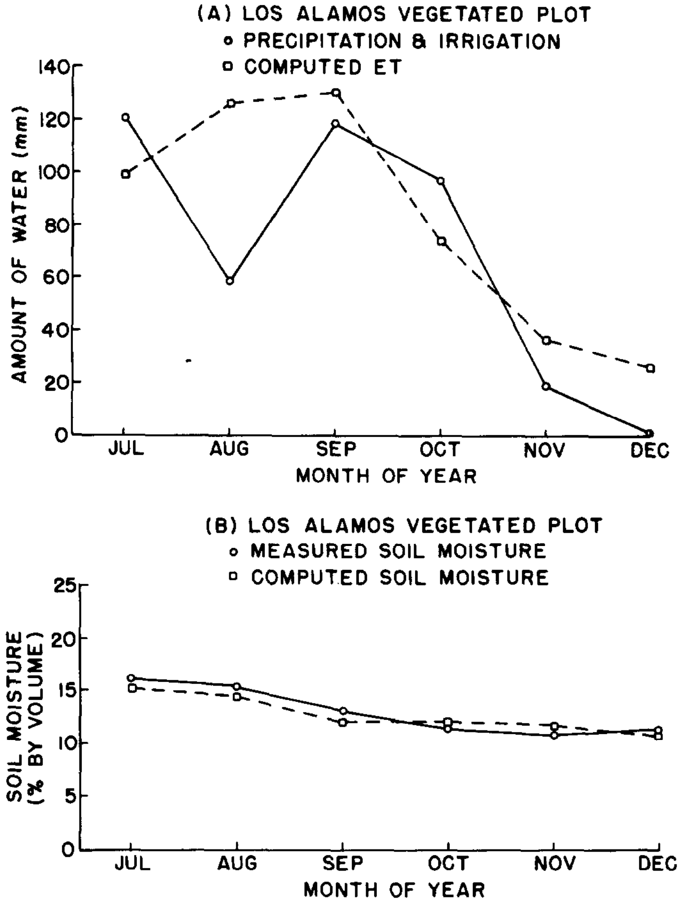

Fig. 2. *Components of the monthly water balance for Los Alamos, vegetated plot, 1981.*

when computed evapotranspiration is less than measured rainfall correspond with periods of increasing soil moisture; the reverse is true when computed evapotranspiration exceeds measured rainfall. Numbers in parentheses, in the upper portion of Figure 3, represent estimated runoff volumes in millimeters. Observed and computed monthly soil moisture for Los Alamos and Rock Valley are shown in Figure 4. Although there are significant differences in computed and measured soil moisture for individual months, the hydrologic model reproduced seasonal trends and explained most of the variance in measured soil moisture (R=0.93).

Based on the criterion of computed vs measured monthly soil moisture, we concluded that the simulation model was reproducing trends in the monthly water balance at Los Alamos and Rock Valley. The next step was to multiply computed transpiration rates by appropriate water use efficiency factors to estimate net production of vegetation (equation (3)).

Floret et al. (1982) reported actual evapotranspiration and net primary production of perennial vegetation for 6 seasons in the southern Tunisian steppe. They reported water use efficiency fac-

Table 4. Annual values of precipitation, computed evapotranspiration and plant transpiration, and observed and computed net production of perennial vegetation at Rock Valley, Nevada, 1968-1976.

Year	Precipitation (mm)	Evapotranspiration Total (mm)	Evapotranspiration Transpiration (mm)	Net production (kg/ha) Observed	Net production (kg/ha) Computed[1]
1968	130.	174.	50.	430.	370.
1969	295.	240.	89.	—[2]	670.
1970	134.	104.	21.	—	160.
1971	146.	126.	27.	157.	200.
1972	118.	152.	32.	183.	240.
1973	211.	216.	67.	573.	500.
1974	130.	120.	18.	181.	130.
1975	67.	91.	16.	180.	120.
1976	220.	198.	67.	404.	500.
Mean[3]	161.	158.	43.	—	321.
S.D.	68.	52.	26.	—	196.
Mean[4]	146.	154.	40.	301.	294.
S.D.	54.	45.	22.	166.	163.

[1]Computed assuming Ke = 0.00075 kg dry matter per kg H_2O.
[2]No record during these years.
[3]Based on 9 years of data, 1968-1976.
[4]Based on 7 years of data, 1968 and 1971-1976.

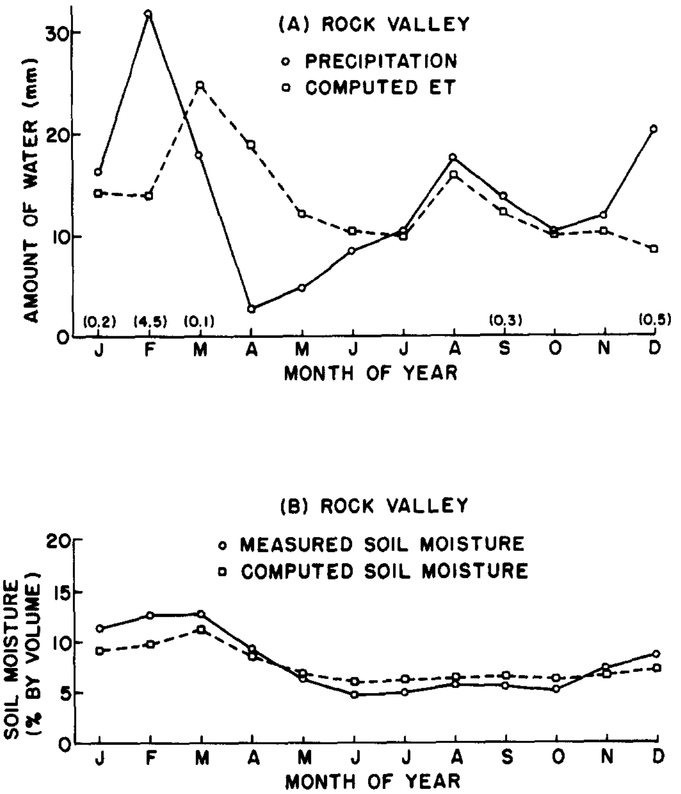

Fig. 3. *Components of the monthly water balance for Rock Valley in the Mojave Desert, 1968-1972.*

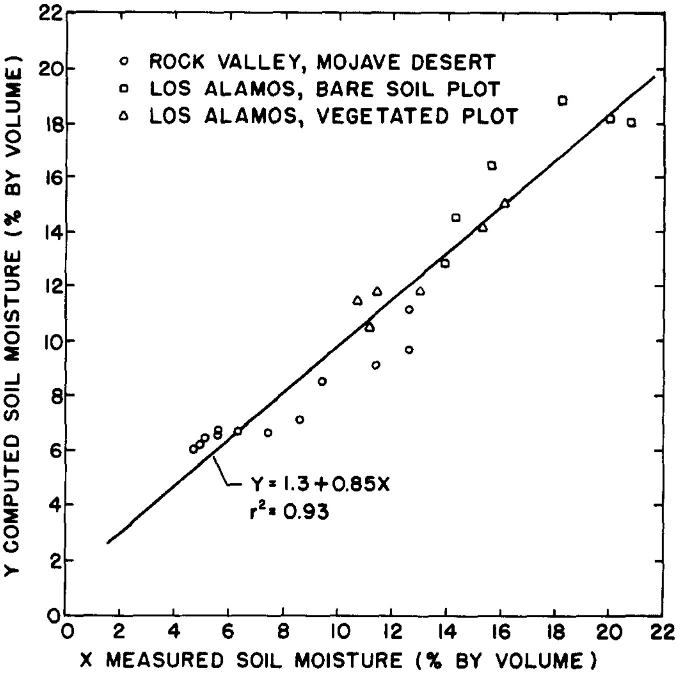

Fig. 4. *Relationship between measured and computed monthly soil moisture for Rock Valley, Nevada and Los Alamos, New Mexico.*

tors of 0.0014 and 0.00033 kg dry matter production per kg of water use for all perennial vegetation species in the spring growing period, and during other periods of the year, respectively. On an annual basis, and for all species, the reported water use efficiency was 0.00045 kg dry matter per kg of water use. Furthermore, on the average, 45% of total evapotranspiration was plant transpiration. Finally, Floret et al. (1982) reported annual and spring (February–May) precipitation; so we took the same ratio for spring to annual transpiration as they observed for spring to annual precipitation. Next, we multiplied spring transpiration estimates times spring water use efficiency and non-spring transpiration estimates times non-spring water use efficiency. The sum of these calculations was then a predicted annual net production estimate for perennial vegetation. The relationship between estimated net production, y, and measured net production, x, in kg/ha, is

$$y = 241. + 0.70\,x \tag{4}$$

with a coefficient of determination of $R^2 = 0.78$.

Therefore, in spite of the obvious approximations involved in this example, equation (3) was used to predict annual plant production at a site in Tunisia. Analysis of predicted and observed vegetation production data suggest that equation (3) explains about 80% of the variance in annual yield.

However, it should be noted that our procedure (the water balance calculations and equation (3)) is only intended for cases when water is the limiting factor. Our procedure is not designed to predict net production when water is not limiting, but nutrient availability is. The water use efficiency factors we used do not account for reduced efficiency due to nutrient limitations. However, the CREAMS model can be used to compute potential and actual transpiration, so that it is possible to identify seasons when actual transpiration approaches its potential.

From our analysis of the water balance calculations at Los Alamos, N. Mex., and Rock Valley, Nev., and from our analysis of the water use-perennial vegetation production calculations in Tunisia, we assumed the method was appropriate for prediction of net production of perennial vegetation at Rock Valley, Nev. Annual values of precipitation, computed transpiration, and net production of perennials are shown in Figure 5. Based on previously published information, such as Gifford's (1976) estimates of water use efficiency for several species of shrubs, we assumed an average water use efficiency factor over all species of 0.00075 kg dry matter production per kg of water use by the Rock Valley vegetation. Szarek (1979) published annual water use efficiency estimates which were averaged over all species at Rock Valley and ranged from 0.00014 to 0.00027 kg dm/kg H_2O. However, these estimates were based on total annual precipitation as an estimate of annual actual evapotranspiration. While these estimates are fairly accurate (e.g., see Table 4, herein), annual evapotranspiration exceeds annual transpiration. We estimate that, at the Rock Valley site, annual transpiration averages some 27% of total evapotranspiration (Table 4). If we divide Szarek's range of estimates by 0.27, then we obtain a range of from 0.00052 to 0.0010 kg dm/kg H_2O where water use refers to transpiration rather than soil evaporation and plant transpiration together.

The upper portion of Figure 5 shows annual precipitation and computed actual transpiration for nine years at the Rock Valley site. Notice that, except for 1969, the annual precipitation varied by a factor of 3 but the corresponding annual transpiration estimates varied by over a factor of 4. This suggests that analyses, using predictors such as annual precipitation, would be expected to mask intra-seasonal variations affecting transpiration rates. Although the data shown in Figure 5 are annual values, they were obtained by summing calculations made on a daily time step. Therefore, we believe that the most useful water balance calculations in soil-water-plant relationship studies of this type are those based on time periods short enough to include seasonal variations affecting soil moisture and transpiration.

The lower portion of Figure 5 shows measured and computed net production of perennial vegetation for 7 years. Although the agreement between computed and measured net production data is not perfect, the procedure reproduced annual variability in net production comparable with measurements, and the model explained the trends in the measured data. Based on these results, the model appears to have potential for predicting net production of perennial vegetation in areas such as Rock Valley, where water is usually the limiting factor.

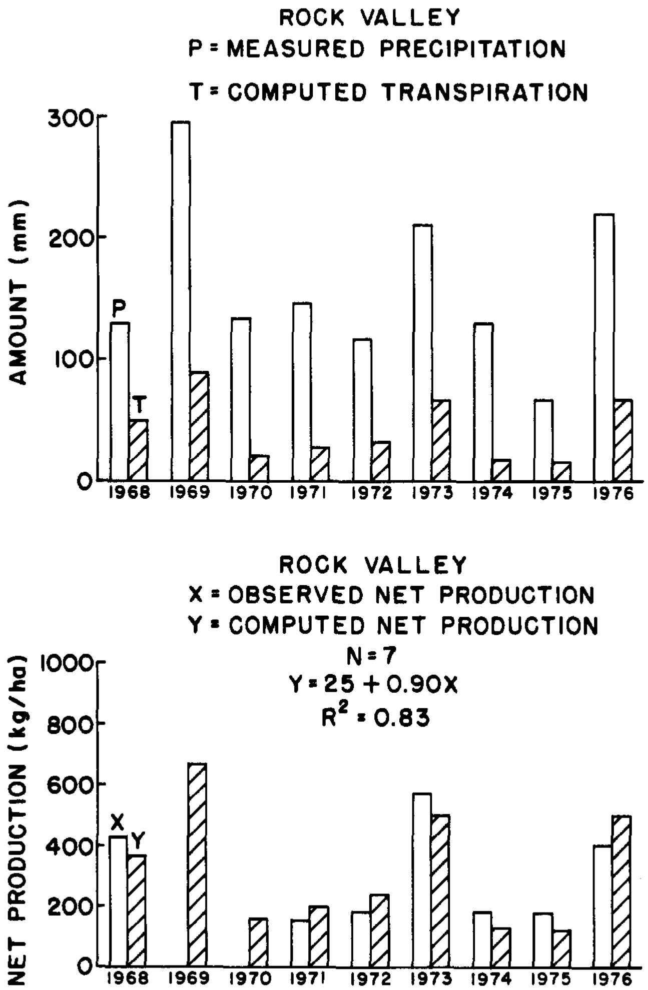

Fig. 5. *Annual values of precipitation, computed transpiration, and net production of perennial vegetation at Rock Valley, Nevada, 1968-1976.*

The data shown in Figure 5 are summarized in Table 4. Based on seven years of data, the coefficients of variation were 0.37 for annual precipitation, 0.29 for annual evapotranspiration, and 0.55 for annual transpiration, measured net production, and computed net production. This suggests that annual net production might exhibit more variability than annual precipitation data, and that we might expect a higher correlation between transpiration estimates and net production than between annual precipitation and net production.

Given observed values of precipitation and net production and computed values of transpiration, it is possible to derive prediction equations for annual net production of perennial vegetation. Then, by comparing statistics of these derived regression equations, it is possible to compare prediction accuracy and precision (or goodness of fit) as a function of model complexity. These comparisons are made in Table 5. The simplest mathematical model is to use mean annual net production as a predictor for annual net production. These results are shown in Row 1 of Table 5. Using the mean as a predictor, we explain none of the annual variability in net production (R^2=0.0), and the width of the 95% confidence interval is from 147 to 455 kg/ha around a mean of 301 kg/ha. Using annual precipitation as a predictor variable, we explain 51 %of the variance and reduce the width of the confidence interval by 19% By using seasonal precipitation as the predictor, we explain 74% of the variance and reduce the width of the confidence interval by 19%. By Using annual transpiration (as shown in Figure 5), we explain 84% of the variance and reduce the width of the confidence interval by 53%. Finally, using seasonal estimates of transpiration, we explain 90 % of the variance and reduce the width of the confidence interval by 63%.

We interpret these results as follows, based on site specific conditions at Rock Valley, Nev. If observed data are available, and we perform regression analysis, then we can explain about 50 to 70% of the variance in annual net production using precipitation data alone. This corresponds with about 20 to 40 % reduction in the width of the 95% confidence interval about the mean. Using a simulation model, such as CREAMS, we can explain about 80 to 90% of the variance in annual net production and reduce the width of the 95% confidence interval about the mean by about 50 to 60%.

However, under conditions where observed data for calibration of regression equations are not available, we can use estimated seasonal transpiration and equation (3) to predict net production. Again, using data from Floret et al. (1982), we computed net production of perennial vegetation with the relation between observed, x, and predicted, y, as

$$y = 241 = 0.70\,x \tag{4}$$

with $R^2 = 0.78$, $\bar{x} = 672$ kg/ha, and $\bar{y} = 713$ kg/ha. If we had used seasonal precipitation data and the regresion coefficients from Rock Valley (Table 5), the results would have been

$$y = 177 + 0.22\,x \tag{5}$$

with $R^2 = 0.56$, $\bar{x} = 672$ kg/ha, and $\bar{y} = 327$ kg/ha. Equation (4) explained 78% of the variance, and the ratio of mean predicted to mean observed net production was 1.06. Equation (5) explained 56% of the variance, and the ratio of mean predicted to mean observed net production was 0.49. For this example, the simulation model predicted the mean within 6% and explained 78% of the variance. The transposed regression equation predicted the mean with a 51% error and explained 56% of the variance.

The data shown in Table 5, and the data summarized in equations (4) and (5), illustrate 2 examples of comparisons of results of fitting and predicting using regression equations and a continuous

Table 5. Summary of regression analysis of predictor variables (x) vs net production of perennial vegetation (y) at Rock Valley, Nevada, 1968 and 1971-1976.

	Regression equation $y = a + b\,x$			Summary of predictions		
Predictor	a	b	R^2	% Explained variance[1] 100 R^2	95% CI width[2] (kg/ha)	% Reduction in CI widths[3]
x = $\bar{y}$ = mean	0	1.0	0.0	0.	147–455	0.
x = annual precip	-21.	2.21	0.51	51.	177–425	19.
x = seasonal precip[4]	136.	2.40	0.74	74.	211–391	42.
x = annual trans	27.	6.94	0.84	84.	229–373	53.
x = seasonal trans[4]	40.	9.33	0.90	90.	244–358	63.

[1]Percent explained variance, relative improvement over using the mean annual net production as a predictor.
[2]Width of the 95% confidence interval about the mean annual net production.
[3]Percent reduction in the width of the 95% confidence interval about the mean annual net production.
[4]Seasonal precipitation and transpiration over the period January through May.

simulation model such as the CREAMS model. While these comparisons are by no means exhaustive, and no doubt counter examples could be found, they do illustrate what we believe to be a useful feature of continuous simulation models in computation of a water balance. If the simulation model includes physical features such as soil and vegetation characteristics and accounts for climatic variables such as precipitation, temperature, and solar radiation, then we feel it has broader applications than site-specific regression equations. Moreover, models such as used herein also have the ability to produce estimates of other variables such as runoff, soil moisture, erosion rates, and sediment yield. Finally, inasmuch as the simulation models parameterize the physical features described earlier, if we can determine the influence of land use and management practices on these parameters, then we are in a position to predict the hydrologic consequences of various land uses and management practices.

Summary and Conclusions

In arid and semiarid areas, water availability is often the limiting factor in plant production, and thus, water balance calculations are often critical in understanding soil-water-plant relationships. Understanding these relationships under climatic extremes, such as is represented by desert conditions, should enhance our ability to understand and predict them under semiarid rangeland conditions.

We applied a continuous simulation model to data from a lysimeter study at Los Alamos, N. Mex., and demonstrated an ability to predict soil moisture under bare soil and vegetated plot conditions. Next, we applied the model, with minor modifications in the parameter estimation techniques, to data from the Rock Valley site in Nevada. Then, we selected an initial estimate for a water use efficiency factor and predicted net production of perennial vegetation at Rock Valley. Seasonal distribution patterns of precipitation are shown to have a strong effect on plant-available soil moisture (Fig. 3), and these patterns are, in turn, reflected in the transpiration and net production estimates (Fig. 5).

In the past, annual precipitation has been used to estimate net production using regression analysis. Improved regression equations can be derived by considering seasonal precipitation. Although these regression equations can probably predict net production as accurately as any other procedure at specific sites where calibration data are available, they are site specific. It is difficult to transpose specific regression coefficients across regions representing variations in climate, soils, and vegetation. Moreover, this link between regression coefficients and characteristics of climate, soils, and vegetation is often indistinct, or even contradictory. Finally, in the absence of long periods of environmental monitoring before and after "treatments," it is difficult to interpret the influence of various land use and conservation measures upon the regression coefficients. For these reasons, we feel that continuous simulation models, which incorporate physical features of the soil and vegetation, as well as variations in precipitation, temperature, and solar radiation, offer a more powerful predictive capability, and require less calibration than regression equations.

Recent advances in technology have produced simulation models (e.g., Wight and Hanks 1981, Knisel 1980b) which can be used to compute a water balance on arid and semiarid rangelands. Under conditions where water availability is limiting, water balance calculations are essential in soil-water-plant relationships studies. Inasmuch as the water balance is predictable, we feel that plant production is predictable. Given this predictive capability, watershed and range managers have a valuable tool in assessing site potential and in developing best management practices on arid and semiarid rangelands.

Literature Cited

Ackerman, T.L., E.M. Romney, A. Wallace, and J.E. Kinnear. 1980. Phenology of desert shrubs in southern Nye County, Nevada. p. 4-23. *In:* Soil-Plant-Aniaml Relationships Bearing on Revegetation and Land Reclamation in Nevada Deserts, Great Basin Naturalist Memoirs No. 4, Brigham Young Univ., Provo, Utah.

Branson, F.A., G.F. Gifford, K.G. Renard, and R.F. Hadley. 1981. Rangeland hydrology. Range Sci. Series No. 1, Second Edition, Soc. for Range Manage. Kendall/Hunt, Dubuque, Iowa.

Brown, R.W. 1977. Water relations of range plants. Ch. 4 in Rangeland Plant Physiology, R.E. Sosebee (ed.). Range Sci. Series No. 4, Soc. for Range Manage., Denver, Colo.

Floret, C., R. Pontanier, and S. Rambal. 1982. Measurement and modeling of primary production and water use in a south Tunisian steppe. J. Arid Environ. 5:77-90.

Gifford, G.F. 1976. Vegetation manipulation - a case study of the pinyon-juniper type. p. 141-148. *In:* Watershed Management on Range and Forest Lands. Proc. 5th U.S./Australian Rangelands Panel, Boise, Ida., June 15-22, 1975.

Green, W.A., and G.A. Ampt. 1911. Studies on soil physics, 1. The flow of air and water through soils. J. Agr. Sci. 4:1-24.

Hakonson, T.E., L.J. Lane, J.G. Steger, and G.L. DePoorter. 1982. Some interactive factors affecting trench cover stability on low-level waste burial sites. Presented at the Nuclear Regulatory Commission Symposium on Low-Level Waste Disposal: Site Characterization and Monitoring, Arlington, Va. June 16-17, 1982.

Johnson, A.W. 1968. The evolution of desert vegetation in western North America. Ch. 4 in Vol. 1, Desert Biology, G.W. Brown, Jr. (ed). Academic Press, New York.

Kleinkopf, G.E., T.L. Hartsock, A. Wallace, and E.M. Romney. 1980. Photosynthetic strategies of two Mojave Desert shrubs. p. 10-109. *In:* Soil-Plant-Animal Relationships Bearing on Revegetation and Land Reclamation in Nevada Deserts, Great Basin Naturalist Memoirs No. 4, Brigham Young Univ., Provo, Utah.

Knisel, W.G., Jr. 1980a. Erosion and sediment yield models—an overview. Proc. Amer. Soc. Civil Engineers Watershed Management Symp., Boise, Ida., July, 1980. Vol. 1.

Knisel, W.G., Jr. (ed.). 1980b. CREAMS: a field-scale model for chemicals, runoff, and erosion from agricultural management systems. USDA Cons. Res. Rep. No. 26, USDA , Washington, D.C.

Lane, L.J., and J.W. Nyhan. 1981. Cover integrity in shallow land burial of low level wastes: Hydrology and erosion. Proc. Third Annual Info-Meeting, U.S. Dep. of Energy Low-Level Waste Manage. Program, New Orleans, La. Nov. 4-6, 1981, ORNL/NFW-81/34.

Logan, R.F. 1968. Causes, climates, and distribution of deserts. Ch. 2 in Vol. 1, Desert Biology, G.W. Brown, Jr. (ed.). Academic Press, New York.

Ritchie, J.T. 1972. A model for predicting evaporation from a row crop with incomplete cover. Amer. Geophysical Union Water Res. Res. 8:1204-1213.

Romney, E.M. et al. 1973. Some characteristics of soil and perennial vegetation in northern Mojave Desert areas of the Nevada Test Site. Univ. of Calif., Los Angeles Lab. of Nuc. Medicine and Rad. Biol., UCLA No. 12-916, UC-48 Biomedical and Environ. Research, TID-4500.

Smith, R.E., and J.R. Williams. 1980. Simulation of the surface water hydrology. Ch. 2. in Vol. 1, CREAMS, USDA Conservation Res. Rep. No. 26, W.G. Knisel, Jr. (ed). USDA, Washington, D.C.

Szarek, S.R. 1979. Primary production in four North American deserts: indices of efficiency. J. Arid Environ., Vol. 2.

Turner, F.B. 1973. Rock Valley Validation Site Report, Univ. of Calif., Los Angeles, Rese. Memo. 73-2, May, 1973.

U.S. Department of Agriculture, Soil Conservation Service. 1972. Section 4, Hydrology in National Engineering Handbook. USDA, SCS, Washington, D.C.

Walter, H., and E. Stadelmann. 1974. A new approach to the water relations of desert plants. Ch. 5 in Vol. II, Desert Biology, G.W. Brown, Jr. (ed). Academic Press, New York.

Wight, J.R., and R.J. Hanks. 1981. A water-balance, climate model for range herbage production. J. Range Manage. 34:307-311.