THE TRANSITION OF THE BLANEY-CRIDDLE FORMULA TO THE PENMAN-MONTEITH EQUATION IN THE WESTERN UNITED STATES

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Abstract

This paper reviews the history of calculating "consumptive water use," later termed evapotranspiration (Et), for plants in the western U.S. The Blaney-Criddle formula for monthly and seasonal consumptive water use was first developed for New Mexico in 1942 for limited crops. The formula was based on the input of monthly mean air temperature and an empirical monthly/seasonal coefficient. Subsequent changes improved the Blaney-Criddle formula by adding more weather and crop variables. The availability of data from automated weather stations, after about 1980, that measure more weather input variables has allowed the empirical Blaney-Criddle formula to be replaced by the mechanistic standardized Penman-Monteith equation with an appropriate crop coefficient to calculate Et. The Penman-Monteith equation calculates Et under non-stressed conditions and represents the maximum Et and associated yield of the crop.

Water rights in the western U. S. have historically, and continue to be, adjudicated using variations of the Blaney-Criddle formula. The Blaney-Criddle formula, derived in farmers' fields under water stress conditions, calculates an Et that is most closely related to average county yields during the years the measurements were taken. But the empirical relationship and the originally derived coefficients are outdated and invalid for today's agriculture production systems and should be replaced with the Penman-Monteith equation when adjudicating water rights.

1. Literature Review

a. Formula development of Evapotranspiration equations

The consumptive water use divided by the water application efficiency is the general approach used to calculate the water requirements of a crop. The term “consumptive water use” was replaced in the literature by “evapotranspiration (Et),” a term more descriptive of the water sources involved, which are the amount of water evaporated from the soil and transpired by the plant per unit area (Jensen, M. E. 1990). Irrigation requirements are determined by subtracting the rainfall that contributes water to the evapotranspiration process, termed “effective rainfall” from the estimated Et.

A large number of evapotranspiration formulas were developed from 1942 to 2005 (table 1) to calculate water uses of crops starting with the development of the Blaney-Criddle formula (BC) and ending with the Penman-Monteith equation that became the American Society of Civil Engineers (ASCE) Standardized Reference Et equation. This equation is the current recommended equation that should be used to calculate the evapotranspiration rate from a non-water stressed crop. The history of the development of these formulas is discussed in the following sections of the paper.

The Blaney-Criddle formula was first developed from soil moisture depletion and air temperature and humidity measurements in alfalfa, cotton, and deciduous trees in farmers’ fields by Blaney and Criddle in the Pecos River, Roswell-Artesia area of New Mexico (Blaney et al. 1942b, Blaney et al. 1950). Measurements in other western states and crops, including potatoes, corn, and small grains in Colorado were later made to extend the formula’s usefulness (Blaney and Criddle 1962). During these periods, water limitations resulted in crops that were regularly stressed for water. Therefore the consumption use values did not represent a non-water stressed condition. The originally published Blaney-Criddle formula included a relative humidity parameter (Blaney et al. 1942). But due to the lack of relative humidity

Table 1. Time table for the development of evapotranspiration equations used in the western US.

Dates	*Event*
1942	Blaney-Criddle (BC) formula was first published from measurements of Consumptive Water Use (CWU) in alfalfa, cotton, deciduous trees in the NM Pecos River Valley (Blaney et al. 1942a)
1942-1962	Measurements of CWU on other crops in other western states (Blaney and Criddle 1962)
1947	Hargreaves formula was developed. It used crop coefficient.
1948	Penman equation was published that is based on Energy and Aerodynamic balance.
1950	BC Formula was simplified leaving out humidity parameter due to lack of measurements at most weather stations.
1958	BC Formula(s) was first used in water rights adjudication (USDI-BIA,1958)
1963	Jensen-Hays formula was developed and used solar radiation and calculated “reference Et”.
1970	USDA SCS modified to reflect crop growth stage and included an empirical “climatic” parameter as the temperature parameter. (USDA SCS 1970)
1975	Modified Penman equation was published for use by Food and Agriculture Organization of the United Nations (FAO) (Doorenbos and Pruitt 1975)
1975	FAO Blaney-Criddle formula was made compatible with crop coefficients developed with the modified Penman equation.
1998	Penman equation was modified to Penman-Montieth (P-M) formula .
2005	P-M equation becomes ASCE Standardized Reference Et equation

data throughout the western United States, a simplified formula excluding the humidity parameter was published in 1950 where the monthly or seasonal consumptive water use (Et) of a crop, in inches was:

$$Et = k_c \times \sum F \quad (1)$$

$$F = (T \times p) / 100 \quad (2)$$

The monthly consumptive water use factor (F) is the mean monthly temperature (T) in Fahrenheit times the monthly percent of daytime hours (p) divided by 100. The crop coefficient k_c is an empirical seasonal factor relating the seasonal plant water usage for a specific crop to the total seasonal consumptive water use factor generated under experimental conditions where k_c can be calculated from measured F and Et. The formula can be applied on a monthly basis by calculating F for each month and scaling it by a monthly k_c, which is dependent on the growth development rate of the crop. Consequently, the Blaney-Criddle formula applies to both seasonal and monthly consumptive water use calculations.

In 1970, the USDA Soil Conservation Service (USDA SCS 1970) expanded the air temperature term to account for the different development rates in different climates so the monthly crop growth stage coefficient could be used throughout the western United States. They used a linear fit for the air temperature data and modified the original Blaney-Criddle formula to:

$$Et\ (\text{monthly}) = k_t \times k_c\ (T \times p / 100) \qquad (3)$$

where:
k_c is a monthly crop growth stage coefficient and k_t is a climatic coefficient related to the mean monthly air temperature (t):

where: $k_t = 0.0173t - 0.314$, with a minimum value of 0.300. (4)

Temperature is again in degrees Fahrenheit and Et in inches. Crop development and the monthly crop growth stage coefficients are different under different climate conditions and the rate of development is related to the seasonal progression, measured by growing degree day that have occurred since planting (Sammis et al. 1985).

During this same time period, the Hargreaves equation was developed from research on consumptive water use conducted in California (Hargreaves 1947). This equation also uses air temperature and a crop coefficient to calculate consumptive water use and was modified by Hargreaves and Samani (1982). Hargreaves adapted his equation to calculate consumptive water use requirements for any location around the world where air temperature data was available (Hargreaves and Allen 2003).

In the 1960s, the energy available to evaporate water was included as an important factor. Jensen and Haise (1963) used the additional climate measurement of solar radiation as the measurement of the energy available for evapotranspiration:

$$Et_r = C_T \times (T - T_x) \times R_S \quad (5)$$

where: Et_r = reference Et is in energy units of langleys per day (41.84 kJ/m2). To convert to inches per day multiply by 0.000673,
R_S = solar radiation in langleys per day,
T = mean air temperature in degrees F,
T_x = a temperature axis intercept with a value of 26.4, and
C_T = an empirical coefficient with a value of 0.014 referenced to alfalfa.

The terminology of reference evapotranspiration was used at that time, with the two major reference crops being fescue grass (maintained at a height of 0.15 m and under non-stressed conditions) and alfalfa. Equation 5 is reference Et for alfalfa. The actual Et for different crops is calculated by multiplying equation 4 by the daily, monthly or seasonal crop coefficient after calculating the reference evapotranspiration for that time period or by accumulating the daily values of Et for the desired time period.

In 1948 the Penman equation was published (Penman 1948) for calculation of potential evapotranspiration (Et_o) based on the energy and aerodynamic balance mechanisms:

$$Et_o = \{\Delta \times R_n + \gamma \times [6.43 \times (1 + (0.536 \times U_2))] \times (e_s - e_a)] / [(\Delta + \gamma) \times L]\} \quad (6)$$

where: Eto= mm/day,
Δ=slope of the saturated vapor pressure curve (kPa K^{-1}),
R_n= net radiation (MJ m^{-2} day^{-1}),
γ = psychrometric constant (kPa K^{-1}),
U_2= wind speed at 2 m (m s^{-1}),
e_s = saturation vapor pressure (kPa),
e_a = actual vapor pressure (kPa), and
L= latent heat of vaporization (MJ kg^{-1}).

It required air temperature, humidity, solar radiation, and wind speed data. The equation has two components: the radiation component controls Et by providing energy to drive the Et process and the wind and vapor pressure deficit component controls the rate of transport of water vapor from the plant and soil surface and the capacity of the air to absorb water vapor. The original Penman equation calculates evaporation for an open water surface and reference evapotranspiration for grass. The equation has different scaling coefficients depending on the reference surface.

Because the climate data was not available to apply this equation in the western United States, it was not used to adjudicate water rights. However by the 1980s automated weather stations were developed that measured the climate parameters to calculate Penman's equation. The first automated weather network was installed in New Mexico and a form of Penman's equation was used to calculated reference Et for grass. The information was placed on the Internet first as a bulletin board site and then later as a web site. In addition to measured data of these climate parameters, the National Weather Service (NWS) produces 7-day forecast climate data for these parameters on a 5-km grid, except for solar radiation, which can be estimated by Doorenbos and Pruitt (1975) from clear sky radiation and percent cloud cover, which is predicted by the NWS. Consequently, the forecast climate data can be used to predict the Et of a crop up to 7 days in the future and can be used to estimate the Et at a location where the weather station has failed for a short time period or where no automatic climate station exists.

The Penman's equation was modified by Doorenbos and Pruitt (1975) for the purpose of using the approach to calculate crop water requirements around the world for Agriculture Organization of the United Nations (FAO) although the adaption of the formula is limited by the availability of the climatic data. The equation is called the modified Penman's equation because the coefficients in the equation are different than those published by Penman in 1948. The modified Penman's equation was referenced to grass, and the FAO24 version (Doorenbos and Pruitt 1975) had coefficients in it that represented the water use of grass in the dry advective conditions of the southwestern United States.

Because most water rights had been adjudicated by this time in the western U. S. using the Blaney-Criddle formula, Doorenbos and Pruitt (1975) provided another modification of the Blaney-Criddle formula, which is generally referred to as the FAO Blaney-Criddle (Et_{BC})

$$Et_{BC} = A_B + B_B \times (p \times (0.46T + 8)) \quad (7)$$

where: Et_{BC} = reference crop (clipped grass) Et in mm/day,
T = mean temperature over the period in degrees C,
p = mean daily percentage of total annual daylight hours for the period, and
A_B, B_B = adjustment factors based on minimum relative humidity, sunshine, and daytime wind speed estimates (exact values of he input parameters are not required but can be based on estimates for an area).

This modification to the Blaney-Criddle formula was made to make the formula compatible with the modified Penman's reference Et equation so that crop coefficients developed for modified Penman's equation (Doorenbos and Pruitt 1975) could be used with $Et_{BC.}$

The Penman's equation was again modified in FAO 56 (Allen et al. 1998) to be the Penman-Monteith equation:

$$Et_o = \{[\Delta \times (R_n - G)] + [p_a \times c_p \times (e_s - e_a) / r_a]\} / \{[\Delta + \gamma] \times [1 + (r_s / r_a)]\} \quad (8)$$

where: R_n = net radiation,
G is the soil heat flux,
(e_s - e_a) represents the vapor pressure deficit of the air,
ρ_a is the mean air density at constant pressure,
c_p is the specific heat of the air,
Δ represents the slope of the saturation vapor pressure temperature relationship,
γ is the psychrometric constant, and
r_s and r_a are the (bulk) surface and aerodynamic resistances.

Equation 7 when solved for a constant value for r_s and r_a under non moisture stress conditions converts to equation 9:

$$Et_o = \{[0.408 \times \Delta \times (R_n - G)] + [\gamma \times (900 / (T+273)) \times U_2 \times (e_s - e_a)]\} / \{(\Delta + \gamma) \times (1 + 0.34 \times U_2)\} \quad (9)$$

where: ET_o = (mm day^{-1}),
R_n =net radiation at the crop surface (MJ m^{-2} day^{-1}),
G =soil heat flux density (MJ m^{-2} day^{-1}),
T =mean daily air temperature at 2 m height (°C),
U_2 =wind speed at 2 m height (m s^{-1}),
e_s =saturation vapor pressure (kPa),
e_a =actual vapor pressure (kPa),
(e_s - e_a)=saturation vapor pressure deficit (kPa),
Δ =slope vapor pressure curve (kPa °C^{-1}), and
γ =psychrometric constant (kPa °C^{-1})

which has evolved into the Standardized Reference Evapotranspiration equation used today for either a short reference crop (similar to clipped grass, 0.12 m tall) Et_o or tall reference crop (similar to full-cover alfalfa, 0.5 m tall) Et_r (Allen et al. 2005). In a study comparing the different reference Et equations, the Penman-Monteith equation was found to be more consistent over a wider range of climatic conditions than the other equations (Allen et al. 2005). Because of the many different forms of Blaney-Criddle, Jensen and Haise, Penman, and Penman-Monteith equations, a crop coefficient used in these formulas is unique to the formula and cannot be used with the other formulas without adjustment. By definition, the crop coefficients for Et calculations are derived under non-stressed conditions where water, fertilizer, insects, and salinity do not limit crop growth and production. In many cases these non-stressed condition were not met when deriving the crop coefficients and consequently, the crop coefficients of many crops have been adjusted upward as new measurements of Et have occurred under better irrigation scheduling conditions in the research fields.

The crop coefficient concept has not only the problem of it being unique to the reference Et formula use but the change in the crop coefficient over time can be a function of days since planting, percent cover or growing degree days, and future research is needed to reconcile which should be the standard method of calculating the change in the crop coefficient over time.

b. Limitation of Blaney-Criddle equation vs. Penman-Monteith equation

At the time of the original consumptive water use research conducted by Blaney and Criddle and Hargreaves, it was thought that there was only one daily, monthly or seasonal Et value for a given location, and that this value was only dependent on the evaporative demand of the air, expressed by the consumptive water use factor which was an estimate of the potential evapotranspiration rate, and the crop coefficient which scaled the potential evapotranspiration rate by the percent cover of the crop. When plants are under any form of stress, stomata close causing Et and photosynthesis to decrease, with a subsequent decrease in total biomass produced by the crop. This stomata closure results in an increase in r_s in the Penman-Monteith equation which can be used to calculate the Et directly if the r_s value is known. Consequently, there is not one estimated Et value for a crop at a given location; instead, there are many values each with a different r_s value depending on the degree of stress to the plant. Experimental evidence from Hanks et al. (1976) in Utah using a sprinkler line source demonstrated that a linear Et function existed, which relates Et to yield or biomass up to a maximum value of Et called the evapotranspiration production function. The maximum Et is controlled by the evaporative demand of the air and the available energy for the evapotranspiration process, both accounted for in the Penman and Penman-Monteith equation. An example of a derived alfalfa evapotranspiration production function from a lysimeter study in New Mexico is presented in Figure 1 (Sammis 1981).

Based on the measured evapotranspiration functions, the original Blaney-Criddle consumptive water use measurements represented an average yield and Et for an area, which is less than the Et value for maximum yield computed using the modified Penman's or Penman-Monteith equations or measured from lysimeter studies (Sammis et al. 1982). As an example, alfalfa Et calculated using the Blaney-Criddle formula shows a comsumptive water use of 38-39 inches at Artesia, NM. After subtracting effective rainfall, it has a crop irrigation requirement of 28 inches (Table 2). The Et of alfalfa from the lysimeter study at Artesia, NM was 72 to 75 inches for the year and 60 inches during the growing season, with a yield of 12.6 ton/ac, considerably greater than the average county yields of 5.34 t/ac. The original Blaney-Criddle seasonal crop co-efficient was 0.85 and the lysimeter-measured seasonal crop coefficient was 1.36, almost 60% greater than that reported by Blaney and Hanson (1965). Et using the Blaney Criddle calculations is 24% to 42% lower than the non-stressed Et values resulting in a corresponding decrease in yield.

Table 2. Non-Stressed Et and Blaney-Criddle Et (Et_{BC}) of selected crops in New Mexico.

Crop	Maximum monthly crop coefficient (k_c) *	Growing Season non-stressed Et (inches)	Growing Season Et_{BC} (inches)	Reference	Ratio of non-stressed Et/Et_{BC}
Alfalfa	1.25	60	38-39	Sammis 1981	1.53
Barley	1.2	26	16	Kallsen et al. 1984	1.63
Cotton	1.25	35	26	Sammis 1981	1.35
Corn	1.25	39	23	Kallsen et al. 1983	1.69
Sorghum	1.15	36	23	Sammis et al. 1985	1.56
Chile	1.25	37	-	Wierenga 1983	
Onions	1.1	39	-	Al-Jamal et al. 1999	
Potatoes	-	27	-	Boman 1983	
Pecans	1.2	48	-	Wang et al. 2007	

* Crop coefficient calculated from measured Et and the Penman's equation defined by Sammis 1981.

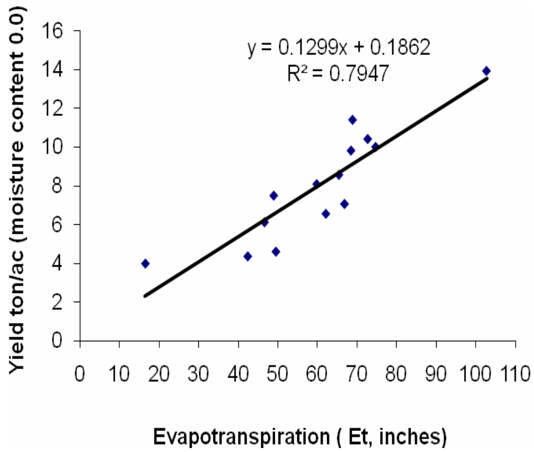

Figure 1. Evapotranspiration production function for alfalfa using only lysimeter data in New Mexico (redrawn from figure in Sammis 1981).

When crop coefficients are calculated for the modified Penman's equation, the peak crop coefficients have a very small range of variation, from 1.15 for sorghum to 1.2-1.25 for all other crops. With no soil moisture stress even desert creosote plants will transpire water and have a maximum crop coefficient of 1.2 (Saucedo et al. 2006).

The crop coefficients in New Mexico are based on the modified Penman's equation but because the Penman-Monteith equation was found to be more consistent over a wider range of climatic conditions than the other equations, consequently, most State Climatology web sites now use that standardized equation to calculate reference evapotranspiration which can then be multiplied by the appropriate crop coefficient to calculate actual Et. However, in New Mexico and other states, the older methods of calculating evapotranspiration are also presented so that the published crop coefficients for those states can continue to be used. However, in the future crop coefficients should be reported in the literature referenced to the new Penman-Monteith equation (Allen et al. 2005).

2. Discussion

Applications of Et equations

Water rights in the western United States have been adjudicated based on the water requirements of crops grown in those states. Water rights based on consumptive water use values divided by irrigation efficiency were adjudicated using the Blaney-Criddle or SCS Blaney-Criddle method of computing consumptive water use in New Mexico (Klett 2002), Montana (Amman et al. 1998), California (U.S. Department of Interior Bureau of Indian Affairs 1958), Colorado (U.S. Supreme Court. 2003), and Colorado River States (U.S. Department of Interior Bureau of Reclamation 1976). An irrigation water application efficiency of 50% was used in many cases when water rights were adjudicated.

In New Mexico, the State Engineer is responsible for adjudicating water rights in the state and, consequently, has supported research in the evapotranspiration of crops since the original work conducted by Blaney-Criddle. The State Engineer's Technical Report 32, "Consumptive Use and Water Requirements in New Mexico" by Blaney and Hanson (1965), uses the Blaney-Criddle formula to calculate the consumptive water use requirements of crops in all the major crop growing locations in the state for which crop coefficients were known. The report was updated by Henderson and Sorensen (1968) to include addition location in New Mexico. The report also presented a table of consumptive water use minus effective rainfall values or crop irrigation requirement (CIR) for selected locations throughout the state.

Effective rainfall was calculated by Blaney and Hanson (Figure 2) based on the method developed by Blaney and Criddle (1962) for each location. But these calculations are difficult to quantify, and currently effective rainfall is calculated using the SCS curve number (USDA 1986). This equation, unlike figure 2, requires knowledge of the hydrologic soils group and the antecedent rainfall conditions which is not always available. Other methods are also used

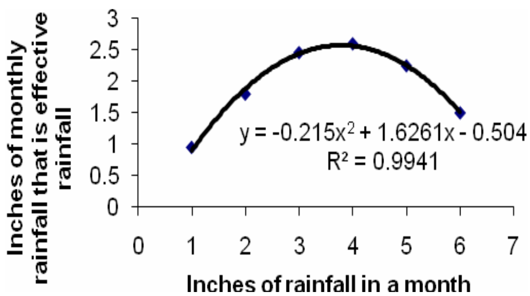

Figure 2. Effective monthly precipitation as a function of total precipitation

to calculate effective rainfall include using the different rainfall infiltration functions or other empirical effective rainfall functions. Consequently, deciding which method to use to calculate effective rainfall when computing irrigation requirements is still an area where a standardized method needs to be developed.

By 1976, the New Mexico Water Resources Research Institute had funded new studies to determine non-stressed Penman crop co-efficients for field crops using non weighing lysimeters (Sammis 1981). Yields were measured, along with the monthly and seasonal Et for alfalfa, barley, corn, cotton, sorghum, wheat, sudangrass, and bluegrass. Following the lysimeter studies, evapotranspiration production functions were determined using a sprinkler line source (Hanks et al. 1976) to derive the Et yield relation under stress conditions for alfalfa and cotton (Sammis 1981), barley (Kellsen et al. 1984), corn (Kellsen et al. 1983), onions (Al-Jamal et al. 1999), and chile (Wierenga 1983). The sprinkler line source data was combined with the lysimeter data to produce a complete evapotranspiration production function. The evapotranspiration production function relates Et to yield and not total biomass. Consequently, the function can vary from year to year depending on climate condition that determine the harvest index or the ratio of yield /total biomass or when the water stress occurs such as during the critical flowering period (Doorenbos and Kassam 1979).

The problem still exists that water allocation based on old Blaney-Criddle coefficients resulted in less water allocation than calculations based on the modified Penman and Penman-Monteith equations. State judicial courts are reluctant to use the modern methods and crop coefficients to calculate water rights because of previous court case precedents, but the Blaney-Criddle formula and the originally derived coefficients are outdated and invalid for today's agriculture production systems and should be replaced with the Penman-Monteith equation when adjudicating water rights.

Irrigation management using irrigation scheduling tools and a change in irrigation technology from flood to micro irrigation can increase water application efficiency (Sammis et al. 1986; Sammis et al. 1990; Asare et al. 1992; Asare et al. 2001) to use the allocated water more efficiently, but currently farmers still practice deficit irrigation resulting in decreased yields but high irrigation efficiency (75 to 82%) (Al-Jamal et al. 1997). Irrigation efficiencies of 75 to 82% can reduce yield below maximum (Wierenga 1983; New Mexico Agricultural Statistics Service 1996) but is practiced by farmers achieving average county yields. Reallocation of the available water to a smaller land base may be more economical in parts of New Mexico where effective rainfall is low. In general low value crop land is being converted when possible to high value crop so that profits per acre are increasing even though limited water and management prevent most farmers from achieving maximum yield.

3. Conclusion

This paper reviews the history of calculating consumptive water use (evapotranspiration, Et) for crops in the western U.S. The Et formulas have been used for irrigation and water rights management and yield prediction. The older Blaney –Criddle type formulas calculate an Et compatible with average county yields. The most commonly used formula today is the standardized reference Et for short grass or tall crop. It is calculated from the Penman-Monteith equation multiplied by a crop coefficient. This formula with the appropriate crop coefficients calculates a non-stressed Et related to maximum yield. Currently the climate data to calculate either Penman's or the Penman-Monteith equation are readily available from automated climate stations. In addition, the NWS forecast climate data can be used to predict 7-day Et.

Regulatory structures that deal with water rights adopted the methodologies from the 1940s and have not changed. A demonstration of the new methods compared to older methods shows that there are enough differences to argue for the regulatory structures to adopt the modern methods. Also, additional research is needed on developing crop coefficients that use the Penman-Monteith equation when calculating Et and a standardized method of calculating the time base for the crop coefficients preferably based on a growing degree day concept.

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