UPDATED PROCEDURES FOR CALCULATING STATE-WIDE CONSUMPTIVE USE IN IDAHO

Richard G. Allen[1]
Clarence W. Robison[2]
James L. Wright[3]

ABSTRACT

Evapotranspiration and net irrigation water requirements were determined for 123 weather station locations across the state of Idaho for available periods of record. Estimates were made for daily, monthly and annual timesteps. Updated methods were employed for calculating reference evapotranspiration (ET_r) and crop coefficients (K_c). The ET estimates cover a wide range of agricultural crops grown in Idaho and, in addition, ET estimates have been made for a number of native plant systems including wetlands, rangeland, and riparian trees. Estimates have been made for evaporation from three types of open water surfaces ranging from deep reservoirs to small farm ponds. The ET and net irrigation water requirement calculations are intended for use in design and management of irrigation systems, for water rights management and consumptive water rights transfers and for hydrologic studies. ET calculations have been made for all times during the calendar year including winter to provide design and operation information for managing land application of agriculture, food processing and other waste streams. The weather stations evaluated include 107 National Weather Service (NWS) cooperative stations measuring primarily air temperature and precipitation and 16 AgriMet agricultural weather stations. The AgriMet stations measure a full compliment of weather data affecting evapotranspiration and are located primarily in the southern part of the state. Estimates at many stations cover more than 80 to 100 year periods of air temperature data. Because only maximum and minimum air temperature are observed at the NWS cooperative stations, the solar radiation, humidity and wind speed data parameters required in the ASCE Penman-Monteith equation (ASCE-PM) were estimated similar to recommendations in ASCE-EWRI (2005) where estimates for solar radiation (R_s) were based on differences between daily maximum and minimum air temperature and estimates for daily dewpoint temperature were based on daily minimum air temperature. Estimates for wind speed were based on long-term mean monthy summaries from AgriMet stations in southern Idaho and some airport locations in central and northern Idaho. Crop evapotranspiration, abbreviated ET_c, was calculated on a daily timestep basis for improved accuracy. Daily calculation timesteps allowed for the calculation of evaporation of water from wet soil surfaces following precipitation or irrigation events. ET_c for monthly, growing season and annual periods were summed from the daily calculations. Basal crop coefficient curves were developed or organized for 42 crop and land-cover types. Scheduling of irrigations was simulated to estimate soil evaporation from irrigation wetting events using a root-zone water balance.

---

[1]Professor of Water Resources Engineering, University of Idaho, Kimberly, Idaho 83341. RAllen@kimberly.uidaho.edu
[2] Research Associate, University of Idaho, Kimberly, Idaho 83341
[3] USDA-ARS (ret), Kimberley, Idaho 83341

INTRODUCTION

Evapotranspiration and net irrigation water requirements have been computed for this report on a daily, monthly and annual basis for 123 weather station locations across Idaho for available periods of record. These calculations supersede calculations previously made for Idaho by Allen and Brockway (1983) and use updated methods for calculating both reference evapotranspiration (ET_r) and crop coefficients (K_c). The ET estimates represent a wide range of agricultural crops grown in Idaho and ET estimates have been made for a number of native plant systems including wetlands, rangeland, and riparian trees. Estimates have been made for three types of open water surfaces ranging from deep reservoirs to small farm ponds. ET calculations have been made for all times during the calendar year including winter to provide design and operation information for managing land application of agriculture, food processing and other waste streams. Specific details are given in Allen and Robison (2007). All data results are available via internet from www.kimberly.uidaho.edu/ETIdaho. The report can be downloaded from that site.

Crop evapotranspiration, ET_c, are needed for design and management of irrigation systems, for water rights management and consumptive water rights transfers and for hydrologic studies. Daily calculation timesteps allow for the calculation of evaporation of water from wet soil surfaces following precipitation or irrigation events. ET_c for monthly, growing season and annual periods were summed from the daily calculations.

Evapotranspiration Calculation Approach

The calculation procedure utilizes the crop coefficient – reference ET method, where a reference ET_r is multiplied by a crop coefficient. The reference ET_r represents ET from a defined, fully vegetated surface, in this case, full-cover alfalfa, and incorporates the influence of weather on the ET quantity. The K_c is defined as the ratio of actual or potential ET by a specific crop or land-cover condition to ET_r. The K_c therefore incorporates plant and cultural factors that cause ET to vary from ET_r. These factors are typically related to stage of vegetation development and wetting by irrigation or precipitation. The K_c ET_r method is widely used due to its simplicity, reproducibility, relatively good accuracy, and transportability among locations and climates. The method, when applied carefully, can produce estimates of ET that are sufficiently accurate for irrigation systems design and operation.

Reference Evapotranspiration

Reference ET has been historically calculated using a number of calculation equations and for both grass and alfalfa reference type, depending on the region of the country and local tradition. In Idaho, Allen and Brockway (1983) used the FAO-24 Blaney-Criddle equation as a reference, where the equation was calibrated to alfalfa reference ET_r using the Wright and Jensen (1972) version of the Kimberly Penman equation. The AgriMet system in southern Idaho has traditionally applied the Wright (1982) version of the Kimberly Penman, often referred to as the 1982 Kimberly Penman, which is also an alfalfa reference. Based on recent work by ASCE-EWRI (2005) on standardizing the reference ET definition and calculation for use across the United States and their recommendation to use the ASCE standardized Penman-Monteith method for standardized congruency among states and regions, we have selected the ASCE standardized Penman-Monteith for the alfalfa reference calculation. The ASCE-PM ET_r method has been shown to compare well against lysimeter measurements of alfalfa ET at Kimberly, Idaho (Wright et al., 2000) and at Bushland, Texas (Wright et al., 2000, Todd et al., 2000). Crop coefficients developed at Kimberly for the 1982 Kimberly Penman method were converted for use with the ASCE-PM-ET_r method (Allen and Wright, 2002). An alfalfa reference ET_r was utilized for consistency with historical and current practice in Idaho. In addition, the rougher aerodynamic properties of the alfalfa reference provide for more consistent values for the K_c values for a wide variety of crops and over a wide range of weather conditions (as opposed to those for grass reference bases) and the K_c values for the alfalfa reference often peak at 1.0.

The ASCE-EWRI (2005) standardized PM method for reference ET_r can be applied to either alfalfa or grass references and has the form:

$$ET_r = \frac{0.408\,\Delta (R_n - G) + \gamma \dfrac{C_n}{T+273} u_2\,(e_s - e_a)}{\Delta + \gamma (1 + C_d\, u_2)} \qquad (1)$$

where ET_r is the standardized reference ET for full-cover, 0.5 m tall alfalfa or for short (0.12 m tall clipped, cool season grass) surfaces (mm d^{-1} for daily time steps or mm h^{-1} for hourly time steps), R_n is calculated net radiation at the crop surface (MJ m^{-2} $d^{-1}$for daily time steps or MJ m^{-2} h^{-1} for hourly time steps), G is soil heat flux density at the soil surface (MJ m^{-2} d^{-1} for daily time steps or MJ m^{-2} h^{-1} for hourly time steps), T is mean daily or hourly air temperature at 1.5 to 2.5-m height (°C), u_2 is mean daily or hourly wind speed at 2-m height (m s^{-1}), e_s is saturation vapor pressure at 1.5 to 2.5-m height (kPa), calculated for daily time steps as the average of saturation vapor pressure at maximum and minimum air temperature, e_a is mean actual vapor pressure at 1.5 to 2.5-m height (kPa), Δ is slope of the saturation vapor pressure-temperature curve (kPa $°C^{-1}$), γ is the psychrometric constant (kPa $°C^{-1}$), C_n is a constant that changes with reference type and calculation time step and C_d is a constant that changes with reference type and calculation time step.

For application on a daily timestep for the alfalfa reference, C_n= 1600 K mm s^3 Mg^{-1} d^{-1} and C_d = 0.38 s m^{-1}. Units for the 0.408 coefficient are m^2 mm MJ^{-1}. The values for C_n consider the time step and aerodynamic roughness of the surface and C_d considers the time step, bulk surface resistance, and aerodynamic roughness of the surface. C_n and C_d were derived by simplifying several terms within the 'full' ASCE-PM equation of ASCE Manual 70 (Allen et al., 1989, Jensen et al., 1990) and rounding the result.

Most National Weather Service (NWS) locations report observations on a 24-hour time step basis, only. Therefore, the 24-hour calculation timestep for ET_r was applied. Daily air temperature data have been utilized in calculations to provide for better within-month sensitivity than if monthly mean data were utilized. Because only maximum and minimum air temperature are observed at the NWS cooperative stations, the solar radiation, humidity and wind speed data parameters required in the ASCE-PM equation were estimated similar to recommendations in ASCE-EWRI (2005), where estimates for solar radiation (R_s) were based on differences between daily maximum and minimum air temperature and estimates for daily dewpoint temperature were based on daily minimum air temperature. However, in this study, the Thornton and Running (1999) procedure was used for R_s rather than the Hargreaves-Samani (1982) method described by ASCE-EWRI.

a. *Daily solar radiation:*
The Thornton and Running (1999) procedure was used to estimate solar radiation where:

$$R_s = R_{so}\left[1 - 0.9 \; exp\left(- B\left(T_{max} - T_{min}\right)^{1.5}\right)\right] \tag{2a}$$

$$B = 0.023 + 0.1 \; exp\left(- 0.2 \; \Delta T_{month}\right) \tag{2b}$$

where R_s is estimated daily solar radiation, R_{so} is theoretical solar radiation on a clear day (R_{so} is computed using exoatmospheric radiation computed as a function of latitude and date and the ASCE-EWRI (2005) atmospheric transmissivity function), T_{max} is daily maximum air temperature and T_{min} is daily minimum air temperature in ^oC. Units for R_s and R_{so} are the same. Parameter ΔT_{month} in Eq. 2b represents long term average values for T_{max} and T_{min} on a monthly basis. The coefficients for Equation 2b were developed during this study using data from Thornton and Running for western locations. The use of Eq. 2a and 2b replaced the use of the Hargreaves and Samani (1982) equation that was suggested by ASCE-EWRI (2005), where $R_s = 0.16\ (T_{max}-T_{min})^{0.5}\ R_a$. Eq. 2a and 2b produce more consistent and accurate estimates of R_s on a daily and monthly basis across southern Idaho than does the Hargreaves-Samani equation, relative to measurements of R_s recorded at Idaho AgriMet weather stations. An additional advantage of Eq. 2a is that it is self limited to a maximum value R_s represented by R_{so}.

b. *Dewpoint temperature*
Dewpoint temperature, T_{dew}, was estimated from daily minimum air temperature:

$$T_{dew} = T_{min} - K_o \tag{3}$$

where T_{min} is daily minimum air temperature (^oC) and K_o is an offset that varied monthly as shown in Table 1. The K_o offsets were based on long-term records of dewpoint and T_{min} averaged from about ten AgriMet weather stations across southern Idaho and varied by month. Negative values during winter indicate that the 24-hour average T_{dew} exceeded T_{min} due to condensation of moisture during nighttime (i.e., frost, etc.) that allows T_{min} to decline with a declining nighttime T_{dew}.

Table 1. Values for dewpoint temperature offset, K_o, (^oC) to estimate T_{dew} in Idaho.

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
-2	-1.5	0	1.5	1.5	1.5	1.5	1.5	1.5	1	-1	-2

c. *Wind speed*
Long term monthly average wind speed data were derived from regional weather stations that collected wind speed data. In southern Idaho, the nearest AgriMet station was used, and in central and northern Idaho a nearest NOAA airport weather station was used. Values varied by month.

Comparisons were made between daily ET from full cover alfalfa measured by lysimeter and reference ET estimated using dewpoint, solar radiation and wind speed data as described in steps a, b, and c. Results indicate that the estimation of these parameters tends to preserve the bulk variance of the original (measured) population of reference ET. Therefore, probability levels based on reference ET computed using these estimates are generally valid. Comparison of estimated vs. measured weather data at a number of AgriMet weather stations is detailed in Allen and Robison (2007) and indicated relatively good estimation accuracy. An example for daily and monthly estimation of solar radiation is shown in Figure 1 for the Picabo AgriMet weather station. Weather data for the 107 NWS stations used for ET_c were comprised of daily maximum and minimum air temperature and precipitation, along with observations of snowfall and snow cover depth (Figure 2). These data are officially collected and housed by the National Climatic Data Center (NCDC) of the National Oceanic and Atmospheric Administration.

Evapotranspiration from Crops and other Land Surfaces

The crop coefficient, K_c, has been developed over the past half-century to simplify and standardize the calculation and estimation of crop water use. The K_c is defined as the ratio of ET from a specific surface to ET_r. The specific surface can be comprised of bare soil, of soil with partial vegetation cover, or of full vegetation cover. The K_c represents an integration of effects of crop height, crop-soil resistance and surface reflectance that distinguish the surface from the ET_r definition and value. The value for K_c often changes during the growing season as plants grow and develop, as the fraction of ground covered by vegetation changes, as the wetness of the underlying soil surface changes, and as plants age and mature.

Two approaches to K_c have historically been applied in Idaho and elsewhere. The first approach uses a ‘mean’ K_c where all time-averaged effects of evaporation from the soil surface are averaged into the K_c value. The mean K_c represents, on any particular day, average evaporation fluxes expected from the soil and plant surfaces under some ‘average’ wetting interval (by rain or irrigation). The second K_c approach is the ‘dual’ K_c method, where the K_c value is divided into a ‘basal’ crop coefficient, K_{cb}, and a separate component, K_e, representing evaporation from the soil surface. The basal crop coefficient represents ET conditions when the soil surface is dry, but with sufficient root zone moisture present to support full transpiration. The K_e component is calculated separately, according to actual or simulated wetting events and is then added to the K_{cb} to produce the total K_c. Generally, a daily calculation time-step is required to apply the dual K_c method. This study applied the dual crop coefficient approach due to its ability to better quantify evaporation from precipitation and irrigation event.

Actual ET_c may be less than potential ET_c when soil water content is less than that able to sustain full rates of evapotranspiration. In this case, ET_c is reduced by applying a stress coefficient, K_s. The form of the equation for actual ET_c with the dual K_c approach is:

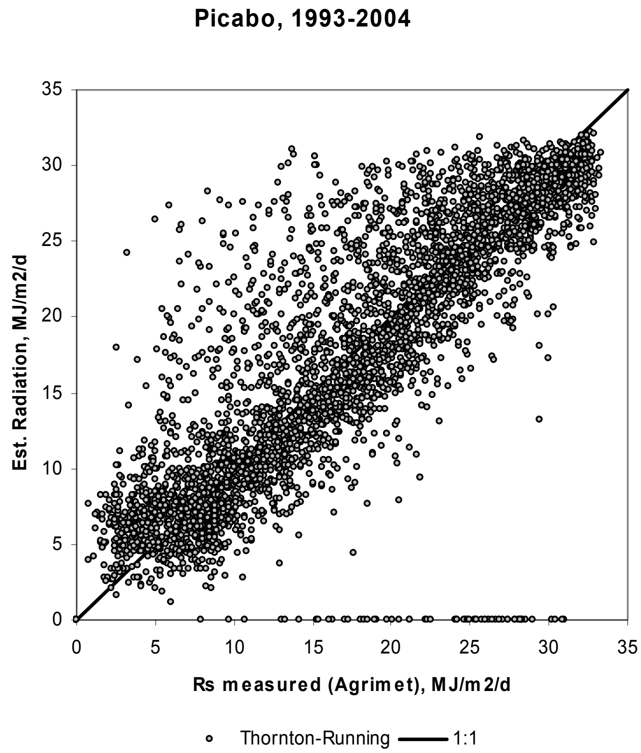
$$ET_{c\ act} = \left(K_s\, K_{cb} + K_e\right) ET_r \qquad (4)$$

where K_{cb} is the basal crop coefficient [0 - ~1.0 when used with ET_r], K_e is a soil water evaporation coefficient [0 - ~1.0 when used with ET_r], and K_s is a reduction coefficient that reduces the value of K_{cb} when the average soil water in the root zone is not adequate to sustain full plant transpiration. K_s = 1.0 when there is no water stress. All K terms are dimensionless.

The soil water balance incorporates the full effective root zone as simulated on a particular date during the growing season. A second and separate soil water balance is required to estimate K_e. In this latter water balance, only the water content of the upper 0.1 m of soil is simulated, since it is this upper soil layer that supplies water for direct evaporation from the soil surface. The daily water balance calculations and the calculation of K_s and K_e follow directly the procedure established in the FAO-56 publication (Allen et al., 1998) and extended by Allen et al., (2005). Departures from the Allen et al., (2005) procedure were made for the Idaho application to account for use of alfalfa reference ET_r rather than grass reference ET_o that is generally applied with the FAO-56 procedure. In addition, curvilinear K_{cb} curves similar to those used by Wright (1982) were used rather than the linear-style of curves generally used by FAO. Therefore, equations for estimating $K_{c\ max}$ and basal K_{cb} are different from those in the 2005 publication. When used with alfalfa ET_r, no weather-based adjustments to $K_{c\ max}$ nor K_{cb} are necessary.

The Crop Coefficient Curve. The crop coefficient curve represents the changes in K_c or K_{cb} over the course of the growing season, depending on changes in vegetation cover and maturation. During the initial period of the growing season, shortly after planting of annuals or after the initiation of new leaves for perennials, the value of K_{cb} is small, often only 0.1 to 0.15 for a dry soil surface (with some moisture at greater depth). When combined with soil evaporation, the total K_c value averages generally less than about 0.4 during the initial period. As the crop begins to develop more and more leaf area and cover more of the soil surface, the K_{cb} curve increases. Late in the growing season, the K_{cb} declines due to aging of leaves or senescence (dying) of leaves. A daily soil water balance is required to calculate K_s, since its value can change daily as soil water declines.

Examples of calculated K_{cb} and $K_{c\ actual}$ curves ($K_{c\ actual} = ET_{c\ actual} / ET_r$) are shown in Figure 3 for a crop of spring wheat and potatoes during the 2004 calendar year near Ashton, Idaho. The $K_{c\ actual}$ traces include the evaporation (K_e component) that appear as 'spikes' above the K_{cb} curves following precipitation and irrigation events. The $K_{c\ actual}$ during winter time peaked at about 0.6 for the spring wheat crop that was assumed to have a mulched soil surface during the nongrowing season. The $K_{c\ actual}$ reduced to about 0.4 when snow cover was present (January-February). Peaks in $K_{c\ actual}$ during winter were reduced when snow cover was noted to account for higher reflectance of the snow. $K_{c\ actual}$ was below K_{cb} when soil stress was estimated to occur during the nongrowing season or prior to initiation of irrigation (generally begun when $K_{cb} > 0.22$). The higher frequency of irrigation of potatoes (caused by a more shallow root zone than for the spring wheat crop) created more evaporation losses from the soil surface as evidenced by the large number of K_e 'spikes' above the K_{cb} curve. The duration of K_e spikes (time-wise) tends to increase during spring and fall as weather cools and more days are required to dry the soil surface. Even though the value estimated for $K_{c\ actual}$ was relatively high during the nongrowing season, the actual ET rate was relatively low (bottom of Figure 3) due to the low value for reference ET_r, which represents the drying power of the atmosphere and energy available for evaporation.



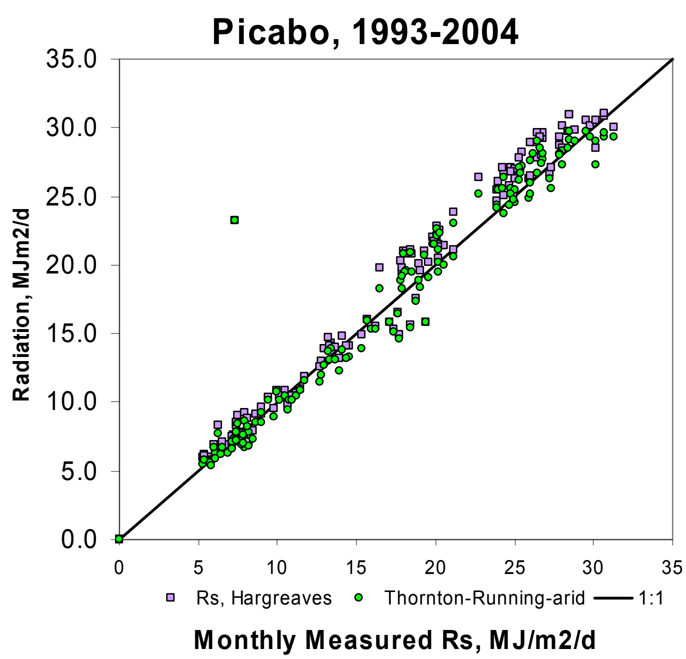


Figure 1. Daily estimated R_S (using the Thornton-Running (with Eq. 2a and 2b) (top) and monthly (bottom) vs. measured R_S from a nearby AgriMet station at Picabo, ID over the period of record.

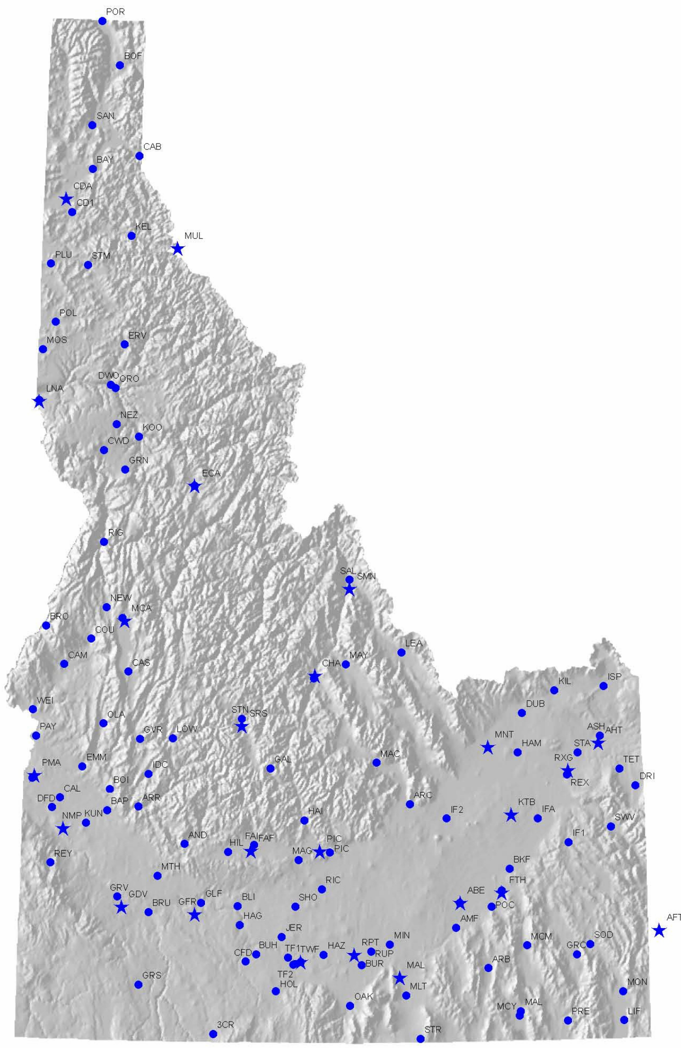


Figure 2. Locations of National Weather Service air temperature stations (circles) and AgriMet full weather stations in southern Idaho and airports used in north and central Idaho for wind (stars).

Application of K_{cb} Curves for a Variety of Locations and Periods of Record. In this study, starts and durations of growing seasons for most crops were determined year by year according to mean air temperature over 30-day periods prior to the start date and in proportion to growing degree days following the start of season. Growing seasons were terminated by estimated maturation date for the crop or by a killing frost. To allow K_{cb} curves to be 'stretched' differently each year, according to weather conditions, the base K_{cb} curves were expressed on relative time scales or relative thermal unit scales. Four different methods were used to express the base K_{cb} curves. These were 1) percent time from planting (or greenup) to harvest; 2) percent time from planting to effective full cover, with this ratio extended until termination; 3) percent time from planting to effective full cover and then days after full-cover; and 4) percent cumulative growing degree days from planting to effective full cover, with this ratio extended until termination. Basal crop coefficient curves were developed or organized for 42 crop and land-cover types. The K_{cb} curves of Wright (1982) that describe the eight most common crops in southern Idaho were converted to normalized cumulative growing degree days (NCGDD), which is method 4 above. K_{cb} values for sagebrush, cheatgrass and bunchgrass were developed based on vegetation index trends from Landsat images. The derived K_{cb} curves represent potential K_{cb} under conditions of readily available soil moisture. The K_{cb} values were reduced for nonirrigated vegetation or during nonirrigation periods using the K_s stress coefficient estimated from a soil water balance. All K_{cb} curves are described in Allen and Robison (2007).

Cumulative growing degree days (CGDD) since planting are commonly used as a basis for crop coefficient development (Sammis et al., 1985, Slack et al. 1996, Howell et al. 1997, Mitchell 1997, Snyder et al. 1999, Wright, 2001, deTar, 2004, Marek et al., 2006, Nebraska-HPCC, 2006) to adjust lengths of growth periods to account for variation in temperature among years and to facilitate transfer of crop coefficients among regions. Plant functions of growth, photosynthesis, water and nutrient absorption and transport, enzyme activity, and other biological and chemical activities are regulated by temperature. Thus, crop development is more closely related to the amount of heat the crop is exposed to than calendar days.

A wide range of computation methods for growing degree days (GDD) are in use. These include the standard method used for corn (maize):

$$GDD_{corn} = \frac{max(min(T_{max},30),10) + max(min(T_{min},30),10)}{2} - 10 \qquad (5)$$

where T_{max} is daily maximum air temperture, ^oC and T_{min} is daily minimum air temperature, ^oC. The standard corn equation is often referred to as a heat unit equation and is also known as the '86/50' method, referring to the maximum threshold of 30^oC and minimum threshold of 10^oC, which are 86 and 50 ^oF. The GDD equation for corn assumes no growth at air temperatures above 30^oC and no negative 'penalty' for growth if the minimum temperature goes below 10^oC.

A common, basic formula[4] for computing daily growing degree days (GDD) for most crops besides corn is to average daily maximum and daily minimum air temperatures for each day and subtract a minimum average daily temperature (base temperature) required for growth to proceed. There is no penalty applied when T_{max} exceeds a threshold, as is done with corn, and no 'boost' is given to T_{min} when it is lower than the minimum threshold, as is the case for corn. The basic equation for the general GDD is:

$$GDD = max\left(\frac{T_{max} + T_{min}}{2} - T_{base}, 0\right) \tag{6}$$

where T_{base} is the base temperature. When T_{min} is far enough below T_{base} to cause the average daily temperature to go below T_{base}, then GDD = 0. Days having high T_{max}, but T_{min} below T_{base} are estimated by Eq. 6 to have lower growth rates than by Eq. 5, where T_{min} is 'boosted.' Wright (2001) suggested that Eq. 6 is realistic for many crops in semiarid climates such as Idaho, where cold nighttime temperatures can retard growth during daytime even when mid day temperatures are high. In the K_c curve conversion, Eq. 5 was applied to corn for consistency with standardized usage within the U.S. and Eq. 6 was applied to all other crops.

Winter Wheat. Winter wheat crops were simulated through the winter for purposes of estimating K_{cb} during winter. For winter wheat, some adjustments were made periodically to the CGDD that was accumulated since Oct. 1 to account for impacts of extremely cold weather that can retard growth for a few days or even 'burn' vegetation. In computing CGDD for the fall, winter and early spring periods for winter wheat, the following adjustments were made that apply to winter wheat only:

- Whenever T_{min} was < -25°C and there was no documented snow cover present, 10% of the established canopy was assumed to be frost burnt. This impact was enacted by reducing any CGDD accumulated since Oct. 1 for the winter wheat by 10% on the day following the low temperature.
- Whenever T_{min} was < -10°C then the GDD for the following day, if greater than 0, was reduced by 5 GDD units. This was done as a sort of retardation penalty to growth of winter wheat on the day after a cold freeze. GDD on all days was limited to 0 or greater.
- If T_{min} was < -4°C on a day, then GDD for that day was assumed to be zero, regardless of the value for T_{max} or T_{mean}. This was done as a sort of delay penalty to growth of winter wheat on the day of cold temperature. The no growth on days where T_{min} < -4°C is based on observations by (Wright, 2002, pers. comm.).

[4] For example, this formula is used by the Canola-Council (http://www.canola-council.org/gdd.aspx), Mitchell (1997) and Wright (2001).

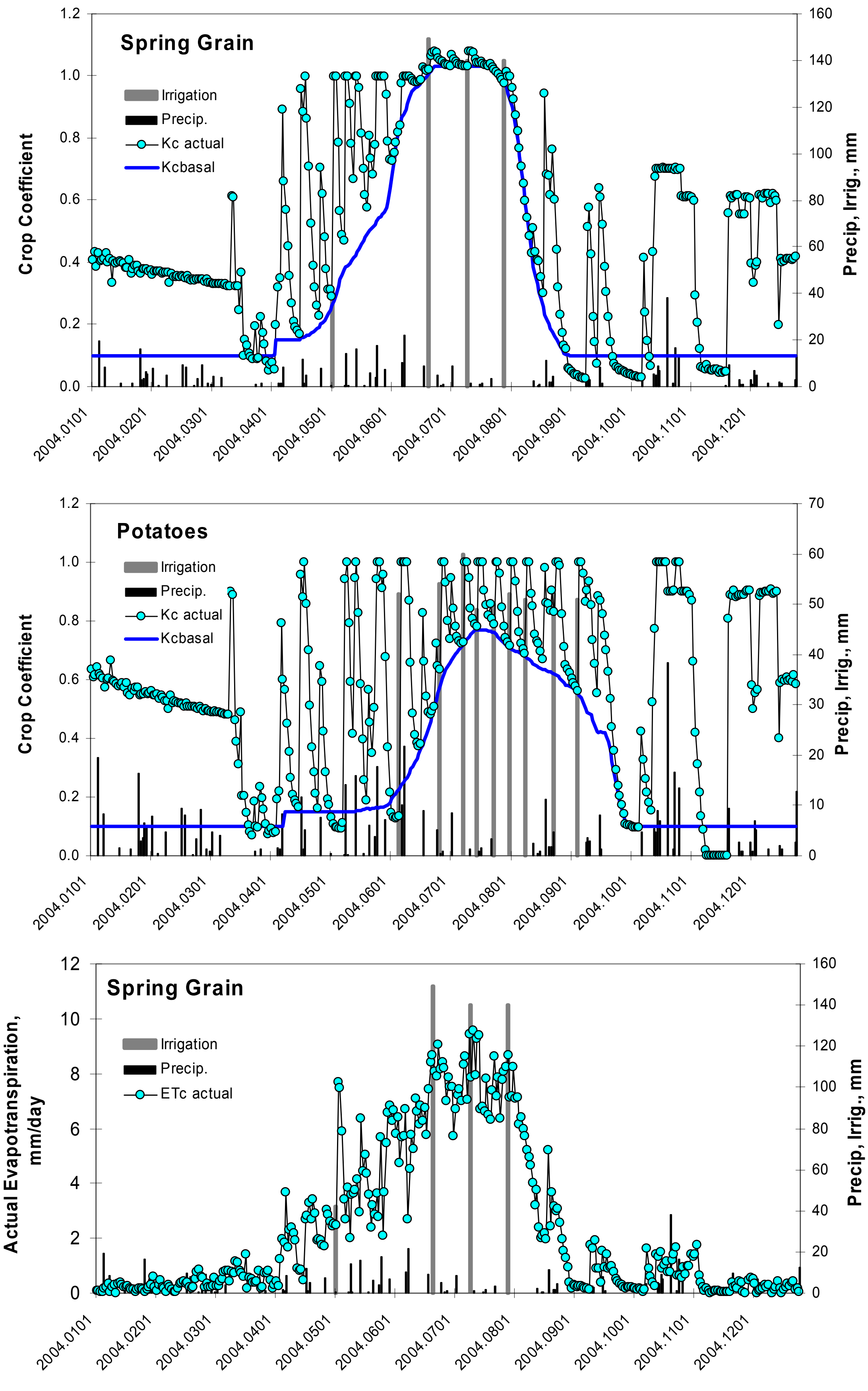


Figure 3. Example K_{cb} ('Kcbasal') and K_c actual curves for spring wheat and potato crops near Ashton, Idaho during 2004. Simulated irrigation events are shown as vertical bars. The K_c actual traces include the evaporation (K_e component) that appear as 'spikes' above the K_{cb} curves following precipitation and irrigation events. Also shown in the bottom figure is daily actual ET_c for the spring grain.

Normalization of Growing Degree Days. In normalizing the basis for K_{cb} curves, a normalized ratio NCGDD was calculated by dividing CGDD accumulated since planting (or greenup of alfalfa) by the $CGDD_{Planting\ to\ FC}$ where 'Planting to FC' is the period from planting to full cover. The NCGDD ratio is applied to the entire season or cutting cycle until either CGDD exceeds the value for $CGDD_{Planting\ to\ Terminate}$ that is in the table or a killing frost occurs. For alfalfa hay, K_c v. NCGDD curves were established for individual cuttings using data from Wright (1981, 1982) and lysimeter records for 1969-1971 period at Kimberly. Separate K_c vs. NCGDD were developed for the first growth period, for intermediate growth periods, and for the final growth period prior to frost. Unique K_c v. NCGDD shapes were established for these three periods. The NCGDD values for the first growing cycle are accumulated beginning at greenup of the crop in spring, and from the time of cutting for all subsequent growth cycles. Green up was estimated for alfalfa using CGDD since January 1 with temperature base of 0^oC. A CGDD of 240 ^oC-days from Jan. 1 was used to signal greenup, based on Kimberly data and observations across southern Idaho. No penalties were applied to CGDD of alfalfa as was the case for winter wheat. Figure 4 shows a summary of the K_{cb} curves of Wright (1982) after conversion to the NCGDD basis. NCGDD = 1.0 generally indicates the time of effective full cover.

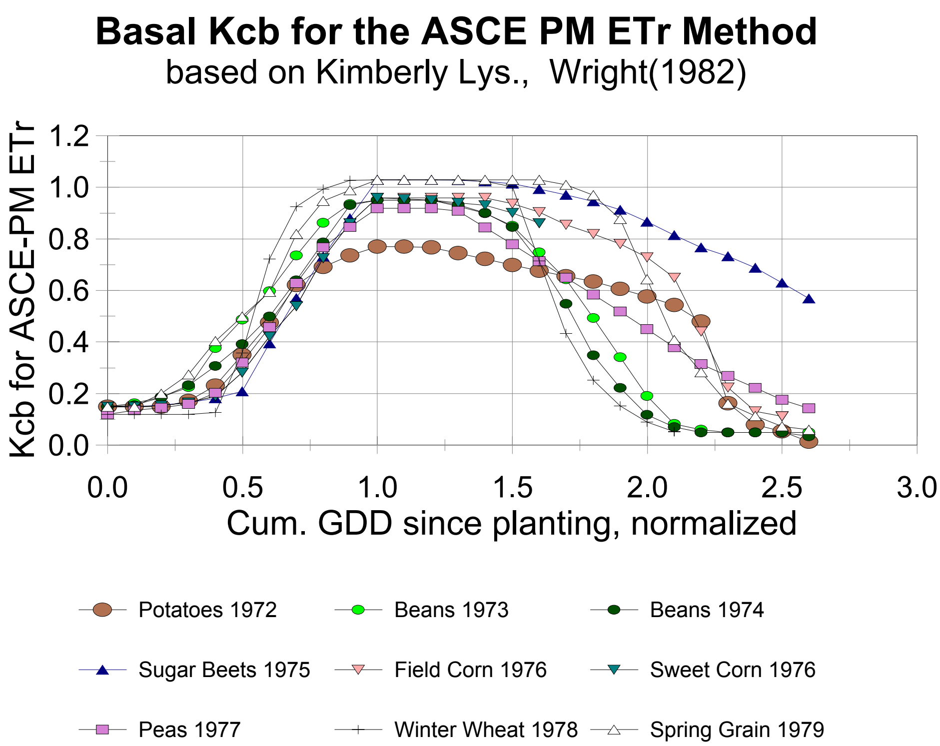


Figure 4. K_{cb} curves of Wright (1982) converted to the normalized cummulative growing degree-day basis (NCGDD).

Open Water Evaporation

Evaporation from open water was estimated for this Idaho study since water bodies are a common component of hydrologic systems and of irrigation supply systems. A special study of evaporation from the American Falls Reservoir was conducted by the University of Idaho during

2003-2005 where micrometeorological, Bowen Ratio and eddy covariance equipment was set up on the reservoir during one growing season (Allen and Tasumi, 2005). Measurements from that study were used to develop and calibrate aerodynamic procedures that were applied with air temperature data, only, to estimate evaporation from deep water bodies. In this study, evaporation was estimated for three classes of open water:

small, shallow stock ponds – K_c = 0.7 was used for all months

large, shallow water bodies or deep water bodies that have high turbidity – K_c = 0.6 for all months. This class may be generally applicable to *relatively shallow* (< 4 m in depth) *ponds, reservoirs and streams*

deep systems (relatively clear lakes and reservoirs deeper than 4 m) – use aerodynamic algorithms developed for American Falls Reservoir (Allen and Tasumi, 2005).

The evaporation estimates for small, shallow stock ponds were the highest of the three categories to account for the impact of generally shallower water on radiant energy absorption closer to the surface and thus generally higher surface temperature for these systems. In addition, shallow ponds tend to have more turbidity and thus higher surface temperature. The evaporation estimations assume that no freezing occurs. If water systems are known to freeze, then the evaporation rate will tend toward zero during the periods of ice cover.

Evaporation during Wintertime

Evaporation during nongrowing (wintertime) periods varies widely, based on availability of moisture, freezing of soils, snow cover, impacts of surface organic mulches (dead vegetation) and availability of energy for evaporation. Quantification of winter time evaporation is important when performing hydrologic water balances and when estimating effectiveness of wintertime precipitation in recharging the soil profile to supply water to vegetation during the subsequent growing season. Evaporation losses during winter, following soil wetting events, reduces the effectiveness of precipitation in recharging soil profiles.

Few studies have measured and documented wintertime evaporation. Wright (1991, 1993) conducted a series of wintertime measurements of evaporation using the dual precision weighing lysimeter systems at Kimberly. Figures 5 and 6 show mean K_c values derived by Wright (1991) that correspond to evaporation during nongrowing (winter) seasons at Kimberly over a six year period from 1985 – 1991. The lysimeter surface conditions included clipped fescue grass on one lysimeter that was dormant during the winter period and various ‘bare soil’ conditions on the other lysimeter representing soil conditions between annual agricultural crops. The bare soil conditions included disked wheat stubble, disked alfalfa, disked soil, alfalfa and winter wheat.

The basis for the mean K_c values in the figures is the ASCE-PM method. The ASCE PM alfalfa reference ET_r standard represents 0.5 m tall green alfalfa, even during winter (the crop is a hypothetical potential reference). Therefore, under even wet conditions, the K_c during winter time is not expected to reach 1.0. Mean K_c (K_{cm}) did approach or exceed 0.8 during Dec. 1988 - Mar. 1989 for the disked soil, a period having a nearly continuous distribution of precipitation. The data by Wright (1993) were used to guide the development of procedures for estimating wintertime evaporation for application throughout the state.

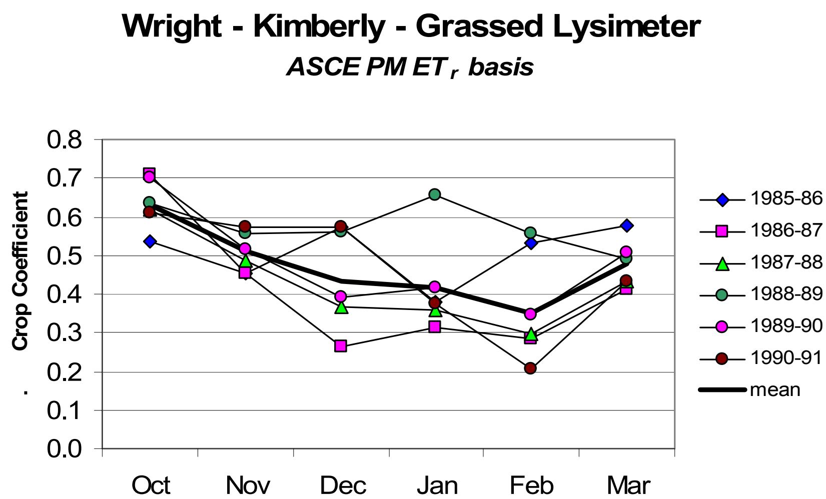


Figure 5. Mean monthly K_c measured by Wright (1993) from a grassed (dormant) lysimeter during nongrowing periods at Kimberly, Idaho converted for use with the ASCE Penman-Monteith alfalfa reference ET_r equation.

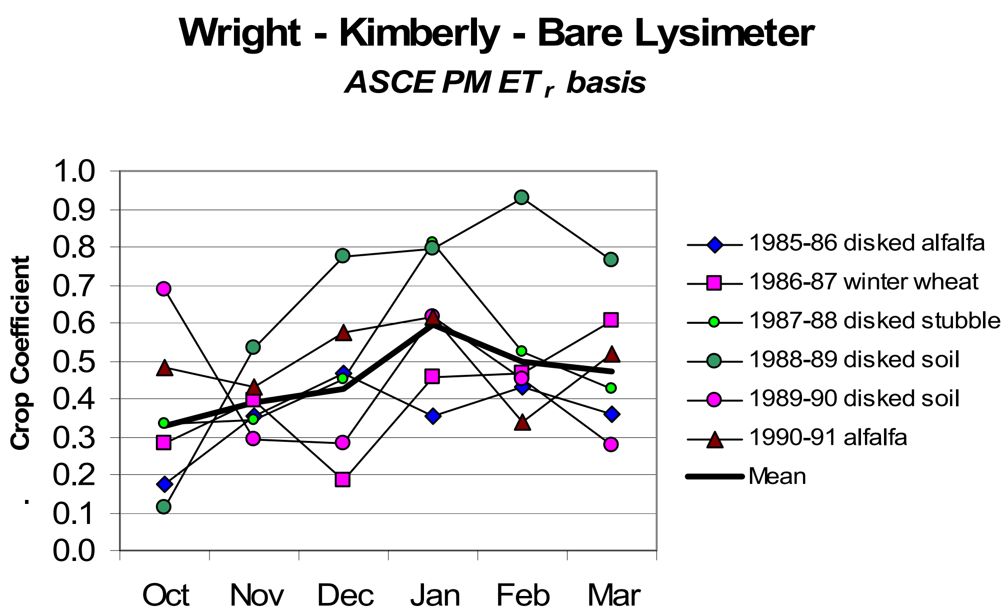


Figure 6. Mean monthly K_c measured by Wright (1993) during nongrowing periods at Kimberly, Idaho for various types of surface cover, converted for use with the ASCE Penman-Monteith alfalfa reference ET_r equation.

The nongrowing season (winter) period was defined as the period beginning at the end of a K_{cb} curve representing the growing cycle for a specific crop or the occurrence of a killing frost, and ending at greenup or planting of the same crop the following year (or Oct. 1 in the case of winter wheat). In estimating K_c for nongrowing season periods, a basal K_{cb} = 0.1 was used for bare soil conditions, for surfaces covered with some amount of mulch, and for dormant turf/sod systems. The K_{cb} represented conditions when these surfaces had a dry soil surface, but with sufficient moisture at depth to supply some diffusive evaporation. The evaporation (K_e) component was estimated separately in the daily soil water balance, where $K_{c\ max}$ during the nongrowing period was set at 0.9 for bare soil, 0.85 for mulched surfaces and to 0.8 for dormant grass cover. The lower value for grass is to account for insulative effects of the grass and higher albedo. The use of a low value for K_{cb} permits the K_e function in the daily calculations to increase the value for total K_c according to wetting frequency by rain and snow. An effective 'rooting zone' of 0.10 m was used for the fraction of surface under the cover. For all surfaces, a daily soil water balance was conducted and a stress coefficient is applied when soil water content drops below a critical value for the upper 0.10 to 0.15 m. Thus, actual K_c reduced below K_{cb} when both the ground surface and subsurface soil were dry. All land use types, including agricultural, landscape, horticultural and natural vegetation, were assigned one of the three winter cover conditions (dormant grass, bare soil or mulch classes) for estimating evaporation losses during winter.

Snow cover information was used to adjust the K_c ($K_{c\ max}$) value to account for higher albedo of snow and absorption of heat by melt by multiplying by a $K_{c\_multiplier}$. The following algorithms were applied:

$$K_{c\_multiplier} = 1 - K_{radiation\_term\_winter} + \frac{(1 - albedo_{snow})}{(1 - albedo_{surface})} K_{radiation\_term\_winter} \qquad (7)$$

where $K_{radiation\_term\_winter}$ represents the weighting of (or contribution to) winter time reference ET estimates by the radiation term of the Penman-Monteith method, $albedo_{snow}$ is the mean albedo of snow cover and $albedo_{surface}$ is the mean albedo of the bare surface. $K_{radiation\_term\_winter}$ is equivalent to:

$$K_{radiation\_term\_winter} = \frac{\Delta}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)} \qquad (8)$$

where Δ is slope of the saturation vapor pressure-temperature curve, γ is the psychrometric constant, r_s is surface resistance to vapor flow and r_a is aerodynamic resistance to heat and vapor flow above the surface. The intent of Eq. (7) is to adjust the ET_r estimates by the Penman-Monteith method, which is parameterized to estimate ET for a vegetated surface to those that would have occurred from snow cover. The primary adjustment is for albedo of the surface, which is higher for snow cover. For ease of calculation, $K_{radiation\_term\_winter}$ was calculated as a function of day of year based on a relation derived using full years of Kimberly weather data and the ASCE standardized Penman-Monteith equation:

$$K_{radiation\_term\_winter} = 2.2E-08\ J^3 - 2.42E-05\ J^2 + 0.006J + 0.011 \quad (9)$$

An additional reduction in evaporation of 30% was made to account for absorbed latent heat of fusion of any melting snow prior to evaporation. Albedo of snow was set at 0.8 in calculations and albedo of the surface was set to 0.25.

Estimating Beginning and End of Growing Seasons

The greening (greenup) of perennial vegetation in spring can be strongly impacted by short-term weather conditions, primarily by air temperature and to some degree by wetting events and general amounts of solar radiation. Strong correlation exists between air temperature, wetness and cloudiness and in general, air temperature can be used as a predictor of when perennial vegetation begins to greenup in spring. In the same manner, planting dates for annual crops are impacted by general temperature conditions. Planting is strongly influenced by soil temperature at seed depth and some relationships have been established for some crops. However, soil temperature is not commonly measured at cooperative NWS weather stations and is available at regional types of stations only. Therefore, 30-day average mean daily air temperature has been used as a surrogate for soil temperature due to the strong correlation between soil temperature and air temperature over an extended period.

The use of a thirty-day running average mean air temperature (T_{30}) to estimate planting of annual crops was investigated using the lysimeter and cropping records at Kimberly, Idaho. The use of 30-day average temperature is similar to that of the SCS TR-21 (1967) where that publication listed typical mean monthly values for air temperature to signal planting and greenup of crops. However, some of those dates, for example, for alfalfa green up do not estimate well for Idaho. The T_{30} temperatures from SCS TR-21 were for dates centered on the 30 day periods, rather than for dates at the end of the 30 day periods, as used in this study. Specific values by Allen and Robison (2007) are listed in Table 2.

Table 2. 30-day mean air temperatures (for the 30-day period prior to the noted date) for Magic Valley crops associated with Wright (1982) dates for lysimeter crops, and also associated with Allen-Brockway (1983) planting dates and from field notes taken by Allen (pers. comm.) between 1999 and 2005, and comparisons with SCS TR-21.

Crop	Year	Plant Date	30-day T (C) ending on date	Equiv. 37 yr ave. date	Recomm. T_{30} to use, ^oC	Mean date over 37 yr. for Recommended T_{30}	TR-21 T_{30m}*, ^oC
based on Wright (1982):							
Barley or S.Wht	1979	4/1/79	4.8	4/3	4.7	4/2	7
Peas	1977	4/10/77	4.4	3/31	5	4/4	
S.Beets	1975	4/15/75	2.1	3/12	5 (8)**	4/4 (for 5^{o}C)	-2 frost
Potatoes	1972	4/25/72	6.0	4/14	7	4/20	16
Corn	1976	5/5/76	7.9	4/29	8 (10)**	4/29 (for 8^{o}C)	13
Beans	1973 1974	5/22	12.5 12.3	5/30	12 (14)**	5/27 (for 12^{o}C)	16
based on Allen-Brockway (1983):							
Pasture	Mean	4/3	4.8		5	4/4	7
Orchards	Mean	4/15			6	4/13	10
Veges.	Mean	5/20			10	5/14	
Onion	Mean	4/20			6.5	4/17	

* The 30 day mean T_{30} value for TR-21 is for the period centered on the date, thus, $T_{30m} > T_{30}$.

** The value in parentheses was used in Allen-Robison (2007) calculations based on comparisons with METRIC results over the Magic Valley area of southern Idaho for year 2000 and based on other local observations of planting dates across southern Idaho.

During the estimation of planting or greenup dates for crops and natural vegetation, a “no earlier than” and “no later than” date was used to constrain the estimated dates to within realistic ranges based on expected behavior of farmers or the vegetation itself. For most crops this was +/- 40 days from the mean date based on a longterm average temperature. For alfalfa, better consistency in estimation of greenup in spring was found using cumulative growing degree days (CGDD) since January 1 rather than T_{30}. Based on a CGDD analysis of daily ET and leaf area and height development data for alfalfa for years 1969-1971 by Wright at Kimberly, CGDD = 240 ^{o}C using a 0^{o}C GDD basis was used to estimate greenup.

Adjustment of K_{cb} for Alfalfa During the Fall

For alfalfa, an additional adjustment was made to the computed K_{cb} during fall periods to account for effects of cold nighttime temperatures and occaisional light, but nonkilling frosts. The adjustment reduced the value for K_{cb} following the first occurrence of a -3^{o}C in the fall by 0.005 each day following the -3^{o}C temperature. This reduced the value for K_{cb}, for example, by 0.10 by the 20th day following the light frost. The killing frost temperature for alfalfa was -7^{o}C. Allen and Robison (2007) contain estimated killing frost temperatures for a wide range of crops and vegetation.

Comparison of Crop Evapotranspiration Products with Other Sources

Illustrative comparisons were made between seasonal ET_c calculated for this study and that reported by USBR AgriMet ET_c for 2000. Comparisons were also made with seasonal ET reported by Allen et al. (2007b) for crops in Magic Valley during year 2000 as determined using the METRIC satellite-based energy balance processing system (Allen et al. 2007a). Growing season ET_c is compared in Figure 7 for weather stations located near Twin Falls and Jerome, which are 30 km apart. The year 2000 was the focus of an intensive application of the METRIC satellite-based energy balance method for estimating ET over large areas. METRIC estimates actual ET for specific fields of crops using short wave and thermal images from the Landsat satellite.

The values shown for METRIC in Figure 7 were sampled from large numbers of fields in the Jerome and Twin falls counties from METRIC ET images of ET (and K_c) between the dates of March 15 and October 17 (Tasumi et al., 2005, Allen et al., 2007c). The METRIC derived images were integrated monthly and over the March 1 – October 31 period. The 'Allen-Robison (2007)' entries in Figure 7 represent ET_c determined in this study for the March-October 2000 period and are presented for ET_c calculations based on the Twin Falls 7E and Jerome NWS weather stations as well as based on data from the Twin Falls AgriMet weather station. The Twin Falls AgriMet weather station is collocated with the Twin Falls 7E NWS station at the USDA-ARS center near Kimberly. The 'Allen-Robison' ET_c calculations for the AgriMet station were made using reference ET_r based on a full complement of AgriMet weather data (solar radiation, air temperature, humidity and wind speed) whereas the Twin Falls 7E NWS ET_r calculations were based on daily air temperature and long-term mean monthly wind speed only. The 'AgriMet – Twin Falls – 2000" entry in Figure 7 represents growing season ET_c reported by the USBR AgriMet web site.

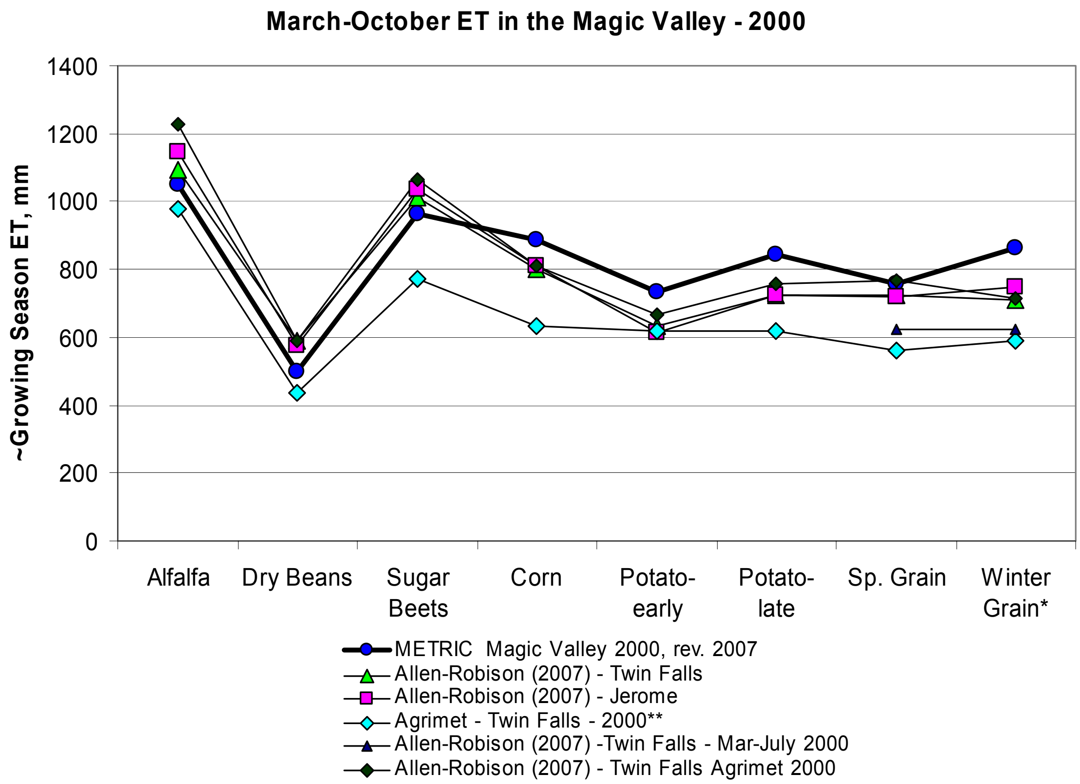


Figure 7. Growing season evapotranspiration during year 2000 for major crops grown in the Twin Falls – Jerome area of Magic Valley from four sources (1. METRIC satellite-based energy balance; 2. this study for Twin Falls 7E and Jerome NWS stations; 3. USBR AgriMet ET reports; and 4. this study using the Twin Falls AgriMet station data). The smaller triangles represent ET_c summed for spring and winter grain for the March – July 2000 period only.
**The AgriMet Twin Falls - 2000 entries were taken from the USBR AgriMet web site for year 2000 and represent calculations by the USBR.

The growing season ET_c from the new (Allen-Robison 2007) computations compared relatively closely with that determined by METRIC for alfalfa hay, sugar beets and spring grain. The new computations exceeded those by METRIC by a small amount for alfalfa hay, dry beans and sugar beets. The new computations were lower than those by METRIC for corn, early and late potatoes and winter grain. Growing season ET_c from the new computations (average of Twin Falls and Jerome stations) was within 7% of METRIC estimates for alfalfa hay, sugar beets and spring grain and all were within 16% of METRIC ET_c. The new estimates averaged about 16% above METRIC estimates for dry beans and 15-16% below METRIC estimates for winter grain and potatoes.

Reasons for the lower ET_c estimation by Allen-Robison (this study) for corn and potatoes, relative to METRIC may stem partly from the assumption of relatively low-frequency irrigation scheduling when simulating irrigation schedules during this study for estimation of soil evaporation. Corn crops tend to be irrigated by center pivot systems and potato crops by center pivots or by solid set sprinkler. Both of these system types tend to be operated so that irrigations are spaced more closely together in time than for wheeline or gravity systems. The consequence of this is more frequent wetting of the soil surface and somewhat higher total ET_c. This may explain some of the 10 to 15% difference between the two estimating approaches (this report vs. METRIC). The 16% underestimation for ET_c of winter wheat as compared to METRIC-produced ET_c appears to stem primarily from estimation of earlier crop development during early spring and earlier maturity and harvest in this study for year 2000 than observed by METRIC.

The AgriMet ET_c that was produced by USBR-AgriMet estimated about 7% below METRIC-derived growing season ET_c for alfalfa hay and 13-15% below METRIC for dry bean and early potato crops. AgriMet ET_c estimated 20-30% below METRIC for the balance of crops (sugar beets, corn, late potatoes, spring grain, winter grain). Agrimet estimated shorter growing periods for sugar beets and field corn, as reflected in the K_c curves for Magic Valley than observed by METRIC and earlier growing periods for winter and spring grain. An additional reason for the lower seasonal ET_c estimates by AgriMet is that their ET_c calculations do not begin until emergence (or greenup) and are discontinued at estimated harvest for annual crops. Therefore, evaporation from precipitation prior to and following the specific growing periods is neglected.

Runoff from Precipitation

Runoff during precipitation events is strongly influenced by soil texture, soil structure, sealing and crusting of the soil surface, land slope, local land forming (tillage and furrowing), antecedent moisture, precipitation intensity and duration. Generally, estimation of runoff during precipitation is fraught with uncertainty. For general purposes, runoff in this study was estimated using the USDA-NRCS Curve Number approach (USDA-SCS 1972), where antecedent soil moisture conditions were estimated in conjunction with the daily soil water balance used in estimating the soil water evaporation coefficient, K_e. Required data are daily precipitation.

Statistics and Time Series

Besides the daily, monthly and annual time series of ET_c that have been compiled, tables of statistics describing 30-year normals (means) for ET_c on monthly, growing season and annual bases have been developed. These tables include means, standard deviations and 20 and 80% exceedence values that describe the expected variation within the populations of ET_c. The statistics were computed for time period lengths of 3, 7, 15 and 30 days within each month. These period lengths were selected to encapsulate expected lengths of irrigation intervals or drying periods that are of interest in irrigation system design and operation.

The statistics were computed over the most recent 30 years of valid (nonmissing) data or over shorter periods if less than 30 years of valid data were available. The 30 year normal periods were used to generate statistics describing the behavior of the ET data rather than the entire periods of record for two reasons. One, lengths of records varied widely from station to station, ranging from as few as eight years at Magic Dam east of Fairfield (1966-1975) to 111 years at Oakley (1893-2004). Secondly, some trends in air temperature and consequently ET estimates have occurred over long periods of time. Some of these trends are caused by changes in relative dryness of the local or regional environment due to irrigation development or land-use change, by station location or relocation, or perhaps by change in overall climate. The last 30 years of usable record are considered to be the more representative of expected future conditions than prior periods. The full records for each station are preserved in the daily, monthly and annual time series files. Therefore, statistics for the full periods of record can be computed as needed from these series.

Time series and statistics have been compiled for the following four basic ET or precipitation parameters: a) actual evapotranspiration; b) potential evapotranspiration; c) basal evapotranspiration; and d) precipitation deficit (i.e., net irrigation water requirement). Actual ET values lie below potential ET values during periods of soil moisture stress in rainfed conditions, during nongrowing periods and occaisionally early in growing seasons prior to initiation of irrigation. The basal ET values represent ET when little or no free water evaporation from the soil surface occurs. The precipitation deficit represents the amount of (irrigation) water beyond any effective precipitation needed to sustain the potential ET rates. The new calculations for ET_c tend to agree with growing season totals presented by Allen and Brockway (1983) for primary agricultural crops and as observed by the METRIC satellite-based ET procedure.

REFERENCES

Allen, R.G. and C. E. Brockway. 1983. Estimating Consumptive Irrigation Requirements for Crops in Idaho, Research Technical Completion Report, Idaho Water and Energy Resources Research Institute, University Idaho, Moscow, ID 130 pages.

Allen, R.G. and C.W. Robison. 2007. Evapotranspiration and net irrigation water requirements for Idaho. Univ. Idaho reported submitted to Idaho Dept. Water Resources. 245 p. www.kimberly.uidaho.edu/ETIdaho.

Allen, R.G. and M. Tasumi. 2004. Evapotranspiration from Riparian Vegetation along the Middle Rio Grande Basin using METRIC™ ET Products. Report to Keller-Bliesner Engineering. University of Idaho Kimberly Research and Extension Center. 18 p.

Allen, R.G. and Tasumi, M.. 2005. Evaporation from American Falls Reservoir in Idaho via a Combination of Bowen Ratio and Eddy Covariance. Proceedings of the EWRI World Water and Environmental Resources Congress 2005: Impacts of Global Climate Change. May 15-19, 2005, Anchorage, Alaska, USA , 17 p.

Allen, R.G. and J.L. Wright. 2002 and 2006. Conversion of Wright (1981) and Wright (1982) alfalfa-based crop coefficients for use with the ASCE Standardized Penman-Monteith Reference Evapotranspiration Equation. Unpublished Univ. of Idaho report. 51 pages.

Allen, R.G., M.E. Jensen, J.L. Wright, and R.D. Burman. 1989. "Operational estimates of reference evapotranspiration." *Agron. J.,* 81:650-662.

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. *"Crop Evapotranspiration: Guidelines for computing crop water requirements."* Irrig. and Drain. Paper 56, Food and Agriculture Organization of the United Nations, Rome, 300 pp.

Allen, R.G., L.S. Pereira, M. Smith , D.Raes , and J.L. Wright. 2005. FAO-56 Dual Crop Coefficient Method for Estimating Evaporation from Soil and Application Extensions. *J. Irrig. and Drain. Engrg.,* ASCE 131(1):2-13.

Allen, R.G., M. Tasumi and R. Trezza. 2007a. Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC) – Model. ASCE *J. Irrigation and Drainage Engineering* (in press).

Allen, R.G., M. Tasumi, A.T. Morse, R. Trezza, W. Kramber, I. Lorite and C.W. Robison. 2007b. Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC) – Applications. ASCE *J. Irrigation and Drainage Engineering* (in press).

Allen, R.G., M. Tasumi, J.L. Wright, R. Trezza, I. Lorite, C. Robison. 2007c. Satellite-based ET mapping for agricultural water management: Estimating evapotranspiration by NDVI. In preparation for submission to *Ag. Wat. Man.*

ASCE – EWRI. (2005). The ASCE Standardized reference evapotranspiration equation. ASCE-EWRI Standardization of Reference Evapotranspiration Task Comm. Report, available at http://www.kimberly.uidaho.edu/water/asceewri/

BOR. 2005. AgriMet; The Pacific Northwest Cooperative Agricultural Weather Network, Bureau of Reclamation. Internet Article: http://137.77.133.1/pn/AgriMet/ (visited Feb. 2005).

DeTar, W. R. 2004. Using a subsurface drip irrigation system to measure crop water use. Irrigation Science 23(3): 111-122.

Hargreaves, G.H. and Z.A. Samani. 1982. "Estimating potential evapotranspiration." Tech. Note, *J. Irrig. Drain. Engrg.*, ASCE, 108(3):225-230.

Hargreaves, G.L., G.H. Hargreaves, and J.P. Riley. 1985. "Agricultural benefits for Senegal River Basin." *J. Irrig. Drain. Engrg*., ASCE 111:113-124.

Howell, T. A., Steiner, J. L., Schneider, A. D., Evett, S. R., and Tolk, J. A. 1997. "Seasonal and maximum daily evapotranspiration of irrigated winter wheat, sorghum, and corn-Southern High Plains." Trans. ASAE, 40(3), 623–634.

Jensen, M.E., R.D. Burman, and R.G. Allen (ed). 1990. *"Evapotranspiration and Irrigation Water Requirements."* ASCE Man. and Rep. on Engineering Pract. No.70, NYork, 332 p.

Marek, T., P. Colaizzi, T.A. Howell, D. Dusek, and D. Porter. 2006. Estimating seasonal crop ET using calendar and heat unit based crop coefficients in the Texas High Plains Evapotranspiration Network. ASABE Pap. no: 062206, 2006 ASABE Ann. Int. Mtg, Portland, Oregon, 9 - 12 July 2006, 11 p.

Mitchell, A.R.. 1997. Irrigating Peppermint. Oregon State Univ. Extension Service. EM 8662

Nebraska High Plains Climate Center. 2006. Crop Coefficients, Phenology, and Growing Degree Day Accumulation. http://www.hprcc.unl.edu/crop/

Sammis, T. W., Mapel, C. L., Lugg, D. G., Lansford, R. R., and McGuckin, J. T. (1985). "Evapotranspiration crop coefficients predicted using growing degree days." Trans. ASAE, 28(3), 773–780

Slack, D. C., Martin, E. D., Sheta, A. E., Fox, F. A., Jr., Clark, L. J., and Ashley, R. O. (1996). "Crop coefficients normalized for climatic variability with growing-degree-days." Proc., International Conf., Evapotranspiration and Irrigation Scheduling, San Antonio, Tex., C. R. Camp, E. J. Sadler, and R. E. Yoder, eds., Am. Soc. Agric. Engr., St. Joseph, Mich., 892–898.

Snyder, R. L., Spano. D., Cesaraccio, C., and Duce, P. 1999. "Determining degree-day thresholds from field observations" Int. J. Biometerology, 42:177-182.

Tasumi, M., R. G. Allen, R. Trezza, J. L. Wright. 2005. Satellite-based energy balance to assess within-population variance of crop coefficient curves, *J. Irrig. and Drain. Engrg,* ASCE 131(1):94-109.

Thornton, P.E. and S.W. Running. 1999. An improved algorithm for estimating incident daily solar radiation from measurements of temperature, humidity, and precipitation. *Agricultural and Forest Meteorology* 93:211-228.

Todd, R.W., S.R. Evett, and T.A. Howell. 2000. The Bowen ratio-energy balance method for estimating latent heat flux of irrigated alfalfa evaluated in a semi-arid, advective environment. *Agric. Forest Meteorol*. 103(2000):335-348.

USDA, 1967. Irrigation Water Requirements. USDA Soil Conservation Service Tech. Release 21 (Rev. 1). 88 p.

USDA-SCS. 1972. National Engineering Handbook, Section 4, Table 10.1.

Wright, James L. 1981. "Crop Coefficient for Estimates of Daily Crop Evapotranspiration." *Proc. Am. Soc. Agric. Engrs., Irrig. Scheduling Conf.*, Dec. 1981, pp. 18-26.

Wright, J.L. 1982. "New Evapotranspiration Crop Coefficients." *J. Irrig. and Drain. Div.*, ASCE, 108:57-74.

Wright, J.L. 1988. Daily and seasonal evapotranspiration and yield of irrigated alfalfa in southern Idaho. *Agron. J.* 80:662-669.

Wright, James L. 1991. Using weighing lysimeters to develop evapotranspiration crop coefficients. pp. 191-199. In: R.G. Allen, T.A. Howell, W.O. Pruitt, I.A. Walter & M.E. Jensen (eds.). Proc. of the International Symposium on Lysimetry, July 23-25, Honolulu, Hawaii. ASCE, 345 E. 47th St., New York, NY 10017-2398.

Wright, James L. 1993. Nongrowing season ET from irrigated fields. p. 1005-1014. In: R.G. Allen and C.M.U. Neale (eds.) Management of Irrigation and Drainage Systems: Integrated perspectives. Proc. Workshop ASCE Irrigation and Drainage Division, Park City, UT, 21-23 July, 1993

Wright, J.L. 2001. Growing degree day functions for use with evapotranspiration crop coefficients. CD-ROM. American Society of Agronomy. *Agronomy Abstracts.*

Wright, J.L. and M.E. Jensen. 1972. "Peak water requirements of crops in Southern Idaho." *J. Irrig. and Drain. Div.*, ASCE, 96(ir1):193-201.

Wright, J.L., R.G. Allen, and T.A. Howell. 2000. "Conversion between evapotranspiration references and methods." p. 251-259, *Proc., 4th Decennial National Irrigation Symp.*, Phoenix, AZ , ASAE, St. Joseph, MI.