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Applications of the Water Balance Approach for Estimating Plant Productivity in Arid Areas

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Abstract—Plant productivity is often estimated using precipitation, evapotranspiration, or transpiration as a predictor for plant water use. Hydrologic models are used to calculate a water balance and to estimate evapotranspiration and transpiration. The water balance approach accounts for first order environmental effects in plant productivity and is adequate for many applications. The water balance approach can be used for screening, experimental design including determining the length of records needed to sample climatic variability, and analysis of soil properties affecting plant productivity. However, it does have limitations. Stresses due to nutrients, competition, herbivory, disease, and so forth are not directly considered. The approach is process-based in terms of climate, hydrology, and soil water dynamics, but is empirically based in terms of biological activities.

Arid and semiarid areas are widespread, generally along two wide belts centered at approximately 30 degrees latitude north and south of the equator, and comprise more than one-third of the world's land surface. Approximately 80% of the world's rangelands are within these arid and semiarid areas where precipitation is generally less than potential evapotranspiration (Branson and others 1981). Under these conditions, water availability is the most important factor controlling plant survival and production (Brown 1974).

The importance of water availability is the basis of the water balance approach in predicting plant water use and annual above-ground net primary productivity (ANPP). The purpose of this paper is to describe applications and limitations of the water balance model-water use efficiency approach for estimating plant productivity in arid areas. Emphasis is on first order environmental effects represented by the CREAMS Simulation Model and the example application emphasizes hydrologic modeling and estimation of ANPP for perennial shrubs at the Rock Valley Site in Nevada.

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Methods and Procedures

A Discrete Form of the Water Balance Equation

Over a discrete time period (day, month or year) and on a unit area (square meter or ha), if we assume no runon, no net subsurface water movement in the horizontal direction, and a plant rooting depth significantly above the permanent water table, a discrete form of the water balance equation can be written as follows:

$$\Delta S/\Delta t = P - Q - ET - L \qquad (1)$$

where:

ΔS = change in soil water content to the plant rooting depth (mm, representing units of volume per unit area),
Δt = time period for calculations (usually days summed to monthly or annual values),
P = precipitation depth for the time period (mm),
Q = runoff from the area for the time period (mm),
ET = combined evaporation and plant transpiration for the time period (mm), and
L = percolation or seepage below the root zone for the time period (mm).

All terms in Eq. 1 depend on the amount of precipitation, P; the other terms (Q, ET, and L) are strongly related to soil water content. Therefore, feedback is an essential feature of water balance equations. For example, ET depletes soil moisture, and soil moisture status often limits the rate of ET.

Potential Evapotranspiration, Soil Moisture, and Actual Evapotranspiration

Potential evapotranspiration (PET) is the rate of ET when water is not limiting; PET represents a maximum from atmospheric demand under a complete plant canopy. Actual evapotranspiration (AET) is always less than or equal to PET and depends on soil moisture and atmospheric demand, as well as on soil and vegetation characteristics when water is limiting. Soil moisture (SM) is often expressed as the soil water content, S in Eq. 1, normalized by the soil water content when the soil is saturated.

Values of AET can be estimated if the ratio of AET to PET is known. Most of our knowledge of the ratio of AET to PET comes from cropland research. Veihmeyer and Hendrickson (1955) suggested that the ratio of AET to PET remains nearly constant as soil moisture decreases from field capacity to near the plant wilting point. Thornthwaite and Mather (1955) suggested a linear relationship between AET/PET and soil moisture; other investigators have proposed a variety of nonlinear relationships (Hanson 1973; Fig. 3, P. 16).

The general relationship among soil moisture, AET, and PET can be summarized in equation form as follows:

$$AET = \begin{cases} PET & SM \geq SM_1 \\ f(SM,PET) & SM_0 < SM < SM_1 \\ 0 & SM \leq SM_0 \end{cases} \quad (2)$$

where SM_1 is a limiting soil moisture above which SM does not influence AET, SM_0 is a limiting soil moisture below which soil water is not available to plants, and f is a function expressing AET/PET when soil moisture is between SM_0 and SM_1. On croplands, SM_1 is often assumed equal to soil moisture at field capacity (usually –1/10 to –1/3 bar) and SM_0 is often assumed equal to soil moisture at the permanent plant wilting point (usually –15 bars).

In contrast with crops, plants in arid and semiarid areas appear to be more efficient in extracting soil moisture under relatively dry soil conditions with soil water potentials below –15 bars (see Ackerman and others 1980). The volume of water stored in soils at potentials less than –15 bars is small compared with the volume stored between –15 bars and –1/3 bar, but that water is important to plant growth and survival in arid and semiarid areas. Plant growth and water balance models applied to arid and semiarid conditions usually assume a wilting point at soil water potentials below –15 bars (Hanson and others 1987), but wilting point values (SM_0 in Eq. 2) under these conditions are not well quantified. However, simple water balance models may not be sensitive to assumed wilting point values (Williams and others 1980; table II-5, p. 173).

Simple Soil-Water-Plant Relationships for Arid and Semiarid Areas

Relationships, models, and applications presented here are intended to illustrate a range of complexity in approaches in estimating ANPP using selected examples. No attempt has been made to represent all approaches, nor are the citations intended to be complete. The general progression of complexity in predicting ANPP varies from using 1) annual or seasonal precipitation, 2) annual or seasonal AET, and 3) annual or seasonal actual plant transpiration.

Models to predict net primary productivity using mean annual precipitation were summarized by Lieth (1975) based on earlier work by Lieth (1962) and by Walter (1939; 1964). The "Walter's Ratio" for arid areas is a linear equation through the origin as follows:

$$Y = 2.0\,P \quad (3)$$

where Y is net productivity ($g/m^2/y$) and P is mean annual precipitation (mm). Equation 3 is limited to application in dry climates, does not consider temperature or life form, and predicts net productivity to be positive even as mean annual precipitation approaches zero. Lieth (1975) solved the problem of extending the precipitation-based predictions to wetter climates by assuming an upper limit on net productivity and a saturation-curve model which approaches the upper limit asymptotically. Lieth's saturation-curve model retains the other limitations of Walter's Ratio.

Rosenzweig (1968) used estimates of AET to predict ANPP as follows:

$$ANPP = 0.0219(AET)^{1.66} \quad (4)$$

where ANPP is in $g/m^2/y$ and AET is annual actual evapotranspiration in mm/y. This is an improvement over Eq. 3 in that AET is a better predictor of plant water use than annual precipitation because temperature is reflected in the AET estimates. However, AET includes water lost from evaporation from plants and litter, as well as from soil evaporation. Finally, like Eq. 3, Eq. 4 predicts productivity to increase without bounds as AET increases, and because 1.66 is an exponent in Eq. 4, ANPP increases even faster than AET increases. Webb and others (1978) proposed an equation of the form:

$$ANPP = 496 - 666(e^{-0.0025\,AET}) \quad (5)$$

where ANPP and AET are as defined above. Notice that Eq. 5 predicts zero ANPP for values of AET below about 118 mm and that ANPP approaches an upper limit of 496. For these reasons it is an improvement over Eq. 4, but like Eqs. 3 and 4 it does not consider soil or vegetation characteristics.

Wight and Hanks (1981) used a simple hydrologic model to solve Eq. 1 and then used the ratio of actual to potential transpiration (AT/PT) to predict site forage yield. Their equation for the growing season forage yield is:

$$Y = Yp(AT/PT) \quad (6)$$

where Y is actual site yield (kg/ha), Yp is potential site yield (kg/ha), AT is actual transpiration (mm) during the growing season, and PT is site potential transpiration (mm) during the growing season. This model represented several conceptual (and complexity) advances over Eqs. 1-5. First, the model solved a daily water balance that accounted for climate, soils, changes in soil moisture, runoff, and percolation. Second, results of the water balance calculations and knowledge of life form seasonal growth patterns and site specific herbage yield data were used to estimate Yp and AT/PT. Third, the Wight-Hanks model used actual transpiration, not actual evapotranspiration, to estimate plant water use and thus avoided the conceptual problem of including evaporation not involved in plant growth in plant growth predictions.

Lane and others (1984) used the CREAMS Model (Knisel 1980) to solve Eq. 1 (daily time step) and estimate AET. The ET component of the CREAMS Model uses a seasonal leaf area index (LAI) to separate AET into actual transpiration and actual evaporation. Estimates calculated on a daily basis were used on monthly, seasonal, and annual bases. The CREAMS Model was applied to lysimeter data from Los Alamos, NM, to field data from the southern Tunisian steppe (Floret and others 1982), and to field data from Rock Valley, NV (Romney and others 1973; Turner 1973; Ackerman and others 1980). The equation used to estimate ANPP is:

$$ANPP = Ke\,AT \quad (7)$$

where Ke is a water use efficiency factor (g dry matter production per m^2 per year per mm of transpiration).

The advantages of this approach over that of Wight and Hanks (1981) include 1) values of Ke can be estimated from greenhouse and field plot studies and can vary through the growing season to reflect phenology, 2) the CREAMS Model is operated on a daily time step throughout the year, has a more detailed description of the soil profile, and thus can better reflect soil moisture status at the beginning of the growing season, and 3) daily variations in rooting development, LAI-AET feedback, and soil moisture status by soil layer make the water balance calculations more responsive to changing weather inputs. Disadvantages include 1) it is not known how well water use efficiency factors derived under controlled conditions apply to field conditions, 2) the use of site specific values of Yp from field measurements may result in improved forage yield predictions, and 3) the CREAMS Model is more complex and requires more input data.

The approaches represented by Eqs. 2 through 7 and the accompanying narrative illustrate increasing sophistication and incorporation of more physically based models at the expense of increasing complexity. Equation 2 represents the influence of annual precipitation only, while Eq. 7 and the water balance model used to calculate AT represent a more process-based approach in terms of climate, hydrology, and soil water dynamics, but remain empirical in representing the biological processes such as root development, leaf area index, and water use efficiency.

Example Application at Rock Valley

Rock Valley is on the Nevada Test Site near Mercury, NV, in the northern Mojave Desert. The experimental site is at latitude 36°40' N and longitude 116°05' W. Elevation at the site is approximately 1,020 m MSL. Based on 9 years of data, mean annual precipitation is 161 mm and mean annual temperature is 17 °C. The climate is classified as hot desert.

Soils were sampled at 72 profiles representing sites with shrub cover and sites with bare soil (with 45 to 60% surface rock cover or desert pavement). Most of the soils are underlain by calcrete at an average depth of 64 cm. Texture under the shrubs ranged from sand to loamy sand and texture in the bare areas ranged from loamy sand to gravelly sandy loam. Average soil properties over the entire area (under the shrubs and in the bare areas) were: depth to calcrete 64 cm, porosity 34%, –1/3 bar soil moisture 16% by volume, and –15 bar soil moisture 7% by volume (Romney and others 1973).

Data from 7 years of measurements on 8 vegetation quadrats (2 x 50 m) were used to estimate percent canopy cover for all species (25.2%) and standing crop for all species (2,440 kg/ha). Four dominant species (*Ambrosia dumosa, Grayia spinosa, Larrea tridentata,* and *Lycium andersonii*) make up 74% of the vegetative cover and 82% of the standing crop.

Daily precipitation and mean daily temperature data for 5 years, the above cited soil and vegetation characteristics, phenology, and seasonal LAI estimates were used as input to the hydrologic component of the CREAMS Model. No observed runoff or ET data were available; however, 60 observed monthly values of average soil moisture at 15 and 35 cm were used to calibrate the hydrologic component of the CREAMS Model by fitting observed and computed mean monthly soil moisture (Lane and others 1984). With n = 60, the regression equation between fitted (y) and observed (x) mean monthly soil moisture is $y = 1.3 + 0.85\,x$, with $R^2 = 0.93$.

Simulated daily water balance data were summed to obtain annual values of AT for the simulation period 1968 through 1976. Annual AT values were then multiplied by an estimated water use efficiency of Ke = 0.75 g d.m./mm to predict ANPP. Observed values of ANPP were available for 1968 and 1971 through 1976. With n = 7, the regression equation between predicted (y) and observed (x) ANPP is $y = 25.0 + 0.90\,x$, with $R^2 = 0.84$.

To interpret these results, we examine reduction in the width of the 95% confidence intervals (95% CI) on ANPP. Observed mean ANPP was 301 kg/ha and the 95% CI was (±154). Using mean annual precipitation in a regression equation ($R^2 = 0.51$), the mean of 301 kg/ha was preserved and the width of the 95% CI was reduced to (±124) or 19%. Using the CREAMS Model and the estimated water use efficiency factor the mean of 301 kg/ha was preserved and the width of the 95% CI was reduced to (±72) or 53%.

Although 7 years of data represents a small sample of weather and ANPP, the results suggest that the water balance-water use efficiency procedure explains more than 80% of the variation in mean ANPP and is a significant improvement over using annual precipitation as a regression predictor.

To illustrate the uncertainty in ANPP estimates further, Turner and Randall (1989) corrected and revised the 7 years of ANPP data from Rock Valley and added two additional years of data not available to Lane and others (1984). The most significant result of their reanalysis was that to fit the corrected and additional data (n = 9), the Lane and others estimates of ANPP would have to be increased by about 21%. This bias of 21% is significant, but not unexpected when basing model predictions on only 7 years of data. Plant productivity studies in arid areas should be of sufficient duration to accurately predict ANPP (surely >7 years in this case) and should be based on experimental designs that incorporate our knowledge of water balance simulations and the affects of climatic variation on ANPP in arid areas such as Rock Valley.

Discussion of Applications and Limitations

.Based on the example and the previous discussion, it is possible to suggest potential applications of the water balance-water use efficiency approach related to prediction of ANPP. These applications include:

1) Screening experimental designs for field studies of abiotic-biotic interactions affecting ANPP. In particular, estimating annual variability in ANPP to determine sampling protocols and sizes.

2) Assessing the influence of climatic variability on ANPP.

3) Determining the influence of soil properties (depth, texture, water holding capacity, hydraulic conductivity, and so forth) on ANPP.

4) Predicting expected productivity for mapping and inventory assessment of vegetation resources. A specific application might be to estimate ANPP for a spatially referenced data base (GIS) in the presence of limited, and point,

measurements of ANPP but more extensive and spatially referenced soil and climate data.

The main weakness of the water balance-water use efficiency approach is that it poorly represents plant physiology and is weak in reflecting feedback and the impacts of land use and management on plant productivity. Specific limitations include:

1) The procedure is weaker in more humid climates where water is less often the limiting factor for plant growth and survival.

2) The procedure accounts for water and temperature stresses, but ignores plant stresses such as nutrient deficiency, toxicity, competition, fire, and herbivory.

3) Land use and management practices that are not strongly reflected in their impacts on LAI (leaf area index) and soil properties are not well represented.

Summary and Discussion

Plant productivity is often estimated using precipitation, evapotranspiration, or transpiration as a predictor for plant water use. Improving estimates of plant productivity by using transpiration as a predictor instead of precipitation represents increasing sophistication at the expense of increasing complexity. Plant transpiration-based calculations represent a more process-based approach in terms of climate, hydrology, and soil water dynamics.

Hydrologic models are used to calculate a water balance and estimate evapotranspiration, which can be separated into evaporation and transpiration components. The water balance approach accounts for first order environmental effects in plant productivity and is adequate for many applications. The water balance approach can be used for screening, experimental design including determining the length of records needed to sample climatic variability, and analysis of soil properties affecting plant productivity. However, it does have limitations. Stresses from nutrient deficiency, competition, herbivory, disease, and so forth are not directly considered. The approach is process-based in terms of climate, hydrology, and soil water dynamics, but is empirically based in terms of biological activities.

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