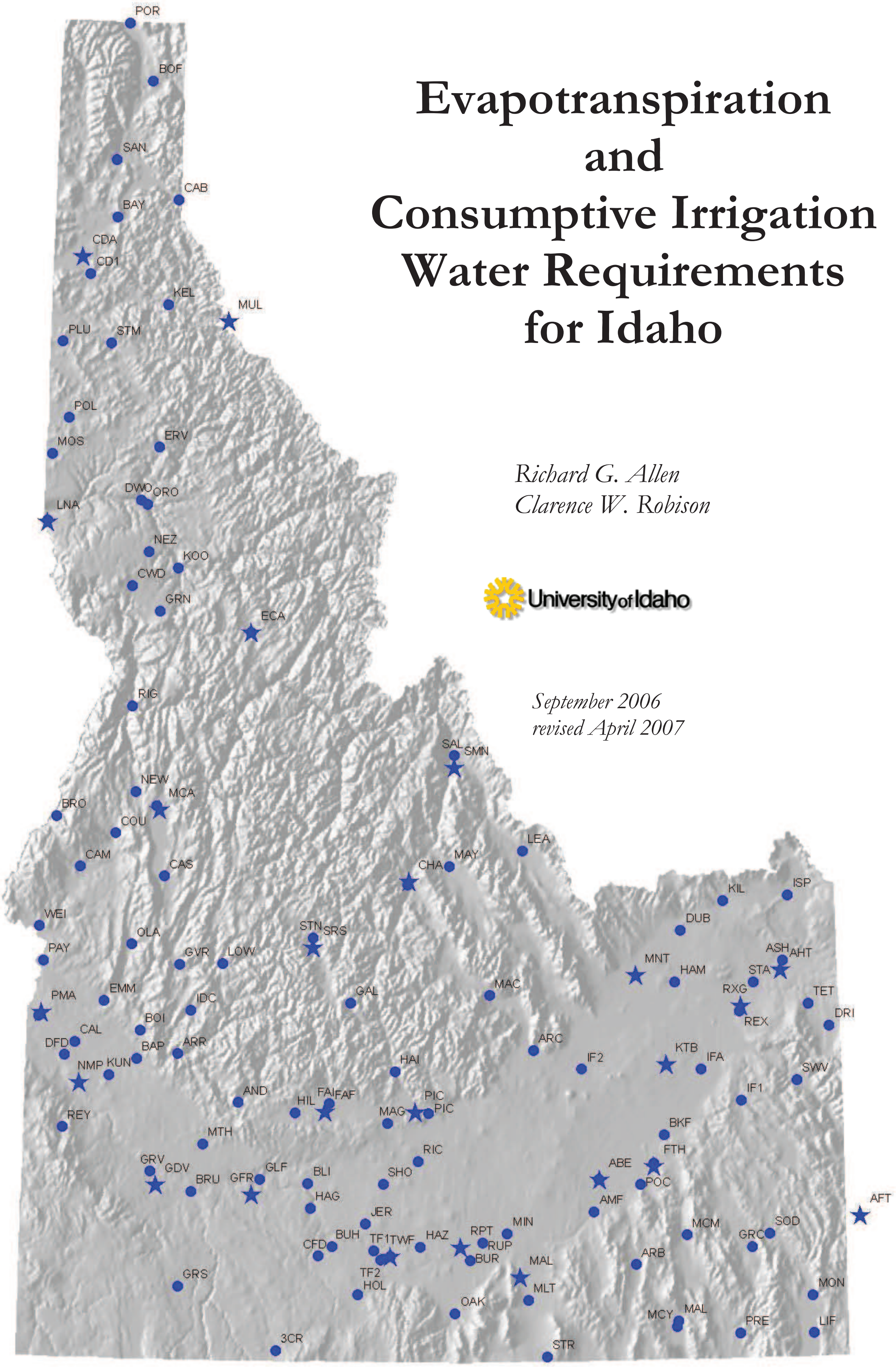

Evapotranspiration and Consumptive Irrigation Water Requirements for Idaho

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All compiled evapotranspiration data files are available via internet download from the following University of Idaho website:

http://www.kimberly.uidaho.edu/ETIdaho/

EXECUTIVE SUMMARY

Evapotranspiration and net irrigation water requirement estimates have been updated in this report for agricultural areas in Idaho. New ET calculation procedures have been employed including an updated type of reference equation (the ASCE standardized Penman-Monteith method) and using an updated procedure to calculate crop coefficients that considers the impact of surface wetting by irrigation and precipitation on total evapotranspiration. ET has been calculated for daily, monthly and annual timesteps for 123 weather station locations across Idaho for complete, available periods of record. These ET calculations supersede calculations previously made for Idaho by Allen and Brockway (1983). The ET estimates represent 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 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. Calculations have been made through December 31, 2004 for the NWS stations and through December 31, 2005 for the AgriMet stations.

The ASCE standardized Penman-Monteith reference evapotranspiration equation is a nationally standardized method (ASCE-EWRI 2005), is well regarded, and serves as a reproducible index approximating the climatic demand for water vapor. Reference ET is the ET rate from an extensive surface of reference vegetation having a standardized uniform height and that is actively growing, completely shading the ground, has a dry but healthy and dense leaf surface, and is not short of water. The ASCE Penman-Monteith (PM) equation was recently standardized by ASCE-EWRI (2005) for application to a full-cover alfalfa reference and to a clipped cool season grass reference.

Because only maximum and minimum air temperature are observed at the National Weather Service 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. 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.

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 according to growing degree days following the start of season. Growing seasons were terminated by predicted maturation of the crop or by a killing frost. The base K_{cb} curves were expressed on relative time scales or relative thermal unit scales to allow K_{cb} curves to be 'stretched' differently each year, according to weather conditions. Four different methods were used to express the base K_{cb} curves, depending on the crop or land-use type: 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 FAO-56 method for estimating evaporation from bare, wet soil, was utilized where a daily water balance was computed for the top 10 cm of soil as a means for reducing evaporation losses as the soil surface dries. In irrigated regions of the state, irrigations were simulated for typically irrigated crops for purposes of estimating evaporation from wet soil surfaces. Scheduling of irrigations was made using a root-zone water balance assuming a nonresistricted root zone and depletion of soil water to an allowable depletion level. Simulated irrigation schedules were typically like those practiced with surface irrigation and with hand-move or wheel-line sprinkler systems (i.e., 'low frequency'). Available water holding capacity and texture of soil for each station was determined using information from the National StatsGo soils information data base using a GIS analysis of the data base for the area assigned to each station. Precipitation runoff was estimated using the NRCS Curve Number method where antecedent moisture was computed from the daily surface soil water balance. The curve number was determined from soil texture based on the StatsGo soils data base.

Snow cover data as observed at many of the NWS stations were used to modify winter time estimates of evaporation caused by high albedo of snow and energy required for heat of fusion and was also used during adjustment of cumulative growing degree days for winter wheat during winter.

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.

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Units Conversions

1 mm = 0.0394 inches
1 inch = 25.4 mm
1 m = 3.28 feet
1 m = 1000 mm
1 foot = 0.3048 m
1 foot = 12 inches
1 km = 0.621 miles
1 km = 1000 m
1 mile = 1.609 km = 1609 m
1 mile = 5280 feet
1 sq. mile = 640 acres
1 acre = 43,560 sq. feet
1 m s^{-1} = 2.24 mph
1 mph = 0.447 m s^{-1}
1 mm d^{-1} = 0.0394 inches d^{-1} = 0.742 gallons per minute per acre (gpm / ac.)
1 mm d^{-1} = 0.00165 cubic feet per second per acre (cfs / ac.)
X $^oC = X * 1.8 + 32\ ^oF$
Y $^oF = (Y - 32) / 1.8\ ^oC$

INTRODUCTION

Evapotranspiration (ET) is the primary component of irrigation water requirements for agricultural crops and landscapes. ET is the combined process by which water is converted from liquid or solid forms via evaporation from soil and wet plant surfaces and via evaporation of water from within plant tissue. The latter process is known as transpiration. ET can be expressed as the energy consumed as latent heat energy per unit area or as the equivalent depth of evaporated water. Units for ET are typically mm t^{-1} where t denotes a time unit (hour, day, month, growing season, or year). Quantification of ET is required to design and size irrigation system components, for operating irrigation and water resources systems, and for conducting water balances. Rates of ET are strongly affected by weather and, during the course of a growing season, by the type of vegetation and availability of water.

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. 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 affecting evapotranspiration and are located primarily in the southern part of the state. Monthly wind summaries from the AgriMet stations and some airport locations in central and northern Idaho were used to parameterize the ET_r calculations. Calculations have been made through December 31, 2004 for NWS stations and through December 31, 2005 for AgriMet stations.

Evapotranspiration Calculation Approach

The approach followed in calculating ET was a 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 such as full-cover alfalfa or clipped cool season grass 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 is a standardized and reproducible index approximating the climatic demand for water vapor. Reference ET is the ET rate from an extensive surface of reference vegetation having a standardized uniform height and that is actively growing, completely shading the ground, has a dry but healthy and dense leaf surface, and is not short of water. This definition is commonly applied to the standardized reference crops of grass (ET_O) and alfalfa (ET_r). The advantage of using the reference concept is that it enables the measurement and validation of estimated reference ET using living, standardized crops.

The Penman-Monteith (PM) equation is the most commonly used method today for calculating ET_r. The PM equation has been recently standardized to both the full-cover alfalfa reference and clipped cool season grass reference by ASCE-EWRI (2005).

Crop evapotranspiration, abbreviated ET_c, is determined as the rate of ET from an extensive surface of a specific crop. The ET_c rate is influenced by crop growth stages, amount and frequency of wetting of the soil surface, environmental conditions and by crop management. Crop ET is usually less than the reference ET_r rate when crop foliage does not completely shade the ground or when the crop has begun to mature and senesce[1]. Crop ET often approaches or equals the alfalfa reference ET_r when the crop has developed substantial leaf area and nearly total ground cover.. Crop ET is normally expressed in units of mm h^{-1}, mm d^{-1}, mm $month^{-1}$, or mm $season^{-1}$ and is synonymous with the term consumptive use.

The 'extensive surface' in the definition of ET_c and calculation methodologies requires that the crop cover a large enough area that the energy exchange at the crop surface and the wind speed, temperature and humidity profiles above the crop are in equilibrium. Only when this equilibrium exists does the standard K_c ET_r approach attain the highest accuracy. The extensive surface condition applies to field sizes having dimensions greater than about 200 m (equivalent to 4 ha (10 acre)).

Calculation of ET_r, K_c and ET_c was done 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..

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 or Penman-Wright equation. 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). Estimates by the ASCE-PM ET_r method can be expected to compare closely with those by the ET_r-calibrated FAO-24 Blaney-Criddle method of Allen and Brockway (1983) and to the 1982 Kimberly Penman equation, especially during growing seasons. The ASCE-PM ET_r typically provides higher ET_r calculations during winter months than the 1982 Kimberly Penman method of AgriMet. 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).

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

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[1] Senescence describes the natural aging process of leaves whereby leaves begin to yellow and die and stomatal function and exchange of carbon dioxide and water vapor reduce. Senescence may be accelerated by environmental stresses such as disease and water shortage.

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

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 (K mm s^3 Mg^{-1} d^{-1} or K mm s^3 Mg^{-1} h^{-1}) and C_d is a constant that changes with reference type and calculation time step (s m^{-1}). Units for the 0.408 coefficient are m^2 mm MJ^{-1}.

Table 1 provides values for coefficients C_n and C_d. The values for C_n consider the time step and aerodynamic roughness of the surface (in this case, for the alfalfa (i.e., 'tall') reference, for daily timesteps C_n = 1600). The constant in the denominator, C_d, considers the time step, bulk surface resistance, and aerodynamic roughness of the surface. For the alfalfa (i.e., 'tall') reference, for daily timesteps C_d = 0.38. 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. Daytime is defined as occurring when R_n during an hourly period is positive.

Table 1. Values for C_n and C_d in Eq. 1 for the ASCE-EWRI (2005) Penman-Monteith Equation.

Calculation Time Step	Short Reference, --termed ET_o (clipped grass)		Tall Reference, --termed ET_r (alfalfa)		Units for ET_o, ET_r	Units for R_n, G
	C_n	C_d	C_n	C_d		
Daily	900	0.34	1600	0.38	mm d^{-1}	MJ m^{-2} d^{-1}
Hourly during daytime	37	0.24	66	0.25	mm h^{-1}	MJ m^{-2} h^{-1}
Hourly during nighttime	37	0.96	66	1.7	mm h^{-1}	MJ m^{-2} h^{-1}

Selection of Calculation Time Step. The ASCE-PM ET_r equation can be applied to hourly and 24-h time steps. The 24-h timesteps can use daily, weekly, 10-d, and monthly averages for weather data. Under many climatic conditions, calculating ET_r using hourly timesteps and then summing over 24-hours provides estimates that closely equal ET_r calculated using 24-h average data with 24-h calculation time steps, especially when applying the standardized ASCE-EWRI PM method (Itenfisu et al., 2003, ASCE-EWRI, 2005). Under some climatic conditions, 24-h ET_r have potential for higher accuracy when computed using hourly or shorter timesteps and then summed to 24-hour totals, since hourly calculations are better able to consider impacts of abrupt and gradual changes in weather parameters during the course of a day on ET (Irmak et al., 2005, Allen et al., 2005b). Examples of this are high wind conditions during afternoon with low humidity, overpass of cloud fronts and rain events, and nighttime calm. However, in the calculations for this state-wide ET and irrigation water requirements report, most weather station locations report observations on a 24-hour time step basis, only. Therefore, the 24-hour calculation timestep for ET_r has been applied here. Daily air temperature data have been utilized in calculations to provide for better within-month sensitivity than if monthly mean data were utilized.

Calculation of Reference ET. The calculation of parameters in Eq. 1 followed the standardized procedure of ASCE-EWRI (2005). This procedure is described in Appendix 1, which is taken from ASCE-EWRI (2005). The full complement of air temperature, solar radiation, humidity and wind speed data are available for less than 20 locations in Idaho that are near or in agricultural areas. The data sets associated with these locations are generally less than twenty years in length. Much longer air temperature data sets are available for the more than 100 National Weather Service cooperative weather stations in Idaho. Some of these extend to the 1880's. Due to the value of these longer time series for historical calculation of ET and more extensive distribution throughout the state, ET calculations were applied to the NWS cooperative stations as well as to AgriMet stations.

Because only maximum and minimum air temperature are observed at the National Weather Service 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). 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. Determination and testing of estimation parameters is described in Appendix 2. Based on the development work summarized in Appendix 2, solar radiation, dewpoint and wind speed were estimated for NWS stations as follow:

a. *Daily solar radiation:*
Thornton and Running (1999) procedure 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_{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, as described in Appendix 2. The use of Eq. 2a and 2b in this April 2007 revision replaced the use of the more simple Hargreaves and Samani (1982) equation that was used in the original September 2006 report, where $R_s = 0.16\ (T_{max}\text{-}T_{min})^{0.5}\ R_a$. 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 AgriMet weather stations (Appendix 2). 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, T_{dew}*

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

where T_{min} is daily minimum air temperature (^oC) and K_o is an offset that varies monthly as shown in the following table:

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

These offsets were based on long-term records of dewpoint and T_{min} collected at AgriMet weather stations across Idaho, as described in Appendix 2. The application of Eq. 3, with the offsets that varied by month, was introduced in this April 2007 revision. This usage contrasts with the approach used in the original Sept. 2006 report where K_o was fixed at 2°C for all months. This prior usage tended to underestimate T_{dew} during the nongrowing season, causing some overestimation of evaporation from wet soil and open water.

c. *Wind speed*

Long term monthly average wind speed was derived from the nearest AgriMet station in southern Idaho and from a nearest NOAA airport weather station in central and northern Idaho.

Analyses using daily measured ET by lysimeter in Appendix 2 indicate that reference ET estimated using dewpoint, solar radiation and wind speed data as described in steps a, b, and c. preserves the bulk variance of the original (measured) population of reference ET. Therefore, probability levels based on computed reference ET are valid.

Daily data files containing daily estimated reference ET_r were created for each weather station for the periods of record. Each file contains the date, T_{max}, T_{min} (Celsius), precipitation (hundredths of inches), observed snow fall (tenths of inches), snow depth (inches), estimated solar radiation (MJ/m^2/day), estimated wind speed at 2 m height (m/s) and estimated dewpoint temperature (C). In addition, reference ET was calculated and reported using five reference methods, including the 1982 Kimberly Penman alfalfa ET_r, the 1996 Kimberly Penman grass reference ET_o (Wright 1995), the ASCE standardized Penman-Monteith alfalfa ET_r, the ASCE standardized Penman-Monteith grass reference ET_o, and the 1985 Hargreaves grass reference ET_o.(Hargreaves et al., 1985). Units for reference ET are in mm/day. The data file names begin with the six digit "WBN" name for the station and end with "ETR2.DAT". The ASCE standardized Penman-Monteith alfalfa reference ET_r is included in the time series and statistics files and is the ET_r used in all crop ET calculations.

Evapotranspiration from Crop 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.
The potential crop ET is calculated by multiplying ET_r by the crop coefficient:

$$ET_{c\,pot} = K_c\,ET_r \tag{4}$$

The reference crop corresponds to a living, agricultural crop (in this application, full cover alfalfa) and it incorporates the the effects of variable weather into the ET_r estimate. Because ET_r represents an index of climatic evaporative demand, the K_c varies predominately with specific crop characteristics. This enables the transfer of standard values for K_c between locations and between climates. The transfer has led to the widespread acceptance and usefulness of the K_c ET_r approach. The K_c and $ET_{c\,pot}$ in Eq. 4 represent ET under potential growing conditions with no stresses caused by shortage of soil water or salinity. These are the general conditions for agricultural production. Both water and salinity stress reduce transpiration and thus ET by causing plant canopies to reduce stomatal opening and water loss. The $ET_{c\,pot}$ from Eq. 4 also includes any evaporation from the soil surface following wetting by precipitation or irrigation.

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, whereas the mean K_c method can be applied on daily, weekly or monthly timesteps. The Allen and Brockway (1983) report applied the mean crop coefficient approach. This report applies the dual crop coefficient approach due to its ability to better quantify evaporation from precipitation and irrigation events that vary from year to year and with location throughout the state.

The form of the equation for potential $ET_{c\ pot}$ in the dual K_c approach is:

$$ET_{c\ pot} = (K_{cb} + K_e) ET_r \tag{5}$$

where K_{cb} is the basal crop coefficient [0 - ~1.0 when used with ET_r], and K_e is a soil water evaporation coefficient [0 - ~1.0 when used with ET_r]. All K terms are dimensionless. K_{cb} is defined as the ratio of ET_c to ET_r when the soil surface layer is dry, but where the average soil water content of the root zone is adequate to sustain full plant transpiration. K_e quantifies the evaporation component from wet soil in addition to the evapotranspiration represented in K_{cb}.

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:

$$ET_{c\ act} = (K_s\, K_{cb} + K_e)\, ET_r \tag{6}$$

where K_s is a reduction coefficient for when there is stress caused by low soil moisture [0 - 1] (dimensionless). K_s reduces the value of K_{cb} when the average soil water content of the root zone is not adequate to sustain full plant transpiration and is described later. $K_s = 1.0$ when there is no water stress.

The value for K_s can decrease below 1.0 for irrigated crops during periods outside the growing season or typical irrigation season and during all periods for rainfed crops or land covers when precipitation does not sufficiently supply the $ET_{c\ pot}$ rate. A daily soil water balance is required to calculate K_s, since its value can change daily as soil water contents decline. This 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 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). The Allen et al., (2005) ASCE paper is appended to this report as Annex 1. Departures from the Allen et al., (2005) FAO-56 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 adjustment to $K_{c\ max}$ nor K_{cb} are necessary. The particular equations for application with the alfalfa reference ET_r are given in Annex 1.

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 shortly 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.

Examples of calculated K_{cb} and $K_{c\ actual}$ curves ($K_{c\ actual} = ET_{c\ actual} / ET_r$) are shown in Figure 1 for a crop of spring wheat and potatoes during the 2004 calendar year near Ashton. 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 and at 0.8 or less for the potato crop that was assumed to have a bare soil surface during the nongrowing season. Setting of these parameters is described later. $K_{c\ actual}$ peaks during winter were reduced when snow cover was noted to account for higher reflectance of the snow (January – March for 2004). $K_{c\ actual}$ 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 figure in Figure 1) due to the low value for reference ET_r, which represents the drying power of the atmosphere and energy available for evaporation.

Figure 2 shows daily estimates of K_c at Kimberly for sweet corn and snap bean crops based on K_{cb} curves by Wright (1982) and with K_e estimated using the FAO-56 (Allen et al., 1998, 2005) K_e evaporation estimation procedure employed in this study. The $K_s\ K_{cb} + K_e$ estimates (solid lines in the figure) are compared with daily lysimeter measurements of K_c (round symbols) collected by Wright (1998, pers. commun.). Agreement between measured and simulated K_c (where $K_c = ET_c/ET_r$) is relatively good. Both measured and simulated actual K_c curves dipped below the potential K_{cb} curve (thicker line) during times when soil water contents of the root zone in the lysimeter were estimated to fall below the threshold for water stress induced reduction in ET.

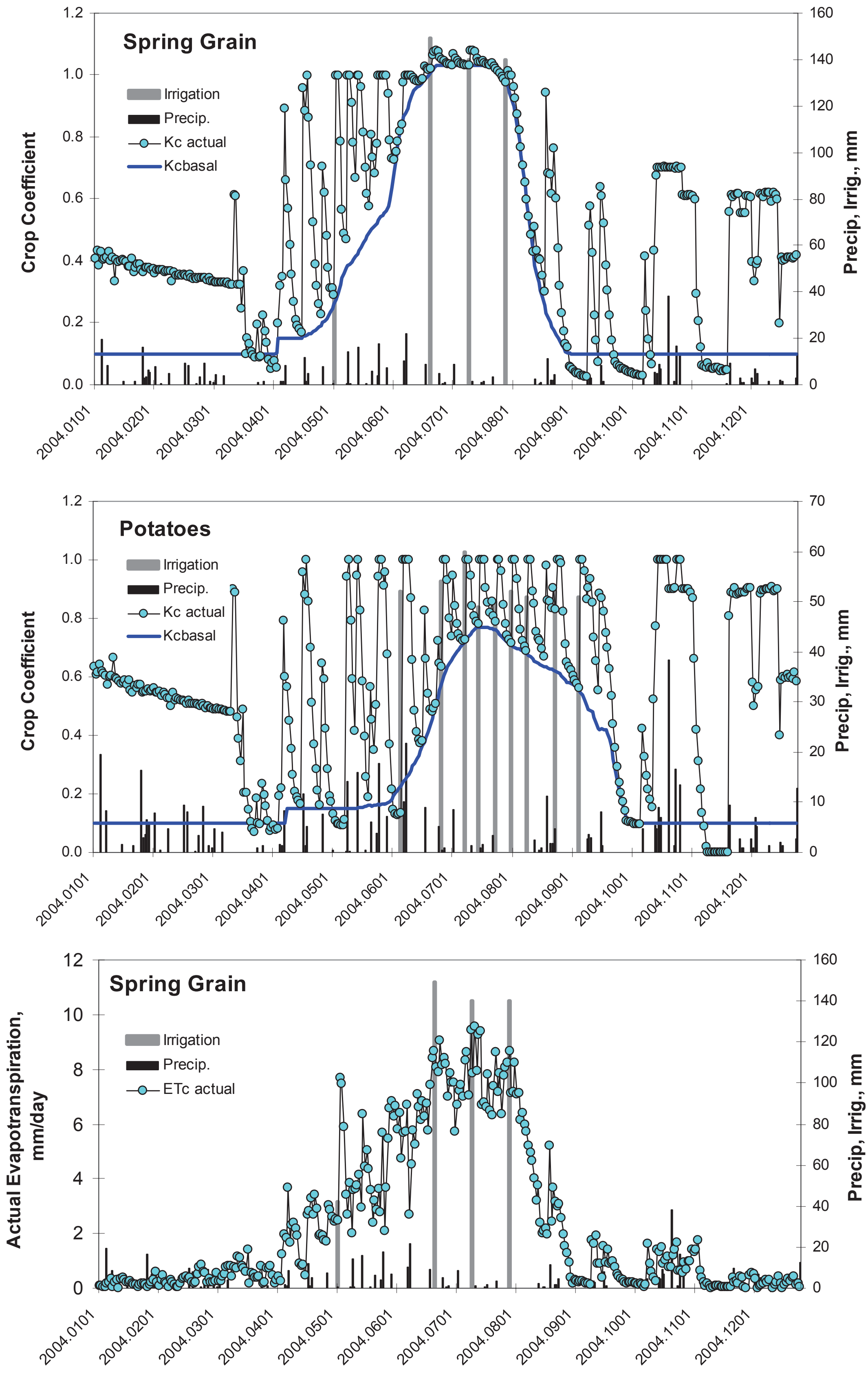
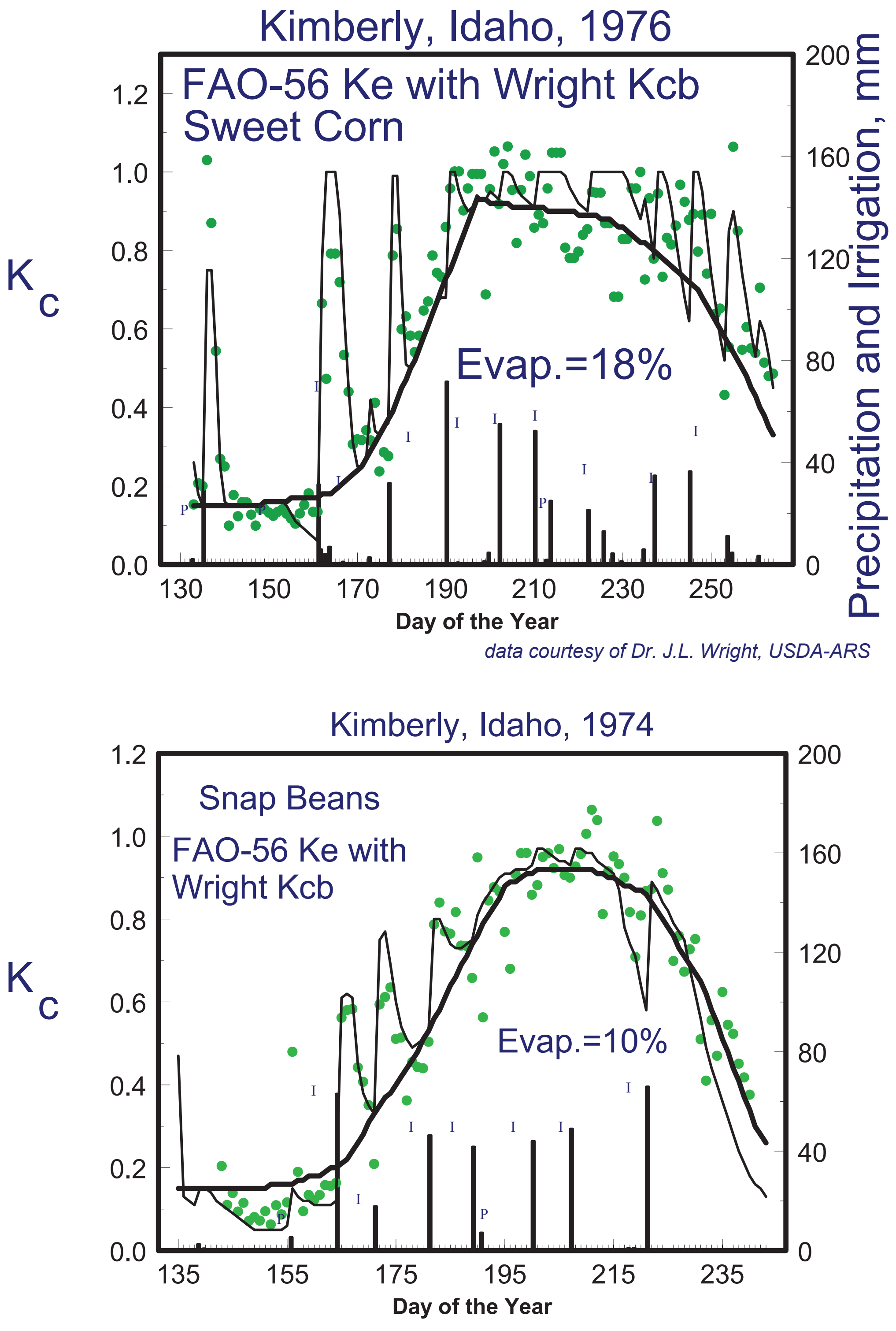


Figure 1. Example K_{cb} ('Kcbasal') and $K_{c\ actual}$ curves for spring wheat and potato crops near Ashton during 2004. Simulated irrigation events are shown as vertical bars. The $K_{c\ actual}$ traces include the evaporation (K_e component) that appear as 'spikes' above the K_{cb} curves following precipitation and irrigation events. Also shown in the bottom figure is daily actual ET_c for the spring grain.



data courtesy of Dr. J.L. Wright, USDA-ARS

data courtesy of Dr. J.L. Wright, USDA-ARS

Figure 2. Actual daily K_c estimated using K_{cb} curves by Wright (1982) and K_e by the FAO-56 evaporation estimation procedure for two crops grown on the precision-weighing lysimeter systems at Kimberly (J.L. Wright 1998, pers. commun.). The round symbols are lysimeter measurements of K_c. Bars are precipitation and irrigation events.

Application of K_{cb} Curves for a Variety of Locations and Periods of Record

The K_{cb} curves shown in Figures 1 and 2 are constructed vs. time of year. The time of start of season, the duration of the growing season and the termination of the growing season can vary from year to year due to temperature conditions during spring and heat availability (i.e. growing degree days). 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, as described in Appendix 3. 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. These four bases are described in Appendix 3 and the K_{cb} curves are presented there.

Basal crop coefficient curves were developed or organized for forty-two crop and land-cover types. These crops are listed in Table 1, along with the basic type of curve, the primary source and the type of normalizing basis used to scale the curve. The specific curves and the background on their development are presented in Appendix 3. The K_{cb} curves of Wright (1982) were converted to normalized cumulative growing degree days as described in Appendix 3.

K_{cb} values for sagebrush, cheatgrass and bunchgrass were developed based on vegetation index (NDVI) trends from Landsat images in the Minidoka area. The derived K_{cb} curves represent potential K_{cb} under conditions of readily available soil moisture. The K_{cb} values from these curves were discounted during calculations using the K_s stress coefficient estimated from a daily soil water balance. The bromegrass curve was developed for a relatively dense stand, assuming that winter soil storage and spring precipitation is sufficient to promote an aggressive stand of grass. The actual stand K_c is decreased during daily calculation based on water stress caused by low soil water. The means for estimating the starts of growing seasons for various crops and land cover types and for terminating growing seasons due to killing frost are described in Appendix 8.

Table 2. Basal crop coefficient curve basis and primary source.

Curve No.	Crop Curve Name	Type of Basis[1]	Primary Source
1	Spring grain (wheat, barley)	1	Wright (1982)
2	Winter grain (wheat, barley)	1	Wright (1982)
3	Peas, seed	1	Wright (1982)
4	Peas, fresh	1	derived from curve 3
5	Sugar Beets	1	Wright (1982)
6	Potatoes (baking)	1	Wright (1982)
7	Potatoes-processing	1	derived from curve 6
8	Field Corn	1	Wright (1982)
9	Sileage Corn	1	Wright (1982)
10	Sweet Corn	1	Wright (1982)
11	Snap Beans-dry	1	Wright (1982)
12	Snap Beans-fresh	1	derived from curve 11
13	Alfalfa 1st cycle	1	Wright (1982)
14	Alfalfa Int cycle	1	Wright (1982)
15	Alfalfa Last cycle	1	Wright (1982)
16	Alfalfa, peak	1	created here
17	Lentils	1	derived from spring grain curve
18	Mint	1	modified from Mitchell, 1997 and alfalfa curve
19	Grass Hay	1	modified from AgriMet
20	Onions	2	modified from AgriMet
21	Winegrapes	2	modified from AgriMet
22	Melons	2	modified from AgriMet
23	Hops	2	modified from AgriMet
24	Apples w/GC	2	modified from AgriMet and FAO-56
25	Apples no GC	2	modified from AgriMet and FAO-56
26	Asparagus	2	modified from AgriMet and FAO-56
27	Canola	2	modified from AgriMet
28	Sunflower/Safflower	2	developed from canola curve
29	Lawn	2	modified from AgriMet
30	Pasture Rotated	3	created here
31	Pasture Low Manag.	3	created here
32	BlueGrass Seed	3	created here
33	Alfalfa Seed	3	modified from Allen and Brockway (1983)
34	Poplar	3	modified from AgriMet
35	Wetlands-Large stand	3	modified from Allen (1998)
36	Wetlands-Small Stand	3	modified from Allen (1998)
37	Sagebrush	4	derived from satellite-based NDVI
38	Cheatgrass	4	created here
39	Bunchgrass	4	created here
40	Bromegrass	4	created here
41	Cottonwood	2	derived from METRIC application in New Mexico
42	Willow	2	derived from METRIC application in New Mexico

[1] Curve Time Basis:

1 = normalized cumulative growing degree days (NCGDD)
2 = percent of time from planting (or greenup) to effective full cover, applied all season
3 = percent of time from planting (or greenup) to effective full cover, then days after effective full cover
4 = percent of time from planting (or greenup) until termination

Weather Stations

NWS Stations.

The listing of the 107 National Weather Service (NWS) weather stations is given in Table 3. The stations were used along with 16 AgriMet stations for calculating reference ET on a daily basis through 2004. Multiple point locations (sharing the same town name), but with overlapping or sequential records, are shown in the Table (for example, Buhl and Buhl2). These records were combined before calculation of crop ET. The 87 NWS stations that were included in ET summaries in the Allen and Brockway (1983) report are identified in the table as well as 25 new stations that were considered to have sufficient length of record by the end of 2004 for inclusion in this report. Three of the 25 new stations are for the same location as a previous station.

AgriMet Stations

Table 4 lists the AgriMet Agricultural Weather stations used in the ET_r and ET_c analyses. The AgriMet stations collect a full complement of weather data required to calculate ET_r, including solar radiation, daily maximum and minimum air temperature, mean daily vapor pressure and wind speed as well as precipitation. The weather measurements are made on an hourly or shorter basis and summarized to 24-hour values based on midnight to midnight periods. The AgriMet stations do not observe snow cover, so that this parameter, used in simulating growth of winter wheat and in adjusting evaporation rates during winter, was borrowed from a nearby station as noted in Table 4. The AgriMet system is supported, maintained and coordinated by the U.S. Bureau of Reclamation Regional Center in Boise, ID. Mr Peter Palmer is the current manager of the AgriMet system.

AgriMet stations are typically located within irrigated agricultural areas. The exception is Kettle Butte and Glenns Ferry stations which are near the interface with desert. The AgriMet web site[2] contains maps and photographs of most AgriMet stations and describes the data measurement, summary, archiving and distribution procedures. The wind speed height for AgriMet stations is at 2 m and the anemometer type is typically an RM Young wind monitor. Solar radiation is typically measured using a LiCor silicon type of pyranometers and vapor pressure and air temperature are measured using Visailla RH sensors. Precipitation is generally measured by tipping bucket rain gage and at a few locations with weighing gages.

In general, the AgriMet daily data sets represent exceptional and relatively complete records of high quality agricultural weather data, especially following adjustments to some solar radiation data as noted in Table 4.1 of Appendix 4. ET_r and ET_c calculations for these locations constitute good estimates of daily evapotranspiration due to the application of the ASCE Penman-Monteith equation with the full weather data sets.

Locations of the 107 NWS stations and 16 AgriMet weather stations are shown in Figures 3 and 4. Figure 3 contains the internal ET numbers associated with stations in Table 3 and Figure 4 shows 3-letter abbreviations for station names. The relative distribution of ET stations within Idaho was considered to be good. In nearly all cases, the weather stations represent agricultural or ranching areas which is the focus of this report. Additional information is given in Appendix 5, including whether the location is in a generally irrigated setting, general aridity rating of the station, soil permeability and soil water holding characteristics.

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[2] http://www.usbr.gov/pn/AgriMet/

Table 3. Idaho NWS Temperature/Precipitation Stations for Consumptive Use Computations**

Internal ET Sta. no.	Heritage Flag[*]	NOAA Station Name	NCDC Coop no.	Lat., deg.	Long, deg.	Elev, feet	Aprx. Start Year	End Year	Approx. no. Yrs	Wind Station
1	1	ABERDEEN EXP. STN	100010	42.95	-112.83	4400	1914	2004	90	Aberdeen
2	1	AMERICAN FALLS 1 SW	100227	42.78	-112.87	4320	1892	2004	100	Aberdeen
3	1	ANDERSON DAM	100282	43.35	-115.47	3880	1948	2004	53	Fairfield
4	1	ARBON 2 NW	100347	42.50	-112.57	5170	1962	2002	40	Logan, UT - USU Drainage Farm
5	1	ARCO	100375	43.63	-113.30	5330	1914	2004	74	Monteview
6	2	ARROWROCK DAM	100448	43.60	-115.92	3240	1911	2004	93	Nampa
7	1	ASHTON	100470	44.08	-111.45	5110	1901	2004	101	Ashton
8	1	BAYVIEW MODEL BASIN	100667	47.98	-116.55	2070	1947	2004	55	Coeur d'alene Airport, ID (KCOE)
9	1	BLACKFOOT	100915	43.18	-112.35	4500	1895	2004	99	Aberdeen
10	1	BLISS	101002	42.93	-114.95	3270	1917	2000	74	Glenns Ferry
11	2	BOISE 7 N	101017	43.72	-116.20	3890	1973	2004	32	Nampa
12	1	BOISE WSFO AIRPORT	101022	43.57	-116.22	2860	1937	2004	68	Nampa
13	1	BONNERS FERRY	101079	48.70	-116.30	1850	1907	2004	76	Coeur d'alene Airport, ID (KCOE)
14	2	BROWNLEE DAM	101180	44.83	-116.87	1840	1966	2004	38	Parma
15	1	BRUNEAU	101195	42.88	-115.80	3000	1962	2004	41	Grand View
16	2	BUHL	101217	42.60	-114.77	3760	1948	1963	14	Twin Falls
--	2	BUHL 2	101220	42.60	-114.75	3800	1978	2004	27	Twin Falls
17	1	BURLEY FAA AP	101303	42.53	-113.77	4160	1948	2004	56	Rupert
18	1	CABINET GORGE	101363	48.08	-116.07	2180	1956	2004	48	Mullan Pass (KMLP)
19	1	CALDWELL	101380	43.65	-116.68	2370	1904	1997	91	Nampa
20	1	CAMBRIDGE	101408	44.57	-116.68	2650	1894	2004	107	Parma
21	1	CASCADE 1 NW	101514	44.53	-116.05	4870	1942	2004	62	McCall Aprt (KMYL)
22	1	CASTLEFORD 2 N	101551	42.55	-114.87	3830	1963	2004	41	Twin Falls
23	1	CHALLIS	101663	44.50	-114.23	5170	1895	1996	84	Challis Aprt (KU15)
24	1	COEUR D ALENE 1 E	101956	47.68	-116.75	2160	1895	2004	86	Coeur d'alene Airport, ID (KCOE)
25	1	COTTONWOOD	102154	46.05	-116.35	3410	1913	1976	53	Lewiston-Nez Perce Cnty Airport (KLWS)
--	2	COTTONWOOD 2 WSW	102159	46.03	-116.38	3600	1976	2004	28	Lewiston-Nez Perce Cnty Airport (KLWS)
26	1	COUNCIL	102187	44.75	-116.42	3150	1911	2004	87	Parma
27	1	DEER FLAT DAM	102444	43.58	-116.75	2510	1916	2004	66	Nampa
28	1	DRIGGS	102676	43.73	-111.12	6110	1904	2004	90	Ashton
29	1	DUBOIS EXPERIMENT STN	102707	44.25	-112.20	5460	1925	2004	80	Monteview
30	2	DWORSHAK FISH HATCHERY	102845	46.50	-116.30	1000	1966	2004	38	Lewiston-Nez Perce Cty Airport (KLWS)
31	2	ELK CITY	102875	45.82	-115.43	3980	1914	2004	63	Elk City, ID (KP69)
32	2	ELK RIVER 1 S	102892	46.78	-116.17	2910	1952	2004	52	Lewiston-Nez Perce Cnty Airport (KLWS)
33	1	EMMETT 2 E	102942	43.87	-116.47	2390	1906	2004	97	Parma
34	1	FAIRFIELD	103108	43.35	-114.80	5070	1948	2004	55	Fairfield
35	1	FORT HALL INDIAN AGENCY	103297	43.03	-112.43	4500	1948	2004	56	Aberdeen

36	2	GALENA	103417	43.88	-114.65	7310	1963	1996	17	Picabo
37	1	GARDEN VALLEY R S	103448	44.07	-115.92	3150	1948	2004	55	Stanley Ranger Station, ID (KSNT)
38	1	GLENNS FERRY	103631	42.95	-115.30	2570	1905	2004	92	Glenns Ferry
39	1	GRACE	103732	42.58	-111.73	5550	1931	2004	73	Afton, WY
40	1	GRAND VIEW	103760	42.98	-116.10	2360	1909	2004	88	Grand View
41	1	GRANGEVILLE	103771	45.92	-116.13	3350	1893	2004	83	Lewiston-Nez Perce Cnty Airport (KLWS)
42	2	GRASMERE	103809	42.38	-115.88	5130	1953	1973	19	Grand View
43	2	HAGERMAN 2 SW	103932	42.80	-114.93	2880	1982	2004	23	Twin Falls
44	1	HAILEY RANGER STN	103942	43.52	-114.32	5350	1894	1988	78	Picabo
45	1	HAMER 4 NW	103964	43.98	-112.25	4800	1948	2004	56	Monteview
46	1	HAZELTON	104140	42.60	-114.13	4060	1948	2004	55	Twin Falls
47	1	HILL CITY	104268	43.30	-115.05	5000	1915	2004	86	Fairfield
48	1	HOLLISTER	104295	42.35	-114.58	4550	1912	2004	92	Twin Falls
49	1	IDAHO CITY	104442	43.83	-115.83	3940	1894	2004	93	Stanley Ranger Station, ID (KSNT)
50	1	IDAHO FALLS 16 SE	104456	43.35	-111.78	5720	1960	2004	43	Rexburg
51	1	IDAHO FALLS FAA ARPT	104457	43.52	-112.07	4740	1904	2001	91	Rexburg
52	1	IDAHO FALLS 46 W	104460	43.53	-112.95	4930	1954	2004	51	Monteview
53	1	ISLAND PARK	104598	44.42	-111.40	6310	1937	2004	64	Ashton
54	1	JEROME	104670	42.72	-114.53	3770	1915	2004	66	Twin Falls
55	1	KELLOGG	104831	47.53	-116.13	2310	1905	2004	99	Mullan Pass (KMLP)
56	1	KILGORE	104908	44.40	-111.88	6160	1960	1977	16	Ashton
57	2	KOOSKIA	105011	46.07	-115.93	1260	1908	1987	78	Lewiston-Nez Perce Cnty Airport (KLWS)
--	2	KOOSKIA 5 SSE	105013	46.07	-115.93	2330	1989	2004	15	Lewiston-Nez Perce Cnty Airport (KLWS)
58	1	KUNA	105038	43.48	-116.42	2680	1907	1996	82	Nampa
59	2	LEADORE 2	105177	44.68	-113.37	6110	1965	2004	29	Salmon-Lemhi Cnty Airport, ID (KSMN)
60	1	LEWISTON WB AP	105241	46.38	-117.02	1420	1946	2004	56	Lewiston-Nez Perce Cnty Airport (KLWS)
61	1	LIFTON PUMPING STN	105275	42.12	-111.30	5940	1919	2004	80	Afton, WY
62	2	LOWMAN	105414	44.08	-115.60	3870	1916	2004	68	Stanley Ranger Station, ID (KSNT)
63	1	MACKAY RANGER STN	105462	43.92	-113.62	5910	1908	2004	95	Challis Arprt (KU15)
64	2	MAGIC DAM	105510	43.25	-114.37	4800	1966	1975	8	Fairfield
65	1	MALAD	105544	42.20	-112.27	4420	1931	1982	50	Logan, UT - USU Drainage Farm
66	2	MALAD CITY	105559	42.17	-112.28	4480	1944	2004	58	Logan, UT - USU Drainage Farm
67	1	MALTA 1 NE	105563	42.32	-113.35	4540	1963	2002	36	Malta
68	1	MAY	105685	44.60	-113.92	5070	1948	2004	45	Challis Arprt (KU15)
69	1	MCCALL	105708	44.90	-116.12	5030	1909	2004	84	McCall Arprt (KMYL)
70	2	MCCAMMON	105716	42.65	-112.20	4770	1949	2004	32	Aberdeen
71	1	MINIDOKA DAM	105980	42.67	-113.50	4210	1947	2004	56	Rupert
72	1	MONTPELIER	106053	42.32	-111.30	5960	1931	1991	60	Afton, WY
73	1	MOSCOW UNIV OF IDAHO	106152	46.73	-117.00	2630	1893	2004	111	Lewiston-Nez Perce Cnty Airport (KLWS)
74	1	MOUNTAIN HOME 1 W	106174	43.13	-115.72	3150	1906	2004	97	Grand View
75	1	NEW MEADOWS RNG. STN	106388	44.97	-116.28	3860	1913	2004	91	McCall Arprt (KMYL)
76	1	NEZPERCE	106421	46.23	-116.23	3080	1948	1951	3	Lewiston-Nez Perce

										Cnty Airport (KLWS)
--	2	NEZPERCE 2 E	106424	46.25	-116.20	3250	1951	2004	52	Lewiston-Nez Perce Cnty Airport (KLWS)
77	1	OAKLEY	106542	42.25	-113.88	4600	1893	2004	111	Malta
78	1	OLA	106586	44.17	-116.28	3080	1991	2004	14	Stanley Ranger Station, ID (KSNT)
79	1	OROFINO	106681	46.48	-116.25	1030	1948	1981	33	Lewiston-Nez Perce Cnty Airport (KLWS)
80	1	PARMA Exp. Station	106844	43.78	-116.95	2220	1922	2004	79	Parma
81	1	PAYETTE	106891	44.07	-116.93	2160	1892	2004	106	Parma
82	1	PICABO	107040	43.30	-114.07	4880	1958	2004	44	Picabo
83	2	PLUMMER 3 WSW	107188	47.32	-116.95	2970	1988	2003	14	Coeur d'alene Airport, ID (KCOE)
84	1	POCATELLO WB AP	107211	42.92	-112.53	4470	1939	2004	66	Aberdeen
85	1	PORTHILL	107264	49.00	-116.50	1800	1902	2004	102	Coeur d'alene Airport, ID (KCOE)
86	1	POTLATCH 3NNE	107301	46.92	-116.88	2550	1915	2002	83	Lewiston-Nez Perce Cnty Airport (KLWS)
87	1	PRESTON 3 NE	107346	42.13	-111.83	4820	1964	2004	29	Logan, UT - USU Drainage Farm
88	2	REXBURG RICKS COLLEGE	107644	43.82	-111.78	4920	1977	2004	27	Rexburg
89	1	REYNOLDS	107648	43.20	-116.75	3910	1961	2004	43	Nampa
90	1	RICHFIELD	107673	43.05	-114.15	4310	1910	2004	77	Twin Falls
91	1	RIGGINS RANGER STN	107706	45.42	-116.32	1800	1896	2004	78	McCall Arprt (KMYL)
92	1	RUPERT	107968	42.62	-113.68	4200	1906	2002	78	Rupert
93	1	ST ANTHONY	108022	43.97	-111.67	4970	1940	2004	65	Rexburg
94	1	SAINT MARIES	108062	47.32	-116.57	2140	1897	2004	104	Coeur d'alene Airport, ID (KCOE)
95	1	SALMON	108076	45.18	-113.88	3950	1930	1967	37	Salmon-Lemhi Cnty Airport, ID (KSMN)
--	2	SALMON 1 N	108080	45.18	-113.90	3970	1967	2004	37	Salmon-Lemhi Cnty Airport, ID (KSMN)
96	1	SANDPOINT KSPT	108137	48.28	-116.57	2100	1910	2004	92	Coeur d'alene Airport, ID (KCOE)
97	1	SHOSHONE	108380	42.93	-114.40	3970	1908	2004	93	Twin Falls
98	2	SODA SPRINGS	108535	42.65	-111.60	5780	1978	2004	25	Afton, WY
99	1	STANLEY	108676	44.22	-114.93	6240	1963	2004	36	Stanley Ranger Station, ID (KSNT)
100	1	STREVELL CAA AIRPORT	108786	42.02	-113.22	5280	1948	1986	36	Malta
101	1	SWAN VALLEY 1 W	108937	43.45	-111.37	5240	1960	2004	45	Afton, WY
102	1	TETONIA EXPERIMENT STN	109065	43.85	-111.27	6170	1952	2004	52	Ashton
103	1	THREE CREEK	109119	42.05	-115.17	5400	1940	1987	47	Twin Falls
104	1	TWIN FALLS 2 NNE	109294	42.58	-114.47	3770	1905	1974	68	Twin Falls
105	2	TWIN FALLS 3 SE	109299	42.53	-114.42	3770	1948	1977	29	Twin Falls
106	1	TWIN FALLS WSO	109303	42.55	-114.35	3960	1963	2004	42	Twin Falls
107	1	WEISER	109638	44.25	-116.97	2110	1982	2004	23	Parma
	107	Temperature stations								
	5	location duplicates/moves								

*Heritage Flag = 1 if station was included in Allen and Brockway (1983); Flag = 2 indicates a "new" station

**Additional information is given in Appendix 5, including whether the location is in a generally irrigated setting, general aridity rating of the station, soil permeability and soil water holding characteristics.

Table 4. AgriMet agricultural weather stations for consumptive use computations. The periods of record for all AgriMet stations ran through 2005.

Internal ET Sta. no.	Internal AgriMet Sta. no.	AgriMet Station Location	Lat, deg-dec	Long, deg-dec	Elev, m	Beg. of AgriMet Record	Coop Sta for Snow Cover	CoopNo for Snow Cover
108	1	Aberdeen	42.95	-112.83	1341.1	3/20/91	Aber.	100010
109	2	Ashton	44.03	-111.47	1615.4	6/23/89	Ashton	100470
110	3	Fairfield	43.31	-114.83	1535.6	6/23/89	Picabo	107040
111	4	Glenns Ferry	42.87	-115.36	922.0	4/14/93	Gl.Fer.	103631
112	5	Grand View	42.91	-116.06	786.4	2/16/93	GrandV	103760
113	6	Malta	42.44	-113.41	1344.2	6/23/89	Malta	105563
114	7	Monteview	44.02	-112.54	1479.8	10/3/96	Rexb	107644
115	8	Nampa	43.44	-116.64	802.8	3/12/96	BoisAP	101022
116	9	Parma	43.80	-116.93	702.6	6/23/89	Parma	106844
117	10	Picabo	43.31	-114.17	1493.5	4/21/93	Picabo	107040
118	11	Rexburg	43.85	-111.77	1485.9	6/23/89	Rexb	107644
119	12	Rupert	42.60	-113.84	1266.4	6/23/89	Rupert	107968
120	13	Twin Falls	42.55	-114.35	1194.8	5/5/90	TF WS	109303
121	14	Afton, WY	42.73	-110.94	1892.8	6/23/89	Lifton	105275
122	15	Fort Hall	43.07	-112.43	1355	4/3/93	Ft. Hall	103297
123	16	Kettle Butte	43.55	-112.33	1565	10/3/96	IF 46W	104460

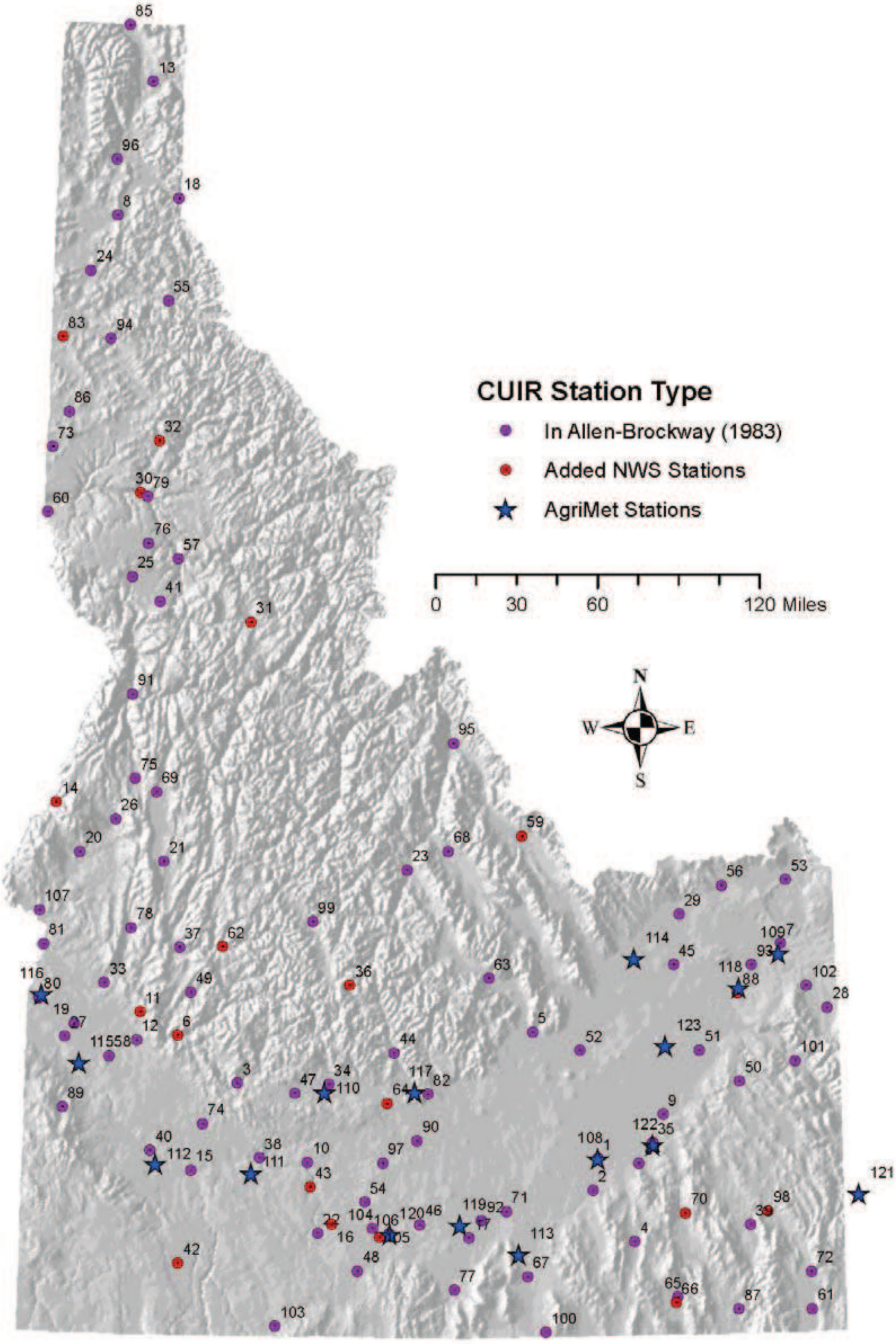

Figure 3. National Weather Service and AgriMett weather station locations used in this report. Numbers are the internal ET station numbers assigned to each station.

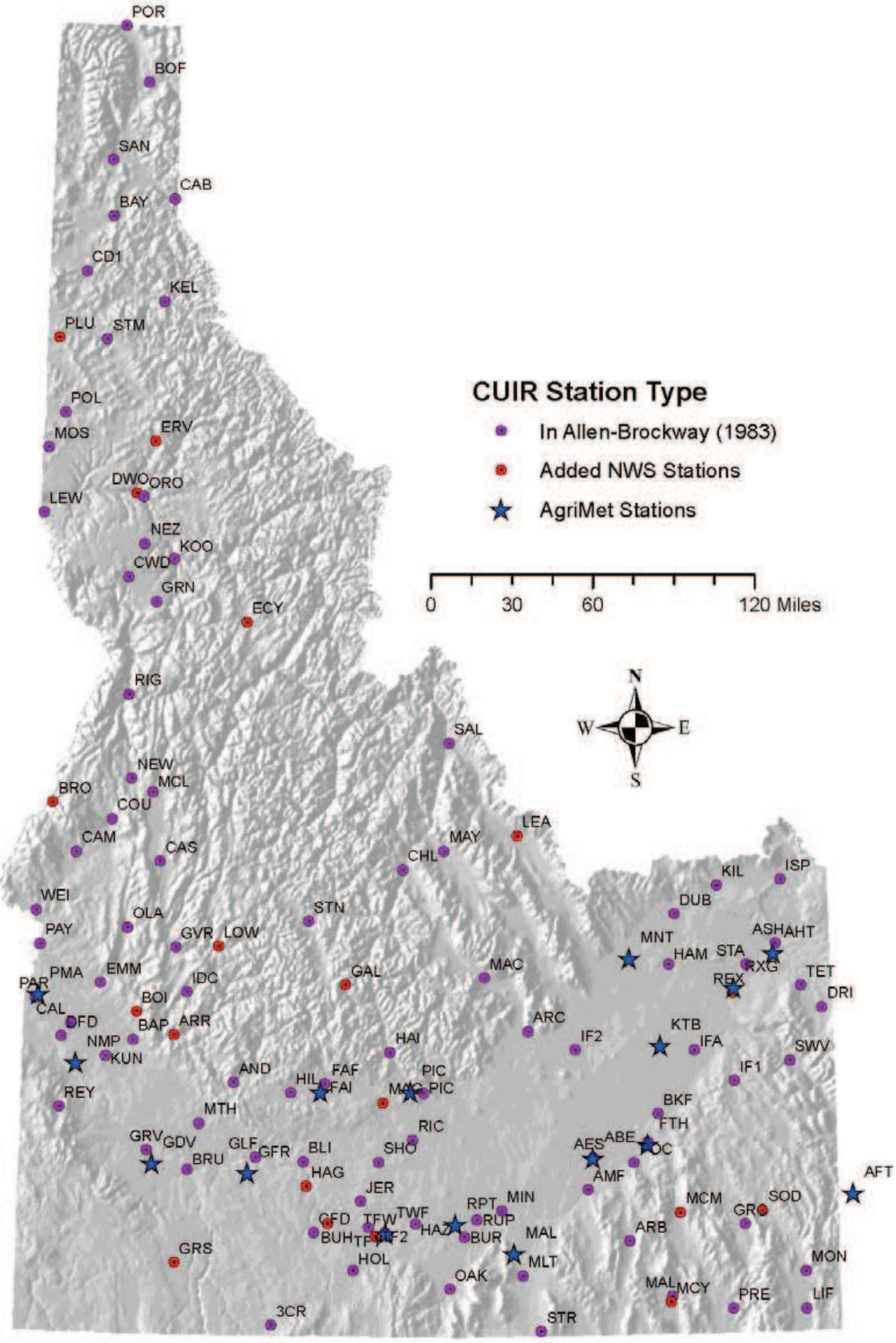

Figure 4. National Weather Service and AgriMett weather station locations used in this report. Abbreviations represent the name of the nearby town or city to a station.

Data Assembly

NWS Stations. 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. These data are officially collected and housed by the National Climatic Data Center (NCDC) of the National Oceanic and Atmospheric Administration. Data are generally available from the NCDC from about 1930 onwards. Earlier data sets for weather data collected in Idaho have been compiled, along with the later data periods by the *Inside Idaho* geospatial data clearinghouse and archiving system of the University of Idaho.

Mean monthly wind data from AgriMet stations in southern Idaho and typically airport locations in central and northern Idaho were assigned to each NWS station based on the station's location and local relief. The assignments are noted in Table 3 and the clustering of NWS stations with the assigned wind station are shown in Figure 5. Descriptions of the wind stations are given in Table 5. Data for the Logan, UT station came from R.Allen, pers. commun. The data are summarized in Table 2.5 of Appendix 2.

Table 5. Wind station names and locations used to assign mean monthly wind speed values to NWS stations. Many of the wind stations are AgriMet agricultural weather stations.

Internal Wind Sta. no.	AgriMet and NOAA Station Location Names	Elev, m	Lat, deg-dec	Long, deg-dec	WBAN no.	Beg. of Record	Abbreviation
1	Aberdeen	1341	42.95	-112.83		3/20/91	ABE
2	Ashton	1615	44.03	-111.47		6/2/87	AHT
3	Fairfield	1536	43.31	-114.83		6/25/87	FAF
4	Glenns Ferry	922	42.87	-115.36		4/14/93	GFR
5	Grand View	786	42.91	-116.06		2/16/93	GDV
6	Malta	1344	42.44	-113.41		6/2/83	MAL
7	Monteview	1480	44.02	-112.54		10/3/96	MNT
8	Nampa	803	43.44	-116.64		3/12/96	NMP
9	Parma	703	43.80	-116.93		3/28/86	PMA
10	Picabo	1493	43.31	-114.17		4/21/93	PIC
11	Rexburg	1486	43.85	-111.77		6/3/87	RXG
12	Rupert	1266	42.60	-113.84		3/9/88	RPT
13	Twin Falls	1195	42.55	-114.35		5/5/90	TWF
14	Afton, WY	1893	42.73	-110.94		10/20/87	AFT
15	Logan, UT - USU Drainage Farm	1350	41.7	-111.8		1988-1993	LOG
16	Challis Airport, ID (KU15)	1534	44.52	-114.22	4114	9/98 -	CHA
17	Coeur d'alene Airport, ID (KCOE)	703	47.77	-116.82	24136	1943 -	CDA
18	Elk City, ID (KP69)	1236	45.82	-115.43	94174	unknown -	ECA
19	Lewiston-Nez Perce County Airport, ID (KLWS)	437	46.37	-117.02	24149	1946 -	LNA
20	McCall Airport, ID (KMYL)	1528	44.88	-116.10	94182	1954	MCA
21	Mullan Pass VOR, ID (KMLP)	1837	47.45	-115.65	24154	1935 -	MUL
22	Salmon-Lemhi County Airport, ID (KSMN)	1233	45.12	-113.88	24196	1966 -	SMN
23	Stanley Ranger Station, ID (KSNT)	1980	44.17	-114.93	4112	3/98 -	SRS

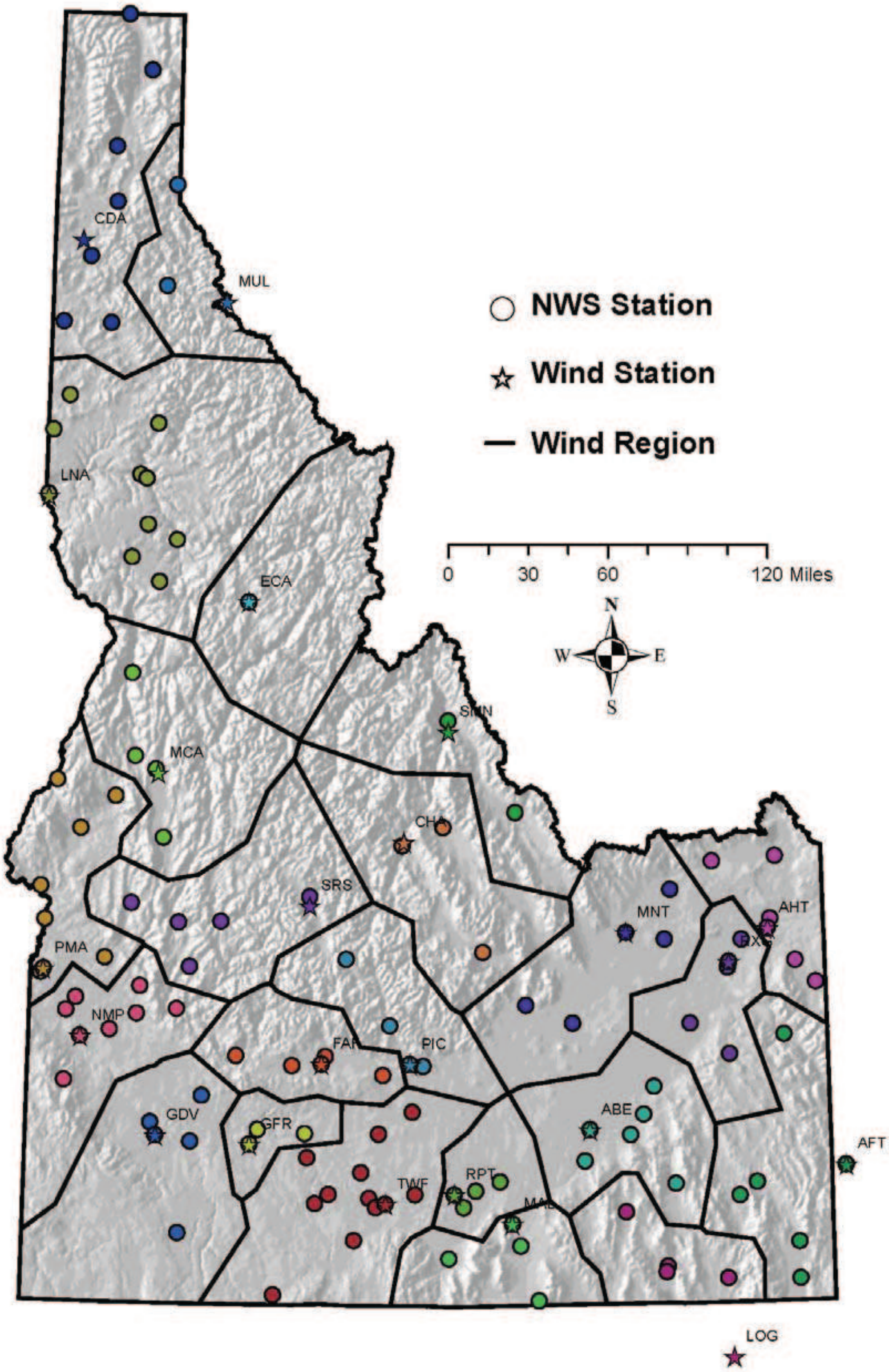

Figure 5. Grouping of National Weather Service weather stations with stations used for assigning mean monthly wind data. Abbreviations represent the name of the wind station as defined in Table 5.

Missing days at NWS stations were flagged using values of –999 for temperature and –99 for other values when more than a few days (commonly an entire month of data) were missing from the original data base. Data for missing days within an otherwise complete month of data were estimated as equal to the value for the preceding day. Periods having more than a few missing days were filled in using long term averages during the ET_c calculations for purposes of computing growing degree days during growing seasons. However, these periods were set back to –999 or –99 values in the final ET_c files.

AgriMet. AgriMet data were assessed for quality of measurements and calibration of sensors. This exercise is important with electronic instrumention as the equipment can, on occaision, malfunction or break or the calibrations can drift. Details on the quality assessment and adjustments made to data are summarized in Appendix 4.

Evapotranspiration Calculation Mechanics

Calculation of reference ET_r and the basic form and approach for crop coefficients is described in earlier sections. Development of crop coefficient curves is described in Appendix 3. This section describes additional calculation steps employed in making ET estimates for specific crop and land-cover types. A daily soil water balance was computed for each crop or land-use type and for each year of record at each weather station. The soil water balance was used to track daily evaporation from the soil surfaces as well as transpiration from vegetation.

All calculations of crop ET including evaporation from bare soil were done in a computer model named UI_KcETr that was coded in Visual Basic language, version 6. The UI_KcETr model read reference ET_r data from files previously created for each weather station and crop parameter information for each station summarized from spreadsheet files. Calculations within UI-KcETr were made on a daily basis. Calculations included the following components:

a. The FAO-56 method for estimating **evaporation from bare, wet soil**, as described in Annex 1, was applied where a daily water balance was computed for the top 10 cm of soil
b. **Irrigations were simulated** for irrigated crops in irrigated regions for purposes of estimating evaporation from wet soil surfaces. Scheduling of irrigations was made using a root-zone water balance assuming a nonresistricted root zone and depletion of soil water to an allowable depletion level (MAD). Simulated irrigation schedules were typically like those practiced with surface irrigation and with hand-move or wheel-line sprinkler systems (i.e., 'low frequency'). The beginning of irrigation was scheduled a specified number of days following planting or greenup (Table 7) with the limitation of no irrigation durng the development period when K_{cb} was < 0.22. This was done to prevent a series of frequent, light irrigations early in the season when the rootzone was shallow.
c. **Available water holding capacity** and texture of soil for each station was determined using information from the National StatsGo soils information data base using a GIS analysis of the national soil data base for the area assigned to each station (polygon) as described in Appendix 5.
d. **Precipitation runoff** was estimated using the NRCS Curve Number method where antecedent moisture was computed from the daily surface soil water balance. The curve number was determined from soil texture based on the StatsGo soils data base and is described in Appendix 6.
e. **Snow cover data** as observed at many of the NWS stations was used to modify winter time estimates of evaporation caused by high albedo of snow and energy required for heat of fusion. as described in Appendix 6. Snow cover was also used during adjustment of cumulative growing degree days for winter wheat during winter.
f. **Timing of greenu**p of natural vegetation, alfalfa, pasture, turf and winter wheat and planting dates for annual agricultural crops was estimated using either cumulated growing degree days or 30-day mean air temperature as described in the following section and in Appendix 8.

Crop and ET Modeling Parameters

Crops Grown. Some parts of the state of Idaho have short growing seasons that limit the types of crops that can be grown. Other parts of the state are traditionally rainfed areas that also limit types of crops. Specific crop and land-cover types were assigned to each weather station according to traditional and current crops grown. The crop categories and general cultural areas in the state are listed in Table 6.

Table 6. Names of Crops and Land Use Covers for Evapotranspiration or Evaporation.

No.	Descriptive Crop and Land Use Name
	General to Idaho (22 classes)
1	Alfalfa Hay - peak (no cutting effects (i.e., alfalfa reference except early and late))
2	Alfalfa Hay - frequent cuttings - dairy style
3	Alfalfa Hay - less frequent cuttings - beef cattle style
4	Grass Hay
5	Snap and Dry Beans - fresh
6	Snap and Dry Beans - seed
7	Field Corn having moderate lengthed season
8	Silage Corn (same as field corn, but with truncated season)
9	Sweet Corn--early plant
10	Sweet Corn--late plant
11	Spring Grain—Irrigated (wheat, barley, oats, triticale)
12	Spring Grain—Rainfed (wheat, barley, oats, triticale)
13	Winter Grain—Irrigated (wheat, barley)
14	Winter Grain—Rainfed (wheat, barley)
15	Grass Pasture – high management
16	Grass Pasture – low management
17	Grass - Turf (lawns) – Irrigated
18	Grass - Turf (lawns) – Rainfed
19	Orchards - Apples and Cherries w/ground cover
20	Orchards - Apples and Cherries no ground cover
21	Garden Vegetables – general
22	Carrots
23	Onions
24	Melons
25	Grapes--wine
36	Sunflower—Irrigated
37	Sunflower—Rainfed
38	Safflower—Irrigated
39	Safflower—Rainfed
	Specific to Southern Idaho (10 classes)
26	Alfalfa Seed
27	Garden Peas--fresh
28	Garden Peas--seed
29	Potatoes--processing (early harvest)
30	Potatoes--cold pack (late harvest)
31	Sugar beets
32	Hops
33	Mint
34	Poplar (third year and older)
43	Asparagus

	Specific to Northern Idaho (6 classes)
35	Lentils
40	Canola
41	Mustard
42	BlueGrass Seed
	Natural land-use conditions (14 classes)
44	Bare soil
45	Mulched soil, including wheat stubble
46	Dormant turf (winter time)
47	Range Grasses- early, short season (cheat, etc.)
48	Range Grasses- long season (bunch, wheatgrass, etc.)
49	Range Grasses- bromegrass
50	Sage brush
51	Wetlands--large stands
52	Wetlands--narrow stands
53	Cottonwoods
54	Willows
55	Open water – shallow systems (large ponds, streams)
56	Open water – deep systems (lakes, reservoirs)
57	Open water – small stock ponds

Land use types 44, 45 and 46 (bare soil, mulched soil and dormant turf) in Table 6 were assigned to nongrowing periods for each crop type during estimation of evaporation occurring during the nongrowing season.

Table 7 contains various crop parameter values assigned to each crop or land-use category for which ET_c was calculated. The crop curve types listed in Table 7 are described in Appendix 3. These are:

No.	Crop curve type
1	Normalized cumulative growing degree days
2	Percent time planting to effective full cover (for entire season)
3	Percent time planting to effective full cover, then days after effective full cover
4	Percent time planting to termination

The 'Irrigation Flag' in Table 7 indicates whether the crop was assumed to be irrigated and therefore some increased evaporation from wet soil. An irrigation flag equal to 0 indicated that the crop or land-use condition was never irrigated, regardless of location and a flag equal to 3 indicated that the crop was always irrigated. An irrigation flag equal to 1 or 2 indicated that the crop or surface was irrigated if in an irrigated region (see Tables in Appendix 5 for station environment information) and was not irrigated if in a region that does not generally have irrigation, for example in much of northern Idaho.

The 'Flag for means to estimate pl or gu' in Table 7 identifies the procedure used to estimate the planting date or greenup. A flag equal to 1 indicates that cumulative growing degree days from January is used and a flag equal to 2 indicates that 30 day mean air temperature is used.

Table 8 indicates the crops that were modeled at each location. In addition, values in Table 8, if not equal to 1, represent the adjustments made to lengths of growing periods estimated using the standard CGDD-based method. These adjustments were made for for some crops and at some locations to produce lengths of growing periods that were more characteristic of actual practice.

Table 7. Crop Parameter Assignments for the 57 crop and land-use categories

	Alfalfa Hay - peak (no cutting effects)	Alfalfa Hay - freq dairy style	Alfalfa Hay - beef cattle style	Grass Hay	Snap and Dry Beans - fresh	Snap and Dry Beans - seed	Field Corn	Silage Corn	Sweet Corn -- early	Sweet Corn -- late
Flag for crop grown	1	2	3	4	5	6	7	8	9	10
Irrigation Flag: 0=no, 1or2=if irr.region, 3=yes	1	1	1	1	1	1	1	1	1	1
Days after pl./gu for earliest irrigation	0	0	0	0	0	0	0	0	0	0
fw: assume sprinkler	1	1	1	1	1	1	1	1	1	1
winter surf. cov.: 1 bare, 2 mulch, 3 sod	1	1	1	3	1	1	1	1	1	1
Kc max: max of value or Kcb+.05	1	1	1	1	1	1	1	1	1	1
MAD during ini. + dev. Stage (%)	60	60	60	50	60	60	60	60	60	60
MAD during midseas. and late seas.	60	60	60	50	50	50	50	50	50	50
Initial rooting depth, m	0.7	0.7	0.7	0.3	0.12	0.12	0.12	0.12	0.12	0.12
Maximum rooting depth, m	1.8	1.8	1.8	1.1	1.2	1.2	1.5	1.5	1	1
End of Root growth, as a fraction of time from pl to EFC (or term if type 4)	0.5	0.5	0.5	0.4	1.2	1.2	1.2	1.2	1.2	1.2
Starting Crop height, m	0.1	0.1	0.1	0.1	0.05	0.05	0.1	0.1	0.1	0.1
Maximum Crop height, m	0.6	0.6	0.6	0.6	0.35	0.35	3	3.5	1.5	1.5
Crop curve number	**16**	**13**	**13**	**19**	**12**	**11**	**8**	**9**	**10**	**10**
Crop curve type	1	1	1	1	1	1	1	1	1	1
Flag for means to estimate pl or gu	1	1	1	2	2	2	2	2	2	2
T30 for pl or gu or CGDD for pl or gu	240	240	240	5	14	14	10	10	10	12
Date of pl or gu[1]	[1] a negative values is an offset to the prior row, pos is months (fraction)									
Tbase: (neg. to use corn curve)	0	0	0	0	5	5	-10	-10	-10	-10
CGDD for EFC, °C-days	700	700	850	1300	670	670	540	540	540	540
CGDD for termination, °C-days	4000	650	900	4000	950	1350	1400	1200	1000	1000
time for EFC, days after pl or gu	For alfalfa, the first CGDD line above is for the first cycle, the 2nd for following cycles									
time for harvest, days after EFC										
Killing frost temperature, °C	-7	-7	-7	-5	-2	-5	-4	-4	-5	---
Invoke Stress, days after pl or gu	2	2	2	2	1	1	1	1	1	2
Curve no: coarse soil	60	60	60	60	67	67	67	67	67	63
Curve no: medium soil	68	68	68	68	75	75	75	75	75	75
Curve no: fine soil	77	77	77	77	85	85	85	85	85	85

	Spring Grain -- Irrigated	Spring Grain -- Rainfed	Winter Grain -- Irrigated	Winter Grain -- Rainfed	Grass Pasture – high manage ment	Grass Pasture – low manage ment	Grass - Turf (lawns) -- Irrigated	Grass - Turf (lawns) -- Rainfed	Orchard - Apples +Cherry w/ground cover	Orchard - Apples +Cherry no grnd cover	Garden Vegetab les – general
Flag for crop grown	11	12	13	14	15	16	17	18	19	20	21
Irrigation Flag: 0=no, 1or2=if irr.region, 3=yes	3		3		2	2	3		1	1	1
Days after pl./gu for earliest irrigation	20	20	155	155	0	0	0	0	0	0	0
fw: assume sprinkler	1	1	1	1	1	1	1	1	1	1	1
winter surf. cov.: 1 bare, 2 mulch, 3 sod	2	2	2	2	3	3	3	3	2	1	1
Kc max: max of value or Kcb+.05	1	1	1	1	1	1	1	1	1	1	1
MAD during ini. + dev. Stage (%)	60	60	60	60	60	60	60	60	50	50	50
MAD during midseas. and late seas.	50	50	50	50	50	50	50	50	50	50	40
Initial rooting depth, m	0.25	0.25	0.25	0.25	0.3	0.3	0.3	0.3	1.5	1.5	0.12
Maximum rooting depth, m	1.8	1.8	1.8	1.8	1	1	0.6	0.6	1.5	1.5	0.6
End of Root growth, as a fraction of time from pl to EFC (or term if type 4)	1.2	1.2	1.2	1.2	0.4	0.4	0.4	0.4	0.5	0.5	1.2
Starting Crop height, m	0.05	0.05	0.05	0.05	0.1	0.1	0.05	0.05	4	4	0.1
Maximum Crop height, m	1	1	1	1	0.25	0.15	0.1	0.1	4	4	0.4
Crop curve number	1	1	2	2	30	31	29	29	24	25	20
Crop curve type	1	1	1	1	3	2	2	2	2	2	2
Flag for means to estimate pl or gu	2	2	3	3	2	2	2	2	2	2	2
T30 for pl or gu or CGDD for pl or gu	4	4			5	5	5	5	6	6	10
Date of pl or gu[1]			10	10							
Tbase: (neg. to use corn curve)	0	0	0	0							
CGDD for EFC, ^{o}C-days	840	840	1080	1080							
CGDD for termination, ^{o}C-days	2160	2160	2600	2600							
time for EFC, days after pl or gu					30	40	60	60	55	80	80
Harvest, days after EFC (neg til frost)	180	180			-220	-220	-270	-270	-260	-260	200
Killing frost temperature, ^{o}C	---	---	---	---	-5	-5	-5	-5	-5	-5	-2
Invoke Stress, days after pl or gu	2	2	2	2	2	2	2	2	1	1	1
Curve no: coarse soil	63	63	65	65	40	40	40	40	60	65	72
Curve no: medium soil	75	75	75	75	70	70	70	70	68	72	80
Curve no: fine soil	85	85	85	85	82	82	82	82	70	82	88

[1] a negative values is an offset to the prior row, pos is months (fraction)

	Carrots	Onions	Melons	Grapes --wine	Alfalfa Seed	Peas--fresh	Peas--seed	Potatoes processing (early harvest)	Potatoes coldpack (late harv.)	Sugar beets	Hops	Mint	Poplar (>=3 yrs)
Flag for crop grown	22	23	24	25	26	27	28	29	30	31	32	33	34
Irrigation Flag: 0=no, 1or2=if irr.region, 3=yes	1	1	1	2	2	2	2	1	1	1	1	1	1
Days after pl./gu for earliest irrigation	0	0	0	20	0	0	0	0	0	0	0	0	0
fw: assume sprinkler	1	1	1	1	1	1	1	1	1	1	1	1	1
winter surf. cov.: 1 bare, 2 mulch, 3 sod	1	1	1	1	2	1	1	1	1	1	1	2	2
Kc max: max of value or Kcb+.05	1	1	1	1	1	1	1	1	1	1	1	1	1
MAD during ini. + dev. Stage (%)	50	50	50	70	70	60	60	50	50	50	50	50	60
MAD during midseas. and late seas.	40	40	50	70	70	50	50	40	40	50	50	50	50
Initial rooting depth, m	0.12	0.2	0.2	1	0.7	0.2	0.2	0.3	0.3	0.15	1	0.5	1.5
Maximum rooting depth, m	0.6	0.8	1.2	2	1.5	1	1	0.8	0.8	1.3	1.5	1.3	1.5
End of Root growth, as a fraction of time from pl to EFC (or term if type 4)	1.2	1.2	1.2	1	0.5	1	1	1	1	1.2	1	0.8	1
Starting Crop height, m	0.1	0.1	0.05	1.5	0.1	0.05	0.05	0.05	0.05	0.05	1	0.1	6
Maximum Crop height, m	0.5	0.4	0.3	1.5	0.6	0.3	0.3	0.4	0.4	0.35	6	0.5	6
Crop curve number	**20**	**20**	**22**	**21**	**33**	**4**	**3**	**7**	**6**	**5**	**23**	**18**	**34**
Crop curve type	2	2	2	3	3	1	1	1	1	1	2	1	3
Flag for means to estimate pl or gu	2	2	2	2	1	2	2	2	2	2	1	1	2
T30 for pl or gu or CGDD for pl or gu	6.5	6.5	9	8	240	5	5	6	7	8	600	600	8
Date of pl or gu[1]													
Tbase: (neg. to use corn curve)					0	0	0	5	5	0	0	0	
CGDD for EFC, ^{o}C-days						637	637	700	740	970		1400	
CGDD for termination, ^{o}C-days						1000	1616	1550	1780	2600		4000	
time for EFC, days after pl or gu	80	70	80	80	80						100		21
Harvest, days after EFC (neg til frost)	200	200	270	-270	100						200		-200
Killing frost temperature, ^{o}C	-2	-2	-2	-3	-7	-4	-4	-2	-2	-4	-2	-4	-5
Invoke Stress, days after pl or gu	1	1	1	1	1	1	1	1	1	1	1	1	1
Curve no: coarse soil	72	72	72	65	60	63	63	70	70	67	65	60	65
Curve no: medium soil	80	80	80	72	68	70	70	76	76	74	72	68	72
Curve no: fine soil	88	88	88	82	77	82	82	88	88	86	82	77	82

	Lentils	Sunflower -- Irrigated	Sunflower -- Rainfed	Safflower -- Irrigated	Safflower -- Rainfed	Canola	Mustard
Flag for crop grown	35	36	37	38	39	40	41
Irrigation Flag: 0=no, 1or2=if irr.region, 3=yes		1		1			
Days after pl./gu for earliest irrigation	0	0	0	0	0	0	0
fw: assume sprinkler	1	1	1	1	1	1	1
winter surf. cov.: 1 bare, 2 mulch, 3 sod	1	1	1	2	2	2	2
Kc max: max of value or Kcb+.05	1	1	1	1	1	1	1
MAD during ini. + dev. Stage (%)	60	60	60	60	60	60	60
MAD during midseas. and late seas.	50	60	60	60	60	60	60
Initial rooting depth, m	0.15	0.2	0.2	0.2	0.2	0.2	0.2
Maximum rooting depth, m	0.9	2.5	2.5	2.5	2.5	1.6	1.4
End of Root growth, as a fraction of time from pl to EFC (or term if type 4)	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Starting Crop height, m	0.05	0.1	0.1	0.1	0.1	0.1	0.1
Maximum Crop height, m	0.5	2	2	1	1	1	1
Crop curve number	**17**	**28**	**28**	**28**	**28**	**27**	**27**
Crop curve type	1	2	2	2	2	2	2
Flag for means to estimate pl or gu	2	2	2	2	2	3	3
T30 for pl or gu or CGDD for pl or gu	4.7	10	10	8	8		
Date of pl or gu[1]						4.83	4.83
Tbase: (neg. to use corn curve)	0						
CGDD for EFC, °C-days	935						
CGDD for termination, °C-days	2160						
time for EFC, days after pl or gu		70	70	70	70	55	55
Harvest, days after EFC (neg til frost)		190	190	190	190	190	190
Killing frost temperature, °C	-4	-4	-4	-4	-4	-4	-4
Invoke Stress, days after pl or gu	1	1	1	1	1	1	1
Curve no: coarse soil	58	58	58	58	58	58	58
Curve no: medium soil	72	72	72	72	72	72	72
Curve no: fine soil	83	83	83	83	83	83	83

	Blue Grass Seed	Asparagus	Bare soil	Mulched soil, including wheat stubble	Dormant turf/sod (winter time)	Range Grasses- short season -cheat, etc.	Range Grasses- bunch, wheat grass, etc.	Range Grasses- brome grass	Sage brush
Flag for crop grown	42	43	44	45	46	47	48	49	50
Irrigation Flag: 0=no, 1or2=if irr.region, 3=yes		1							
Days after pl./gu for earliest irrigation	0	40	0	0	0	0	0	0	0
fw: assume sprinkler	1	1	1	1	1	1	1	1	1
winter surf. cov.: 1 bare, 2 mulch, 3 sod	3	2	1	2	3	2	2	2	2
Kc max: max of value or Kcb+.05	1	1	1	1	1	1	1	1	1
MAD during ini. + dev. Stage (%)	60	60	60	60	60	60	60	60	60
MAD during midseas. and late seas.	50	60	60	60	60	60	60	60	60
Initial rooting depth, m	0.3	1	0.08	0.08	0.08	0.3	0.6	0.6	3
Maximum rooting depth, m	1	1	0.08	0.08	0.08	0.6	1.8	1.2	3
End of Root growth, as a fraction of time from pl to EFC (or term if type 4)	0.4	1	1	1	1	0.3	0.3	0.3	1
Starting Crop height, m	0.1	0.1	0.05	0.05	0.05	0.05	0.05	0.05	1
Maximum Crop height, m	0.3	1	0.05	0.05	0.05	0.3	0.7	0.7	1
Crop curve number	**32**	**26**	--	--	--	**38**	**39**	**40**	**37**
Crop curve type	3	2	**--**	**--**	**--**	4	4	4	4
Flag for means to estimate pl or gu	2	2	4	4	4	2	2	2	2
T30 for pl or gu or CGDD for pl or gu	5	5				5	5	5	5
Date of pl or gu[1]						-10	-10	-10	-10
Tbase: (neg. to use corn curve)									
CGDD for EFC, ^{o}C-days									
CGDD for termination, ^{o}C-days									
time for EFC, days after pl or gu	35	60	--	--	--	--	--	--	--
Harvest, days after EFC (neg til frost)	-230	-230	--	--	--	--	--	--	--
Killing frost temperature, ^{o}C	-5	-3	-50	-50	-50	-5	-5	-5	-5
Invoke Stress, days after pl or gu	2	1	2	2	2	1	1	1	2
Curve no: coarse soil	40	65	77	70	40	49	49	49	70
Curve no: medium soil	70	72	86	76	70	69	69	69	76
Curve no: fine soil	82	82	92	88	82	81	81	81	88

	Wetlands--large stands	Wetlands--narrow stands	Cottonwoods	Willows	Open water – shallow systems (large ponds, streams)	Open water – deep systems (lakes, reservoirs)	Open water – small stock ponds
Flag for crop grown	51	52	53	54	55	56	57
Irrigation Flag: 0=no, 1or2=if irr.region, 3=yes							
Days after pl./gu for earliest irrigation	0	0	0	0	0	0	0
fw: assume sprinkler	1	1	1	1	1	1	1
winter surf. cov.: 1 bare, 2 mulch, 3 sod	2	2	2	2			
Kc max: max of value or Kcb+.05	1	1	1	1	1	1	1
MAD during ini. + dev. Stage (%)	60	60	60	60	60	60	60
MAD during midseas. and late seas.	60	60	60	60	60	60	60
Initial rooting depth, m	1	1	2	2	0	0	0
Maximum rooting depth, m	2	2	2	2	0	0	0
End of Root growth, as a fraction of time from pl to EFC (or term if type 4)	1	1	0.5	0.5	0	0	0
Starting Crop height, m	0.3	0.3	10	5	0.005	0.005	0.005
Maximum Crop height, m	1.5	1.5	10	5	0.005	0.005	0.005
Crop curve number	**35**	**36**	**41**	**42**	**--**	**--**	**--**
Crop curve type	3	3	2	2	--	--	--
Flag for means to estimate pl or gu	2	2	2	2			
T30 for pl or gu or CGDD for pl or gu	11	11	6	4	4	4	4
Date of pl or gu[1]							
Tbase: (neg. to use corn curve)							
CGDD for EFC, ^{o}C-days							
CGDD for termination, ^{o}C-days							
time for EFC, days after pl or gu	45	45	60	60			
Harvest, days after EFC (neg til frost)	-200	-200	-260	-260			
Killing frost temperature, ^{o}C	-2	-2	-4	-6	-50	-50	-50
Invoke Stress, days after pl or gu	0	0	0	0	1	1	1
Curve no: coarse soil	30	30	60	65			
Curve no: medium soil	40	40	68	72			
Curve no: fine soil	50	50	70	82			

Table 8. Idaho NWS Temperature/Precipitation Stations used for Consumptive Use Computations for crops 1-27 ('1' indicates that the crop was modeled, 1+'.xx' or '0.yy' indicates that the crop was modeled with and that the Cumulative Growing Degree Days since planting required to achieve effective full cover was increased or reduced by multiplying by 1.xx or 0.yy during ET_c calculations, relative to the standard modeling estimates). Crop numbers (line one) are defined in Table 9.2.

No.	Crop No.: NOAA Station Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	ABERDEEN EXP.STN	1	1	1	1			1	1	1	1	1.00		0.97		1	1	1		1	1	1					1	1
2	AMERICAN FALLS 1 SW	1	1	1	1			1	1	1	1	1.00	1.00	1.00	1.00	1	1	1	1	1	1	1					1	1
3	ANDERSON DAM	1	1	1	1			1	1	1	1	1.00	1.00	1.00	1.00	1	1	1	1	1	1	1					1	1
4	ARBON 2 NW	1	1	1	1			1	1	1	1	1.00	1.00	0.96	0.96	1	1	1	1	1	1	1					1	1
5	ARCO	1	1	1	1			1	1	1	1	0.97	0.97	0.94	0.94	1	1	1	1	1	1	1					1	1
6	ARROWROCK DAM	1	1	1	1							1.00	1.00	1.00	1.00	1	1	1	1	1	1	1				1	1	
7	ASHTON	1	1	1	1			1	1	1	1	0.93	0.93	0.93	0.93	1	1	1	1	1	1	1					1	1
8	BAYVIEW MODEL BASIN	1	1	1	1			1	1	1	1	1.00	1.00	0.93	0.93	1	1	1	1	1	1	1						1
9	BLACKFOOT	1	1	1	1	1	1	1	1	1	1	1.00	1.00	1.00	1.00	1	1	1	1	1	1	1					1	1
10	BLISS	1	1	1	1	1	1	1	1	1	1	1.00		1.00		1	1	1		1	1	1	1	1	1	1	1	1
11	BOISE 7 N	1	1	1	1	1	1	1.15	1	1	1	1.00	1.00	1.00	1.00	1	1	1	1	1	1	1	1	1	1	1	1	1
12	BOISE WSFO AIRPORT	1	1	1	1	1	1	1.15	1	1	1	1.00		1.00		1	1	1		1	1	1	1	1	1	1	1	1
13	BONNERS FERRY	1	1	1	1			1	1	1	1	1.00	1.00	0.97	0.97	1	1	1	1	1	1	1				1	1	1
14	BROWNLEE DAM	1	1	1	1	1	1	1.15	1	1	1	1.00	1.00	1.00	1.00	1	1	1	1	1	1	1	1	1	1	1	1	1
15	BRUNEAU	1	1	1	1	1	1	1.15	1	1	1	1.00		1.00		1	1	1		1	1	1	1	1	1	1	1	1
16	BUHL	1	1	1	1	1	1	1	1	1	1	1.00		1.00		1	1	1		1	1	1	1	1	1	1	1	1
17	BURLEY FAA AP	1	1	1	1	1	1	1	1	1	1	1.00		1.00		1	1	1		1	1	1	1	1	1	1	1	1
18	CABINET GORGE	1	1	1	1			1	1	1	1	1.00	1.00	0.97	0.97	1	1	1	1	1	1	1						1
19	CALDWELL	1	1	1	1	1	1	1.15	1	1	1	1.00		1.00		1	1	1		1	1	1	1	1	1	1	1	1
20	CAMBRIDGE	1	1	1	1	1	1	1.15	1	1	1	1.00	1.00	1.00	1.00	1	1	1	1	1	1	1	1	1	1	1	1	1
21	CASCADE 1 NW	1	1	1	1									0.94	0.94	1	1	1	1			1						
22	CASTLEFORD 2 N	1	1	1	1	1	1	1	1	1	1	1.00		1.00		1	1	1		1	1	1	1	1	1	1	1	1
23	CHALLIS	1	1	1	1					1	1	1.00	1.00	0.95	0.95	1	1	1	1	1	1	1						
24	COEUR D ALENE 1 E	1	1	1	1			1	1	1	1	1.00	1.00	1.00	1.00	1	1	1	1	1	1	1						1
25	COTTONWOOD	1	1	1	1			1	1	1	1	1.00	1.00	0.98	0.98	1	1	1	1	1	1	1				1	1	1
26	COUNCIL	1	1	1	1	1	1	1.15	1	1	1	1.00	1.00	1.00	1.00	1	1	1	1	1	1	1	1	1	1	1	1	1
27	DEER FLAT DAM	1	1	1	1	1	1	1.15	1	1	1	1.00		1.00		1	1	1		1	1	1	1	1	1	1	1	1
28	DRIGGS	1	1	1	1					1	1	0.77	0.77	0.93	0.93	1	1	1	1	1	1	1					1	1
29	DUBOIS EXP.STN	1	1	1	1			1	1	1	1	0.92	0.92	0.95	0.95	1	1	1	1	1	1	1					1	1
30	DWORSHAK FISH HAT.	1	1	1	1			1	1	1	1	1.00	1.00	1.00	1.00	1	1	1	1	1	1	1				1	1	1
31	ELK CITY	1	1	1	1					1	1			0.94	0.94	1	1	1	1			1						
32	ELK RIVER 1 S	1	1	1	1			1	1	1	1	1.00	1.00	0.94	0.94	1	1	1	1	1	1	1						
33	EMMETT 2 E	1	1	1	1	1	1	1.15	1	1	1	1.00		1.00		1	1	1		1	1	1	1	1	1	1	1	1
34	FAIRFIELD	1	1	1	1							1.00	1.00	0.94	0.94	1	1	1	1								1	
35	FORT HALL	1	1	1	1			1	1	1	1	1.00	1.00	1.00	1.00	1	1	1	1	1	1	1					1	1
36	GALENA	1	1	1	1											1	1	1	1									
37	GARDEN VALLEY R S	1	1	1	1							1.00	1.00	0.98	0.98	1	1	1	1									
38	GLENNS FERRY	1	1	1	1	1	1	1	1	1	1	1.00		1.00		1	1	1		1	1	1	1	1	1	1	1	1
39	GRACE	1	1	1	1			1	1	1	1	1.00	1.00	0.95	0.95	1	1	1	1			1						1
40	GRAND VIEW	1	1	1	1	1	1	1.15	1	1	1	1.00		1.00		1	1	1		1	1	1	1	1	1	1	1	1
41	GRANGEVILLE	1	1	1	1			1	1	1	1	1.00	1.00	0.99	0.99	1	1	1	1	1	1	1				1	1	1

Table 8, continued. Idaho NWS Temperature/Precipitation Stations used for Consumptive Use Computations for crops 1-27 ('1' indicates that the crop was modeled, 1+'.xx' or '0.yy' indicates that the crop was modeled with and that the Cumulative Growing Degree Days since planting required to achieve effective full cover was increased or reduced by multiplying by 1.xx or 0.yy during ET_c calculations, relative to the standard modeling estimates). Crop numbers (line one) are defined in Table 9.2.

No.	**Crop No.:** NOAA Station Name	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**
42	GRASMERE	1	1	1	1							1.00	1.00	0.99	0.99	1	1	1	1			1						
43	HAGERMAN 2 SW	1	1	1	1	1	1	1	1	1	1	1.00		1.00		1	1	1		1	1	1	1	1	1	1	1	1
44	HAILEY RANGER STN	1	1	1	1					1	1	0.97	0.97	0.94	0.94	1	1	1	1			1						
45	HAMER 4 NW	1	1	1	1				1	1	1	1.00		0.94		1	1	1				1					1	1
46	HAZELTON	1	1	1	1	1	1	1	1	1	1	1.00		1.00		1	1	1		1	1	1	1	1	1	1	1	1
47	HILL CITY	1	1	1	1							0.93	0.93	0.93	0.93	1	1	1	1								1	
48	HOLLISTER	1	1	1	1	1	1	1	1	1	1	1.00	1.00	1.00	1.00	1	1	1	1	1	1	1	1	1	1	1	1	1
49	IDAHO CITY	1	1	1	1							1.00	1.00	0.95	0.95	1	1	1	1									
50	IDAHO FALLS 16 SE	1	1	1	1			1	1	1	1	0.79	0.79	0.93	0.93	1	1	1	1	1	1	1					1	1
51	IDAHO FALLS FAA ARPT	1	1	1	1			1	1	1	1	1.00	1.00	0.96	0.96	1	1	1	1	1	1	1					1	1
52	IDAHO FALLS 46 W	1	1	1	1			1	1	1	1	0.84		0.93		1	1	1		1	1	1					1	1
53	ISLAND PARK				1							1.00				1	1	1	1									
54	JEROME	1	1	1	1	1	1	1	1	1	1	1.00		1.00		1	1	1		1	1	1	1	1	1	1	1	1
55	KELLOGG	1	1	1	1							1.00	1.00	0.98	0.98	1	1	1	1			1						
56	KILGORE				1									0.93	0.93	1	1	1	1									
57	KOOSKIA	1	1	1	1			1	1	1	1	1.00	1.00	1.00	1.00	1	1	1	1	1	1	1				1	1	1
58	KUNA	1	1	1	1	1	1	1.15	1	1	1	1.00		1.00		1	1	1		1	1	1	1	1	1	1	1	1
59	LEADORE 2	1	1	1	1					1	1			0.93	0.93	1	1	1	1									
60	LEWISTON WB AP	1	1	1	1			1	1	1	1	1.00	1.00	1.00	1.00	1	1	1	1	1	1	1			1	1		1
61	LIFTON PUMPING STN	1	1	1	1					1	1	1.00	1.00	0.94	0.94	1	1	1	1			1						1
62	LOWMAN	1	1	1	1							1.00	1.00	0.94	0.94	1	1	1	1									
63	MACKAY RANGER STN	1	1	1	1				1	1	1	0.95	0.95	0.95	0.95	1	1	1	1			1						
64	MAGIC DAM	1	1	1	1			1	1	1	1	1.00	1.00	0.94	0.94	1	1	1	1			1						1
65	MALAD	1	1	1	1				1	1	1	1.00	1.00	1.00	1.00	1	1	1	1	1	1	1						
66	MALAD CITY	1	1	1	1				1	1	1	1.00	1.00	0.99	0.99	1	1	1	1	1	1	1						
67	MALTA 1 NE	1	1	1	1				1	1	1	1.00	1.00	1.00	1.00	1	1	1	1	1	1	1						
68	MAY	1	1	1	1					1	1	1.00	1.00	0.94	0.94	1	1	1	1	1	1	1						
69	MCCALL	1	1	1	1									0.93	0.93	1	1	1	1			1						
70	MCCAMMON	1	1	1	1				1	1	1	1.00	1.00	1.00	1.00	1	1	1	1	1	1	1						
71	MINIDOKA DAM	1	1	1	1	1	1	1	1	1	1	1.00		1.00		1	1	1		1	1	1	1	1	1	1	1	1
72	MONTPELIER	1	1	1	1					1	1	0.87	0.87	0.94	0.94	1	1	1	1			1						1
73	MOSCOW	1	1	1	1			1	1	1	1	1.00	1.00	1.00	1.00	1	1	1	1	1	1	1				1	1	1
74	MOUNTAIN HOME 1 W	1	1	1	1	1	1	1	1	1	1	1.00		1.00		1	1	1		1	1	1	1	1	1	1	1	1
75	NEW MEADOWS	1	1	1	1									0.94	0.94	1	1	1	1									
76	NEZPERCE	1	1	1	1			1	1	1	1	1.00	1.00	0.97	0.97	1	1	1	1	1	1	1				1	1	1
77	OAKLEY	1	1	1	1			1	1	1	1	1.00	1.00	1.00	1.00	1	1	1	1	1	1	1						1
78	OLA	1	1	1	1				1	1	1	1.00	1.00	1.00	1.00	1	1	1	1			1						1
79	OROFINO	1	1	1	1			1	1	1	1	1.00	1.00	1.00	1.00	1	1	1	1	1	1	1				1	1	1
80	PARMA Exp. Station	1	1	1	1	1	1	1.15	1	1	1	1.00		1.00		1	1	1		1	1	1	1	1	1	1	1	1
81	PAYETTE	1	1	1	1	1	1	1.15	1	1	1	1.00		1.00		1	1	1		1	1	1	1	1	1	1	1	1
82	PICABO	1	1	1	1					1	1	1.00	1.00	0.95	0.95	1	1	1	1			1						

Table 8, continued. Idaho NWS Temperature/Precipitation Stations used for Consumptive Use Computations for crops 1-27 (‘1’ indicates that the crop was modeled, 1+’.xx’ or ‘0.yy’ indicates that the crop was modeled with and that the Cumulative Growing Degree Days since planting required to achieve effective full cover was increased or reduced by multiplying by 1.xx or 0.yy during ET_c calculations, relative to the standard modeling estimates). Crop numbers (line one) are defined in Table 9.2.

No.	Crop No.: NOAA Station Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
83	PLUMMER 3 WSW	1	1	1	1			1	1	1	1	1.00	1.00	0.97	0.97	1	1	1	1	1	1	1						1
84	POCATELLO WB AP	1	1	1	1			1	1	1	1	1.00	1.00	1.00	1.00	1	1	1	1	1	1	1					1	1
85	PORTHILL	1	1	1	1				1	1	1	1.00	1.00	0.94	0.94	1	1	1	1	1	1	1				1	1	1
86	POTLATCH 3NNE	1	1	1	1			1	1	1	1	1.00	1.00	0.97	0.97	1	1	1	1	1	1	1				1	1	1
87	PRESTON 3 NE	1	1	1	1				1	1	1	1.00	1.00	0.99	0.99	1	1	1	1	1	1	1						
88	REXBURG	1	1	1	1			1	1	1	1	1.00	1.00	0.97	0.97	1	1	1	1	1	1	1					1	1
89	REYNOLDS	1	1	1	1			1	1	1	1	1.00	1.00	1.00	1.00	1	1	1	1	1	1	1				1	1	
90	RICHFIELD	1	1	1	1			1	1	1	1	1.00	1.00	1.00	1.00	1	1	1	1	1	1	1						1
91	RIGGINS RANGER STN	1	1	1	1				1	1	1	1.00	1.00	1.00	1.00	1	1	1	1	1	1	1			1	1		
92	RUPERT	1	1	1	1	1	1	1	1	1	1	1.00		1.00		1	1	1		1	1	1	1	1	1	1	1	1
93	ST ANTHONY	1	1	1	1			1	1	1	1	0.89	0.89	0.93	0.93	1	1	1	1	1	1	1					1	1
94	SAINT MARIES	1	1	1	1			1	1	1	1	1.00	1.00	0.98	0.98	1	1	1	1	1	1	1						1
95	SALMON	1	1	1	1			1	1	1	1	1.00	1.00	0.95	0.95	1	1	1	1	1	1	1					1	
96	SANDPOINT KSPT	1	1	1	1			1	1	1	1	1.00	1.00	0.95	0.95	1	1	1	1	1	1	1						1
97	SHOSHONE	1	1	1	1			1	1	1	1	1.00		1.00		1	1	1		1	1	1				1	1	1
98	SODA SPRINGS	1	1	1	1			1	1	1	1	0.91	0.91	0.93	0.93	1	1	1	1			1						1
99	STANLEY				1											1	1		1									
100	STREVELL	1	1	1	1				1			1.00	1.00	0.99	0.99	1	1	1	1			1						
101	SWAN VALLEY 1 W	1	1	1	1							0.94	0.94	0.94	0.94	1	1	1	1			1						
102	TETONIA EXP. STN	1	1	1	1					1	1	0.75	0.75	0.93	0.93	1	1	1	1	1	1	1					1	1
103	THREE CREEK	1	1	1	1									0.93	0.93	1	1	1	1			1						
104	TWIN FALLS 2 NNE	1	1	1	1	1	1	1	1	1	1	1.00		1.00		1	1	1		1	1	1	1	1	1	1	1	1
105	TWIN FALLS 3 SE	1	1	1	1	1	1	1	1	1	1	1.00		1.00		1	1	1		1	1	1	1	1	1	1	1	1
106	TWIN FALLS WSO	1	1	1	1	1	1	1	1	1	1	1.00		1.00		1	1	1		1	1	1	1	1	1	1	1	1
107	WEISER	1	1	1	1	1	1	1.15	1	1	1	1.00	1.00	1.00	1.00	1	1	1	1	1	1	1	1	1	1	1	1	1
108	Aberdeen AgriMet	1	1	1	1			1	1	1	1	1.00		1.00		1	1	1		1	1	1					1	1
109	Ashton AgriMet	1	1	1	1			1	1	1	1	0.95	0.93	0.94	0.93	1	1	1	1	1	1	1					1	1
110	Fairfield AgriMet	1	1	1	1							0.94	1	0.93	0.94	1	1	1	1								1	
111	Glenns Ferry AgriMet	1	1	1	1	1	1	1	1	1	1	1.00		1.00		1	1	1		1	1	1	1	1	1	1	1	1
112	Grand View AgriMet	1	1	1	1	1	1	1.15	1	1	1	1.00		1.00		1	1	1		1	1	1	1	1	1	1	1	1
113	Malta AgriMet	1	1	1	1				1	1	1	1.00	1	1.00	1	1	1	1	1	1	1	1						
114	Monteview AgriMet	1	1	1	1				1	1	1	1.00		0.94		1	1	1				1					1	1
115	Nampa AgriMet	1	1	1	1	1	1	1.15	1	1	1	1.00		1.00		1	1	1		1	1	1	1	1	1	1	1	1
116	Parma AgriMet	1	1	1	1	1	1	1.15	1	1	1	1.00		1.00		1	1	1		1	1	1	1	1	1	1	1	1
117	Picabo AgriMet	1	1	1	1					1	1	1.00	1	1.00	0.95	1	1	1	1			1						
118	Rexburg AgriMet	1	1	1	1			1	1	1	1	1.00	1	0.95	0.97	1	1	1	1	1	1	1					1	1
119	Rupert AgriMet	1	1	1	1	1	1	1	1	1	1	1.00		1.00		1	1	1		1	1	1	1	1	1	1	1	1
120	Twin Falls AgriMet	1	1	1	1	1	1	1	1	1	1	1.00		1.00		1	1	1		1	1	1	1	1	1	1	1	1
121	Afton, WY AgriMet	1	1	1	1					1	1	0.89	0.87	0.93	0.94	1	1	1	1			1						1
122	Fort Hall AgriMet	1	1	1	1			1	1	1	1	1.00	1	1.00	1	1	1	1	1	1	1	1					1	1
123	Kettle Butte AgriMet	1	1	1	1			1	1	1	1	1.00		0.97		1	1	1		1	1	1					1	1

Table 8. Continued. Idaho NWS Temperature/Precipitation Stations used for Consumptive Use Computations for crop/land-uses 28-57 ('1' indicates that the crop was modeled, 1+'.xx' or '0.yy' indicates that the crop was modeled with and that the Cumulative Growing Degree Days since planting required to achieve effective full cover was increased or reduced by multiplying by 1.xx or 0.yy during ET_c calculations, relative to the standard modeling estimates). Crop numbers (line one) are defined in Table 9.2.

No.	Crop No: NOAA Station Name	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51 to 57
1	ABERDEEN EXP.STN	1	1	1	1			1		1	1	1	1	1	1			1	1	1	1	1	1	1	1
2	AMERICAN FALLS 1 SW	1	1	1	1			1		1	1	1	1	1	1			1	1	1	1	1	1	1	1
3	ANDERSON DAM	1	1	1				1		1	1	1	1	1	1			1	1	1	1	1	1	1	1
4	ARBON 2 NW	1	1	1	1			1		1	1	1	1	1	1			1	1	1	1	1	1	1	1
5	ARCO	1	1	1	1			1				1	1	1	1			1	1	1	1	1	1	1	1
6	ARROWROCK DAM							1				1	1	1	1			1	1	1	1	1	1	1	1
7	ASHTON	1	1	1	1			1				1	1	1	1			1	1	1	1	1	1	1	1
8	BAYVIEW MODEL BASIN	1						1	1	1	1	1	1	1	1	1		1	1	1	1	1	1		1
9	BLACKFOOT	1	1	1	1			1		1	1	1	1	1	1			1	1	1	1	1	1	1	1
10	BLISS	1	1	1	1.2	1	1	1		1		1		1	1		1	1	1	1	1	1	1	1	1
11	BOISE 7 N	1	1	1.25	1.4	1	1	1		1	1	1	1	1	1		1	1	1	1	1	1	1	1	1
12	BOISE WSFO AIRPORT	1	1	1.25	1.4	1	1	1		1		1		1	1		1	1	1	1	1	1	1	1	1
13	BONNERS FERRY	1	1	1				1	1	1	1	1	1	1	1	1		1	1	1	1	1	1		1
14	BROWNLEE DAM		1	1.25	1.4		1	1		1	1	1	1	1	1			1	1	1	1	1	1	1	1
15	BRUNEAU	1	1	1.25	1.4		1	1		1		1		1	1		1	1	1	1	1	1	1	1	1
16	BUHL	1	1	1	1.2		1	1		1		1		1	1		1	1	1	1	1	1	1	1	1
17	BURLEY FAA AP	1	1	1	1.2		1	1		1		1		1	1		1	1	1	1	1	1	1	1	1
18	CABINET GORGE	1						1	1	1	1	1	1	1	1	1		1	1	1	1	1	1		1
19	CALDWELL	1	1	1.25	1.4	1	1	1		1		1		1	1		1	1	1	1	1	1	1	1	1
20	CAMBRIDGE	1	1	1.25	1.4	1	1	1		1	1	1	1	1	1		1	1	1	1	1	1	1	1	1
21	CASCADE 1 NW							1										1	1	1	1	1	1	1	1
22	CASTLEFORD 2 N	1	1	1	1.2		1	1		1		1		1	1		1	1	1	1	1	1	1	1	1
23	CHALLIS							1				1	1	1	1			1	1	1	1	1	1	1	1
24	COEUR D ALENE 1 E	1	1	1				1	1	1	1	1	1	1	1	1		1	1	1	1	1	1		1
25	COTTONWOOD	1						1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1
26	COUNCIL	1	1	1.25	1.4	1	1	1		1	1	1	1	1	1		1	1	1	1	1	1	1	1	1
27	DEER FLAT DAM	1	1	1.25	1.4	1	1	1		1		1		1	1		1	1	1	1	1	1	1	1	1
28	DRIGGS	1	1	1				1				1	1	1	1			1	1	1	1	1	1	1	1
29	DUBOIS EXP.STN	1	1	1				1				1	1	1	1			1	1	1	1	1	1	1	1
30	DWORSHAK FISH HAT.	1	1	1				1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1
31	ELK CITY																	1	1	1	1	1	1		1
32	ELK RIVER 1 S								1	1	1	1	1	1	1	1		1	1	1	1	1	1		1
33	EMMETT 2 E	1	1	1.25	1.4	1	1	1		1	1	1	1	1	1		1	1	1	1	1	1	1	1	1
34	FAIRFIELD																	1	1	1	1	1	1	1	1
35	FORT HALL	1	1	1	1			1		1	1	1	1	1	1			1	1	1	1	1	1	1	1
36	GALENA																	1	1	1	1	1	1	1	1
37	GARDEN VALLEY R S																	1	1	1	1	1	1	1	1
38	GLENNS FERRY	1	1	1	1.2		1	1		1		1		1	1		1	1	1	1	1	1	1	1	1
39	GRACE	1	1	1	1					1	1	1	1	1	1			1	1	1	1	1	1	1	1
40	GRAND VIEW	1	1	1.25	1.4		1	1		1		1		1	1		1	1	1	1	1	1	1	1	1
41	GRANGEVILLE	1						1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1

Table 8. Continued. Idaho NWS Temperature/Precipitation Stations used for Consumptive Use Computations for crop/land-uses 28-57 ('1' indicates that the crop was modeled, 1+'.xx' or '0.yy' indicates that the crop was modeled with and that the Cumulative Growing Degree Days since planting required to achieve effective full cover was increased or reduced by multiplying by 1.xx or 0.yy during ET_c calculations, relative to the standard modeling estimates). Crop numbers (line one) are defined in Table 9.2.

No.	Crop No: NOAA Station Name	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51 to 57
42	GRASMERE											1	1	1	1			1	1	1	1	1	1	1	1
43	HAGERMAN 2 SW	1	1	1	1.2		1	1		1		1		1	1		1	1	1	1	1	1	1	1	1
44	HAILEY RANGER STN							1				1	1	1	1			1	1	1	1	1	1	1	1
45	HAMER 4 NW	1	1	1	1			1				1	1	1	1			1	1	1	1	1	1	1	1
46	HAZELTON	1	1	1	1.2		1	1		1		1		1	1		1	1	1	1	1	1	1	1	1
47	HILL CITY																	1	1	1	1	1	1	1	1
48	HOLLISTER	1	1	1	1.2		1	1		1	1	1	1	1	1		1	1	1	1	1	1	1	1	1
49	IDAHO CITY																	1	1	1	1	1	1	1	1
50	IDAHO FALLS 16 SE	1	1	1	1			1		1	1	1	1	1	1			1	1	1	1	1	1	1	1
51	IDAHO FALLS FAA ARPT	1	1	1	1			1		1	1	1	1	1	1			1	1	1	1	1	1	1	1
52	IDAHO FALLS 46 W	1	1	1	1			1		1		1		1	1			1	1	1	1	1	1	1	1
53	ISLAND PARK																	1	1	1	1	1	1	1	1
54	JEROME	1	1	1	1.2		1	1		1		1		1	1		1	1	1	1	1	1	1	1	1
55	KELLOGG											1	1	1	1			1	1	1	1	1	1	1	1
56	KILGORE											1	1	1	1			1	1	1	1	1	1	1	1
57	KOOSKIA	1	1	1				1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1
58	KUNA	1	1	1.25	1.4	1	1	1		1		1		1	1		1	1	1	1	1	1	1	1	1
59	LEADORE 2							1				1	1	1	1			1	1	1	1	1	1	1	1
60	LEWISTON WB AP	1	1	1			1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1
61	LIFTON PUMPING STN	1										1	1	1	1			1	1	1	1	1	1	1	1
62	LOWMAN																	1	1	1	1	1	1	1	1
63	MACKAY RANGER STN		1	1								1	1	1	1			1	1	1	1	1	1	1	1
64	MAGIC DAM	1	1	1				1				1	1	1	1			1	1	1	1	1	1	1	1
65	MALAD		1	1				1				1	1	1	1		1	1	1	1	1	1	1	1	1
66	MALAD CITY		1	1				1				1	1	1	1		1	1	1	1	1	1	1	1	1
67	MALTA 1 NE		1	1	1			1				1	1	1	1		1	1	1	1	1	1	1	1	1
68	MAY							1				1	1	1	1			1	1	1	1	1	1	1	1
69	MCCALL							1										1	1	1	1	1	1	1	1
70	MCCAMMON		1	1				1				1	1	1	1			1	1	1	1	1	1	1	1
71	MINIDOKA DAM	1	1	1	1.2		1	1		1		1		1	1		1	1	1	1	1	1	1	1	1
72	MONTPELIER	1										1	1	1	1			1	1	1	1	1	1	1	1
73	MOSCOW	1	1	1			1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
74	MOUNTAIN HOME 1 W	1	1	1	1.2		1	1		1		1		1	1		1	1	1	1	1	1	1	1	1
75	NEW MEADOWS																	1	1	1	1	1	1	1	1
76	NEZPERCE	1						1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
77	OAKLEY	1	1	1	1.2			1				1	1	1	1		1	1	1	1	1	1	1	1	1
78	OLA	1	1	1				1				1	1	1	1			1	1	1	1	1	1	1	1
79	OROFINO	1	1	1				1	1			1	1	1	1	1	1	1	1	1	1	1	1	1	1
80	PARMA Exp. Station	1	1	1.25	1.4	1	1	1		1		1		1	1		1	1	1	1	1	1	1	1	1
81	PAYETTE	1	1	1.25	1.4	1	1	1		1		1		1	1		1	1	1	1	1	1	1	1	1
82	PICABO							1				1	1	1	1			1	1	1	1	1	1	1	1

Table 8. Continued. Idaho NWS Temperature/Precipitation Stations used for Consumptive Use Computations for crop/land-uses 28-57 ('1' indicates that the crop was modeled, 1+'.xx' or '0.yy' indicates that the crop was modeled with and that the Cumulative Growing Degree Days since planting required to achieve effective full cover was increased or reduced by multiplying by 1.xx or 0.yy during ET_c calculations, relative to the standard modeling estimates). Crop numbers (line one) are defined in Table 9.2.

No.	Crop No: NOAA Station Name	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51 to 57
83	PLUMMER 3 WSW	1	1	1				1	1	1	1	1	1	1	1	1		1	1	1	1	1	1		1
84	POCATELLO WB AP	1	1	1	1			1		1	1	1	1	1	1			1	1	1	1	1	1	1	1
85	PORTHILL	1	1	1				1	1			1	1	1	1	1		1	1	1	1	1	1		1
86	POTLATCH 3NNE	1	1	1			1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1
87	PRESTON 3 NE		1	1				1				1	1	1	1			1	1	1	1	1	1	1	1
88	REXBURG	1	1	1	1			1				1	1	1	1			1	1	1	1	1	1	1	1
89	REYNOLDS		1	1				1				1	1	1	1			1	1	1	1	1	1	1	1
90	RICHFIELD	1	1	1	1.2			1				1	1	1	1			1	1	1	1	1	1	1	1
91	RIGGINS RANGER STN		1	1				1		1	1	1	1	1	1			1	1	1	1	1	1	1	1
92	RUPERT	1	1	1	1.2		1	1		1		1		1	1		1	1	1	1	1	1	1	1	1
93	ST ANTHONY	1	1	1	1			1				1	1	1	1			1	1	1	1	1	1	1	1
94	SAINT MARIES	1	1	1				1	1	1	1	1	1	1	1	1		1	1	1	1	1	1		1
95	SALMON	1						1				1	1	1	1			1	1	1	1	1	1	1	1
96	SANDPOINT KSPT	1	1	1				1	1	1	1	1	1	1	1	1		1	1	1	1	1	1		1
97	SHOSHONE	1	1	1	1.2			1		1		1		1	1		1	1	1	1	1	1	1	1	1
98	SODA SPRINGS	1	1	1	1					1	1	1	1	1	1			1	1	1	1	1	1	1	1
99	STANLEY																	1	1	1	1	1	1	1	1
100	STREVELL		1	1	1			1				1	1	1	1			1	1	1	1	1	1	1	1
101	SWAN VALLEY 1 W							1				1	1	1	1			1	1	1	1	1	1	1	1
102	TETONIA EXP. STN	1	1	1				1				1	1	1	1			1	1	1	1	1	1	1	1
103	THREE CREEK																	1	1	1	1	1	1	1	1
104	TWIN FALLS 2 NNE	1	1	1	1.2		1	1		1		1		1	1		1	1	1	1	1	1	1	1	1
105	TWIN FALLS 3 SE	1	1	1	1.2		1	1		1		1		1	1		1	1	1	1	1	1	1	1	1
106	TWIN FALLS WSO	1	1	1	1.2		1	1		1		1		1	1		1	1	1	1	1	1	1	1	1
107	WEISER	1	1	1.25	1.4	1	1	1		1	1	1	1	1	1		1	1	1	1	1	1	1	1	1
108	Aberdeen AgriMet	1	1	1	1			1		1	1	1	1	1	1			1	1	1	1	1	1	1	1
109	Ashton AgriMet	1	1	1	1			1				1	1	1	1			1	1	1	1	1	1	1	1
110	Fairfield AgriMet																	1	1	1	1	1	1	1	1
111	Glenns Ferry AgriMet	1	1	1	1.2		1	1		1		1		1	1		1	1	1	1	1	1	1	1	1
112	Grand View AgriMet	1	1	1.25	1.4		1	1		1		1		1	1		1	1	1	1	1	1	1	1	1
113	Malta AgriMet		1	1	1			1				1	1	1	1		1	1	1	1	1	1	1	1	1
114	Monteview AgriMet	1	1	1	1			1				1	1	1	1			1	1	1	1	1	1	1	1
115	Nampa AgriMet	1	1	1.25	1.4	1	1	1		1		1		1	1		1	1	1	1	1	1	1	1	1
116	Parma AgriMet	1	1	1.25	1.4	1	1	1		1		1		1	1		1	1	1	1	1	1	1	1	1
117	Picabo AgriMet							1				1	1	1	1			1	1	1	1	1	1	1	1
118	Rexburg AgriMet	1	1	1	1			1				1	1	1	1			1	1	1	1	1	1	1	1
119	Rupert AgriMet	1	1	1	1.2		1	1		1		1		1	1		1	1	1	1	1	1	1	1	1
120	Twin Falls AgriMet	1	1	1	1.2		1	1		1		1		1	1		1	1	1	1	1	1	1	1	1
121	Afton, WY AgriMet	1										1	1	1	1			1	1	1	1	1	1	1	1
122	Fort Hall AgriMet	1	1	1	1			1		1	1	1	1	1	1			1	1	1	1	1	1	1	1
123	Kettle Butte AgriMet	1	1	1	1			1		1		1		1	1			1	1	1	1	1	1	1	1

Root Growth.

Root growth was estimated as a function of time between the initial root zone, assumed to occur at the time of planting or greenup until the time of maximum effective rooting depth, which was specified for each crop. The root depth between these two values was estimated using the Borg and Grimes (1986) sigmoidal function:

$$z_r = z_{\min} + [0.5 + 0.5\ \sin(3.03 F_{time\,root} - 1.47)][z_{\max} - z_{\min}]$$

where z_r is the effective root depth at some time during the growing season, z_{min} is the starting effective root depth (at planting or greenup), z_{max} is the maximum effective root depth and $F_{time\ root}$ is the fraction of time from start of root growth until time of maximum root depth. The root depth variables can have units of meters or feet. The Borg and Grimes root growth function is illustrated in Figure 6.

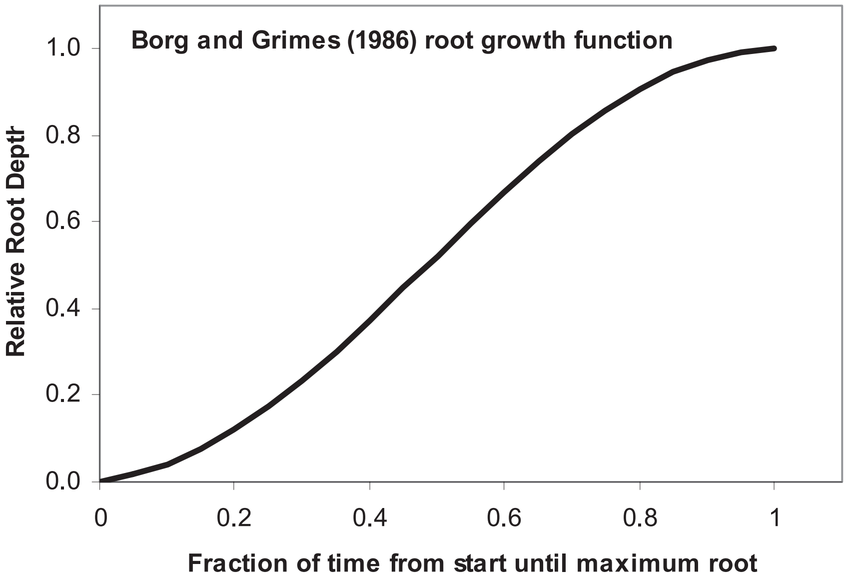

Figure 6. Relative root depth (between initial and final values) as estimated using the Borg and Grimes (1986) foot growth function.

Specific K_{cb} Application Instructions for Various Crop and Land-use Types

The following application instructions were followed during construction and application of K_{cb} curves for various crop and land-use types, as summarized from Appendix 3. More specific details on each K_{cb} curve are provided in Appendix 3.

Apples. To apply the apple K_{cb} curve patterned after AgriMet, one needs to estimate the effective full cover to occur approximately 55 days after bloom (greenup). The curves are run until a killing frost.

Asparagus. The curve shape of AgriMet is used. Estimate time from GU to EFC as 60 days and run until a killing frost.

Bluegrass seed. Bluegrass grown in northern Idaho has a typical greenup of April 1 and effective full cover of May 5 with swathing for harvest around June 30 (55 days following attainment of full cover) (Dr. Stephen Guy, UI, pers. commun. 2006). The crop generally remains dormant for the rest of the growing season until rains occur during September. Burning may be applied during August and September. No irrigation is assumed. The bluegrass K_{cb} curve was generated assuming that the bluegrass will attain about 0.2-0.3 m height and behave similar to the clipped grass reference until stressed. Therefore, the maximum K_{cb} will be about 0.8.

Canola. In northern Idaho, canola typically has an April 25 plant with flowering in July and August 1 harvest, with effective full ground cover about June 5 (Dr. Stephen Guy, UI, pers. commun. 2006).

Carrots (seed). Use onion curve and dates.

General garden vegetables. Use onion curve and and similar dates.

Hops. Estimate greenup at CGDD (base 0) = 600 ^{o}C-d. Estimate cover at 100 days following GU. Harvest will occur during August and September, with some residual green material left in fields.

Lawn. Use $T_{30} = 5^{o}C$ to estimate green up and 60 days from GU to EFC to work with AgriMet based turf curve (converted to K_{cb}). Run curve until killing frost.

Lentils. Lentils have similar seeding dates as spring grain in northern Idaho. Therefore, the T_{30} for spring grain will be used to estimate planting date for lentils and the spring grain K_{cb} v. NCGDD curve was used, but with values for K_{cb} multiplied by 0.9 to account for shorter, thinner stand and density for lentils as compared to spring grain. Harvest dates are typically similar to spring grain or a few days earlier. (Typically 120 days planting to harvest, 65 days to bloom, mid August swath). The crop is typically swathed when fields are 2/3 brown, so actual K_{cb} curve will follow spring grain. No irrigation is assumed for lentils.

Mint. Use CGDD base 0 and K_{cb} curve for the first growing cycle of alfalfa. Use CGDD since January 1 = 600 ^{o}C-d for green up and 1400 ^{o}C-d from GU to Harvest (at EFC). Use K_{cb} curve shape for second alfalfa cycle, with upper limit of 0.75 and run until mint is frozen (-4^{o}C)

Pasture is estimated to reach effective full cover 30 days after greenup for rotation grazing and 40 days after greenup for low management. K_{cb} curve is continued until killing frost.

Peas in Northern Idaho. The peas in northern Idaho can be harvested fresh or as seed. The characteristics are similar to spring pea crops grown in southern Idaho and therefore the peas K_{cb} curve from Wright is utilized with the same thermal (CGDD) parameters.

Poplar trees are estimated to bud out at $T_{30} = 8^{o}C$ and to reach full leafout (at EFC) at 21 days. K_{cb} curve is continued until killing frost.

Safflower. In northern Idaho, typically late April to mid May plant with a 110-140 day growing season (late September harvest after drydown). Use $T_{30} = 8^{o}C$ for planting date and and Sunflower/Safflower K_{cb} curve with 70 days from planting until EFC.

Sunflower. In northern Idaho, typically mid May to early June plant with a 120 day growing season (late September harvest after drydown) (Dr. Stephen Guy, UI, pers. commun. 2006). Use $T_{30} = 10^{o}C$ for planting date and Sunflower/Safflower K_{cb} curve with 70 days from planting until effective full cover (EFC). The

Sunflower/Safflower curve was developed during this study from the Canola K_{cb} curve by subtracting 0.10 during the peak period. This was done to account for generally less dense planting and ground cover for sunflower and safflower as compared to canola and for the tendency of these plants to exhibit some stomatal control under high vapor pressure deficit[3].

Wetlands are generally associated with submerged systems and near continuous water supply, therefore no stress factor is applied. Greenup is estimated to occur when T_{30} = 11°C. This coincides with a May 20 date, on average, at Kimberly. The development period is assumed to last 45 days. The full cover period is run until a killing frost, which in the case of cattails is set at –2 °C, as cattails are highly susceptible to freezing. The use of -2°C rather than 0°C is intended to compensate for air temperature differences between the weather station and wetlands, where surrounding water tends to contribute warmth to the air. Upon freezing in fall, the K_{cb} reverts to 0.2, with fraction of cover (f_c) set to 0.4 to characterize effectiveness of dead mulch in reducing evaporation during the nongrowing season.

In application of the K_{cb} curves for the four **desert vegetation classes**, the green-up in spring was estimated to occur when the 30 day average air temperature has reached 5°C, less 10 days. The 30 day Tmean = 5 °C is posted on the date at end of the 30 day period. Total season length was estimated by assuming that end of season was equal to July 15 + (July 15 - Greenup) (i.e., symmetry around July 15). The seasons progressed until a killing frost or end of the K_{cb} curve. Once desert vegetation was highly stressed (when $K_s < 0.2$), they were assumed to become permanently dormant for the balance of the growing season. Only turf and bluegrass for seed are presumed to wake up from stress-induced dormancy.

Yellow mustard has planting and harvest patterns similar to canola, with perhaps slightly earlier harvest (Dr. Stephen Guy, UI, personal commun. 2006). The Canola ET calculations are used for yellow mustard. No irrigation is assumed for both crops.

Daily Computation Example

An example of a time series of daily K_c over a multiyear period is shown in Figure 7 for six crop categories at Parma, Idaho for the 1988-1990 period. The K_c values shown are the basal K_{cb} curve (solid line) and actual K_c curve (symbols). During processing, these K_c values were converted to crop ET_c by multiplying by reference ET_r. The difference between actual K_c and basal K_{cb} when K_c exceeds K_{cb} represents evaporation from the bare or partially covered soil surface. K_c is occasionally below K_{cb} when there is insufficient soil moisture to support the evaporation process. Even though values for total K_c are 'high' during winter following wetting events, the resulting ET_c is relatively low, since ET_r averages less than 1 mm d^{-1} during much of winter. This was demonstrated in Figure 1. The values for K_c during winter varied with crop type due to assumptions made regarding the type and nature of cover during winter (mulch, bare soil or dormant sod-like surface). Other computation examples showing daily computed K_c are included in Appendix 14.

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[3] Stomatal control by fed or endogenous xylem ABA in sunflower: interpretation of correlations between leaf water potential and stomatal conductance in anisohydric species. F. TARDIEU, T. LAFARGE & Th. SIMONNEAU. 1996. Plant, Cell and Environment, Volume 19 Page 75 - January 1996

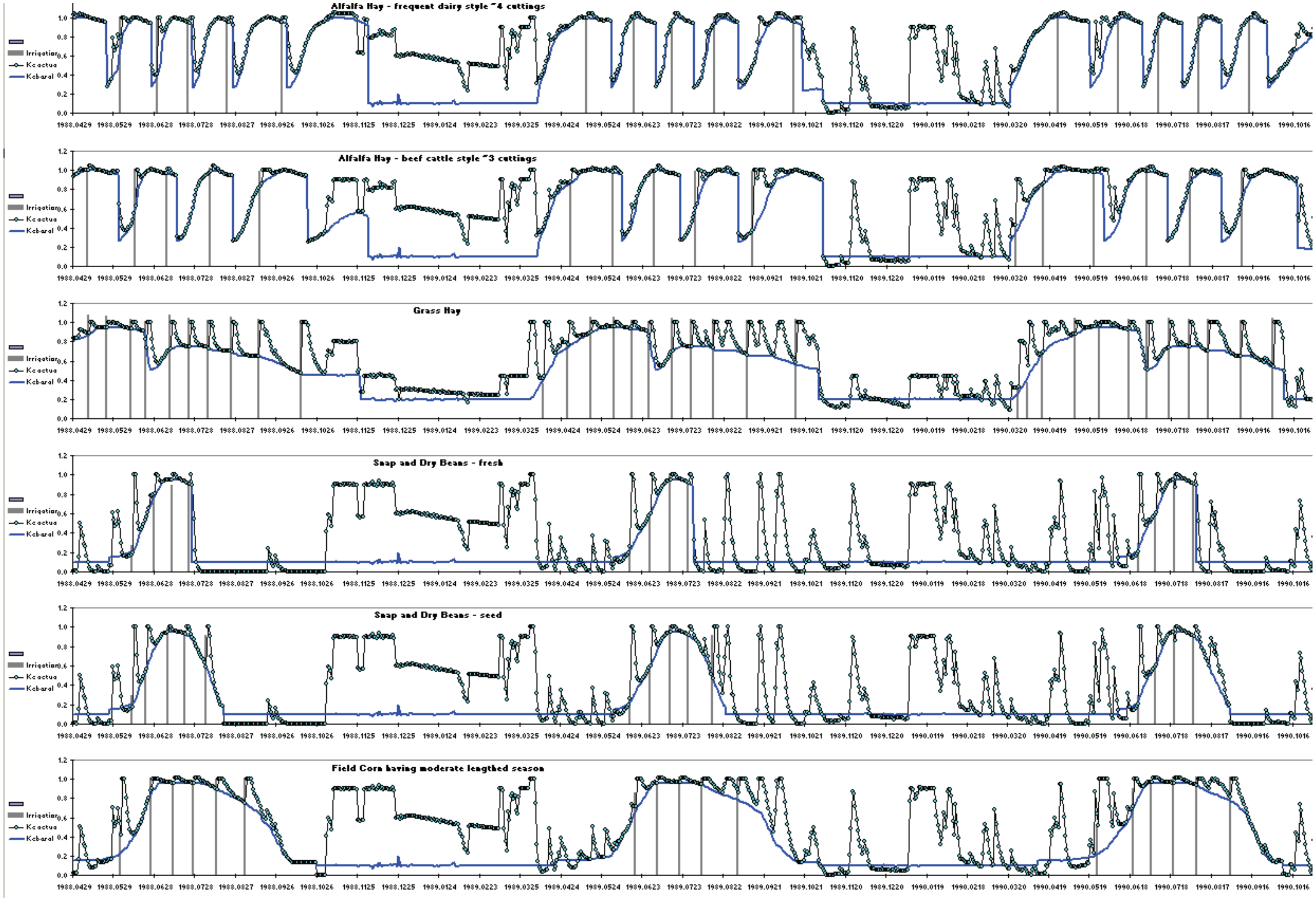

Figure 7. A time series of daily crop coefficients for alfalfa hay (top two crops for frequent and less frequent cutting), grass hay (third crop), dry beans harvested fresh (fourth), dry beans harvested dry (fifth) and field corn (bottom) over a three year period (1988-90) including wintertime at Parma.

Open Water Evaporation

Evaporation from open water was estimated for this report 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 equipment was set up on the reservoir during one growing season. Measurements from this study were used to develop and calibrate aerodynamic procedures that can be applied with air temperature data, only, to estimate evaporation from deep water bodies.

In this report, evaporation from three classes of open water was simulated:

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 evaporation algorithms developed for American Falls Reservoir (Allen and Tasumi, 2005). Appendix 10 provides details on the procedure development and application.

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.

Computation of Evapotranspiration Time Series and Statistics

Evapotranspiration Products

Evapotranspiration was computed on a daily timestep for the periods of record for each weather station listed in Table 3. The time series of daily crop and land-use ET are available through the internet in the form of text (data) files and include actual ET_c, potential ET_c, basal ET_c and precipitation deficit (irrigation water requirement). The time series are useful to hydrologic modelers requiring information for specific years.

Daily ET_c was summarized to monthly and annual time series for periods of record and is available via the internet in the form of text (data) files.

Perhaps the most common usage of ET_c results is through the use of **statistics** describing long-term mean values for ET_c on monthly, growing season and annual bases as well as standard deviations and 20 and 80% exceedence values that describe the expected variation of the populations of ET_c. These statistics have been computed for the following lengths of time periods within each month: 3, 7, 15 and 30 days. 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. For example, a potato crop may be irrigated each 3 days during the peak month of July, so that users may be interested in reviewing the statistics describing the 3 day periods within the month of July for irrigation systems design. Or, for example, if a crop of sugar beets having a deeper effective root zone is irrigated on average each two weeks during August, then users may be interested in reviewing the statistics describing 15 day periods within the month of August for irrigation systems design. An example of statistical calculations is presented in Table 9.

The standard deviation, skew and kurtosis statistics (described in the following section) describe the variation properties of the populations of calculated ET_c values over each of the 3, 7, 15 and 30 day averaging periods within each month for a specified number of years of record. For example, the standard deviation for a 7 day averaging period in June describes the expected deviation of 7 day average values for ET_c within the month of June over the period (years) of record from the mean 7 day ET_c value for June. As the lengths of the averaging period increase, the standard deviations of the ET_c during these periods decrease. The skew and kurtosis parameters describe the 'shape' of the ET_c populations for the monthly means. These parameters may be useful if users wish to apply specific frequency distributions such as the normal or Pearson distributions that require testing or use of values for skew.

In this report, statistics were computed over the most recent 30 years of valid (nonmissing) data at each weather station or over shorter periods if less than 30 years of valid data were available. The span of the 30 year *'normals'* (i.e., first and last year) could potentitally change with crop type, depending on the timing of any missing data (inside or outside growing periods) and with weather station, depending on amounts of missing data and beginning or ending year of data collection. The span of the normal periods exceeded 30 years if some intervening years were omitted due to missing data.

The 30 year normal periods were used to generate means and other 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 (1966-1795) 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 (or wetness) of the local or regional environment due to irrigation development or land-use change, by specific station location, or perhaps by change in overall climate. The last 30 years of usable record are considered to be the more representative of expected near-future conditions than prior periods. The full record 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.

The 20% exceedence values (*20%Ex*) for ET_c represent the *value* for ET_c (or for the precipitation deficit) *that has a 20% chance of being exceeded* that month during any particular year (i.e., the value will be exceeded in 2 years out of 10). Conversely, there is an 80% chance that the value (for the particular length of averaging period) will be less than the *20%Ex* value. The *20%Ex* value is commonly used in design of capacity for irrigation and water supply systems where adequate water is made available to fulfill all ET requirements in 8 years out of 10. Some shortage is tolerated in 2 years out of 10. Units for *20%Ex* are expressed in mm/day for monthly periods and in mm for annual and seasonal periods. The *20%Ex* values were computed assuming a 'distribution free' probability density function. The values were selected by ranking the highest 3-, 7-, 15- or 30-day value within the month for *ETact, ETpot, ETbas* or *P_def* for each year and selecting the value that was positioned 20% of the way down from the highest value. There were '*nyrs*' values that were ranked (one for each year). In this way, the *20%Ex* value represents that value for the parameter (*ETact, ETpot, ETbas* or *P_def*) that, when averaged over any 3-, 7-, 15- or 30- day period within the month, would have only a 20% chance of being exceeded at any time during that month for the given year. Thus, if an irrigation system were designed with capacity to provide the *20%Ex* amount of *P_def* over a 7-day period, for example, the systems 'net' output if operated continually (less any incidental leakage, spray drift or uniformity 'losses') would exceed the actual precipitation deficit (i.e., the ET less any infiltrating precipitation) 8 years out of 10. During two years out of any 10 year period, the ET less any infiltrating precipitation would exceed the net system capacity (and water supply) during at least one 7 day period during the particular month by some amount. The amount of the exceedence might range from only a millimeter to perhaps 15 to 20 mm. Some of the excedance of ET over water supply might be fulfilled by soil moisture carryover froma prior month.

The 80% exceedence values (*80%Ex*) for ET_c represent the *value* for for ET_c (or for the precipitation deficit) *that has an 80% chance of being exceeded* that month during any particular year. Conversely, there is a 20% chance that the value of the parameter (for the particular length of averaging period) will be less than the *80%Ex* value. The *80%Ex* value is commonly used in design of land application systems where water application may need to be limited to amounts that have at least 80% chance of being evaporated. Units for *80%Ex* are expressed in mm/day for monthly periods and in mm for annual and seasonal periods. The *80%Ex* values were computed assuming a 'distribution free' probability density function. The values were selected by ranking the lowest 3-, 7-, 15- or 30-day value during the month for *ETact, ETpot, ETbas* or *P_def* for each year and selecting the value that was positioned 80% of the way down from the highest value. There were '*nyrs*' values that were ranked (one for each year). In this way, the 80%Ex value represents that value for the parameter (*ETact, ETpot, ETbas* or *P_def*) that, when averaged over any 3-, 7-, 15- or 30- day period within the month, would have an 80% chance of being exceeded at all times during that month for the given year. Thus, if a land application system were designed with capacity to provide the *80%Ex* amount of *P_def* over a 7-day period, for example, then the systems 'net' output (less any incidental leakage, spray drift or uniformity 'losses') would exceed the actual precipitation deficit (i.e., the ET less any infiltrating precipitation) during 2 years out of a 10 year period. During eight years out of any 10 year period, the ET less any infiltrating precipitation would exceed the application amount during all 7 day periods during the particular month by some amount. The amount of the exceedence might range from only a millimeter to perhaps 15 to 20 mm. One should bear in mind that use of the 80% value would result in plant 'stress' and ET reduction 8 years out of 10.

The *AveHi* parameter complements the *20%Ex* parameter, where *AveHi* represents the average (over the 30 year normal period) of the highest value for the parameter within the 3, 7, or 15 day period for each month. Therefore, each month of each year was assigned one 'highest' value for the parameter for the 3, 7 or 15 day averaging length. Then, for each month of the year, the 30 values over the normal period were averaged to obtain *AveHi*. The value for *AveHi* for 3, 7 and 15 day periods is always greater than the average for the month itself (i.e., the 'mean'), since the *AveHi* is the mean of the highest value for the 3, 7, or 15 day period within the month. The value for *AveHi* increases as the length of the averaging period (3, 7 or 15 days) decreases. The same 30 values used to calculate *AveHi* were used in calculating the *20%Ex* value.

The *AveLo* parameter complements the *80%Ex* parameter, where *AveLo* represents the average (over the 30 year normal period) of the lowest value for the parameter within the 3, 7, or 15 day period for each month. Therefore, each month of each year was assigned one 'lowest' value for the parameter for the 3, 7 or 15 day averaging length. Then, for each month of the year, the 30 values over the normal period were averaged to obtain *AveLo*. The value for *AveLo* for 3, 7 and 15 day periods is always less than the average for the month itself (i.e., the 'mean'), since the *AveLo* is the mean of the lowest value for the 3, 7, or 15 day period within the month. The value for *AveLo* decreases as the length of the averaging period (3, 7 or 15 days) decreases. The same 30 values used to calculate *AveLo* were used in calculating the *80%Ex* value.

On an annual or growing season basis, the mean, *20%Ex* and *80%Ex* values were computed only for annual or growing season totals and therefore represent the distribution of annual or growing season values. The seasonal values for *P_def* represent *net irrigation water requirements* (*NIR*) for a particular crop during the defined growing season only. These values represent the amount of water required in excess of infiltrating precipitation (gross precipitation less any precipitation that runs off or deep percolates) to fulfill the potential ET requirements during the growing season. The value for *P_def* is not discounted for soil water that is stored during the nongrowing season prior to the growing season. This amount of water can be approximated by summing differences between *P_rz* and *ETact* on a daily basis over the nongrowing season periods using data contained in the daily ET_c time series files. This parameter is reported as *P_efT* in the monthly and annual time series files and is described later in this section. *P_efT* was not computed for the daily time series.

When computing the 20% probability exceedence levels, the 3, 7 and 15 day ET_c were chosen as the maximums of the running average values computed for each month. These entries apply to irrigation design concerning the design level required for full irrigation on a 3, 7, 15, or 30 day irrigation interval that is adequate for no stress 8 years out of 10.

When computing the 80% probability exceedence levels, the 3, 7 and 15 day ET_c were chosen as the minimums of the running average values computed for each month. These entries apply to land application design concerning the minimum design or application level required for full consumption (evaporation) on a 3, 7, 15, or 30 day irrigation interval for 8 years out of 10.

The lengths of the 3-, 7- or 15-day periods in each month impacted the number of periods per month and the relative 'weighting' of sampled days during a month (a period was only included for sampling in the statistics if all of its member days were fully contained in the month). Therefore, days toward the center of the month were more likely to be 'members' of more sampled periods than days near the beginning or end of the month. This impacted the values for the means computed for the 3-, 7- or 15-day periods and therefore, the computed means for each period for a month typically vary from one another by small amounts. The mean reported for the 30-day period (i.e, for the month), should be regarded as the 'true' mean.

Formats of ET Product Files

Formats of daily, monthly and annual time series files and monthly statistics files are described in Appendix 11. These files are available for internet download from the following University of Idaho website:

http://www.kimberly.uidaho.edu/ETIdaho/

The ETIdaho website layout and types of file availability is briefly described in Appendix 15.

Table 9 illustrates the format used for the statistics files. Four statistics files were produced for each weather station: a) actual evapotranspiration; b) potential evapotranspiration; c) basal evapotranspiration; and d) precipitation deficit (i.e., net irrigation water requirement):

The ***Actual daily ET$_c$*** (ET_{act}) represents the total estimated flux of ET given any reduction in potential ET caused by soil water shortage or soil surface dryness. ET_{act} was computed using Eq. (6) as $ET_{act} = K_s\, ET_{bas} + K_e\, ET_r$ where K_s is a stress factor (0 – 1 where 1 means no stress) and K_e is the evaporation coefficient and ET_r is the alfalfa reference ET. ET_{bas} is defined below. ET_{act} was often less than potential ET (ET_{pot}) for rainfed crops and occasionally for irrigated crops prior to the growing season when the low-level, basal crop coefficient assigned to the *nongrowing season* cover could not be sustained by precipitation, and, therefore, the actual *ET*, in the form of mostly evaporation, could not be sustained at the ET_{pot} level. On occaision, ET_{act} fell below ET_{pot} early in the growing season, prior to initiation of irrigation, for the same reasons (the soil surface dried to levels that could not sustain evaporation at the ET_{pot} levels prescribed by the assigned K_{cb} ET_r value). ET_{act} includes evaporation from the soil surface from both precipitation and any simulated irrigation. For many crops, irrigation was not enacted (i.e., simulated) until the value for K_{cb} reached 0.22 during crop development. This was done to preclude uncontrolled simulation of frequent irrigation during early growing periods when the root zone depth is shallow and to follow typical practice where irrigation during the initial growing period is often withheld and root development pursues extraction of moisture at greater depth. As a consequence, some 'stress' and reduction in ET_{act} to below ET_{pot} was estimated to occur with typical irrigation practices at times early in growing seasons.

The ***Potential daily ET$_c$*** (ET_{pot}) represents the total estimated flux of ET that would occur if there were no moisture stress imposed by soil water shortage in the 'root zone' at any time. ET_{pot} includes evaporation from the soil surface from both precipitation and any simulated irrigation. ET_{pot} was computed using Eq. (5) as $ET_{pot} = ET_{bas} + K_e. ET_r$.

The ***Basal ET*** (ET_{bas}) represents the ET that would occur under no water stress and with no surface wetting by precipitation or irrigation. In other words, ET_{bas} represents potential ET for a dry soil surface. ET_{bas} should not be used to estimate irrigation water requirements, and is included to provide an indication of the partitioning of ET_{pot} between 'transpiration', as represented by ET_{bas}, and evaporation of water from the soil surface layer.

The ***Precipitation deficit*** (P_{def}) is the difference between the potential ET (ET_{pot}) and the amount of precipitation in the root zone. P_{def} was calculated as $ET_{pot} - P_{rz}$ where P_{rz} is the precipitation infiltrating into and residing in the root zone. P_{def} is synonymous with the ***irrigation water requirement*** when occuring during the growing season for an irrigated crop. P_{def} represents the amount of additional water that the soil and crop would evaporate or transpire beyond P_{rz} if that water were made available at the right time during the growing or nongrowing season. Because the ET_{pot} estimate only includes soil evaporation for known precipitation and irrigation events, any additions of P_{def} outside of the simulated growing season would tend to increase ET_{pot} and thus P_{def} to some extent, causing a type of positive feedback process.

Precipitation deficit (net irrigation water requirement), P_{def}, can have a negative value if the depth of precipitation during a period (3-, 7-, 15- or 30-day) is greater than the value of ET_{pot}. This is more likely to occur during winter and spring periods and in northern Idaho. A negative value indicates a precipitation 'excess.' When viewing P_{def} for 'nonirrigated' crops vs. the same crop that is irrigated (for example, spring grain in some areas, which has both irrigated and 'rainfed' classes), the P_{def} for the rainfed class is often lower than that for the irrigated class. This is an artifact of the calculation of ET_{pot} for the rainfed crop in that ET_{pot} does not contain impacts of evaporation from soil following irrigation events for the rainfed crop, but does for the irrigated condition. If using the P_{def} to determine the net irrigation water requirement, then one should use the P_{def} for the irrigated condition. For rainfed crops, the P_{def} represents the amount of ET reduction caused by shortage of precipitation and subsequent plant water 'stress.'

The ***Precipitation residing in the root zone*** (P_{rz}) is the amount of gross reported precipitation that infiltrates into the soil (i.e., less any surface runoff) and that remains in the root zone for later consumption by evaporation or transpiration. P_{rz} is computed as $P - \mathit{Runoff} - \mathit{DPerc}$ where P is gross reported precipitation, *Runoff* is estimated surface runoff and *DPerc* is deep percolation of any precipitation below the maximum rootzone for the crop or land-use condition. The difference between P_{rz} and ET_{act} during the nongrowing season (where ET_{act} includes evaporation following precipitation events) represents the amount of 'recharge' to the root zone during the nongrowing season (i.e., increase in soil water storage) that would be available at the start of the growing season to fulfill plant water requirements. The ratio of $(P_{rz} - ET_{act})/P$ represents the 'efficiency' or effectiveness of gross precipitation, including snow, in building soil water for use during the growing season.

The **P*recipitation residing in the root zone that is available for transpiration*** *(rather than for evaporation)* *(P_efT)* is the amount of gross reported precipitation that infiltrates into the soil (i.e., less any surface runoff) and that *remains in the root zone for use in supplying transpiration* by the crop or land use cover. *P_efT* does not include the amount of infiltrated precipitation that evaporates from the surface evaporation layer (upper 100 mm of soil). The *P_efT* parameter is useful in estimating the amount of precipitation during the nongrowing season that is stored over the long term and made available for transpiration requirements during the subsequent growing season. *P_efT* is also useful during the growing season to determine how 'efficient' precipitation is in fulfilling transpiration requirements of crops, as opposed to simply 'burning off' as evaporation from the soil surface. *P_efT* was calculated as *P_efT = P_rz - surface evaporation losses = P – Runoff – DPerc - surface evaporation losses*, where *P_rz* is precipitation infiltrating and residing in the maximum root zone for the crop, *P* is gross reported precipitation, *Runoff* is estimated surface runoff and *DPerc* is deep percolation of any precipitation below the maximum rootzone for the crop or land-use condition.

Table 9. Example Tabular layout of Statistics describing Crop ET (ET_{act}) for each month for four within-month averaging periods.

Twin Falls WSO		Monthly Averages (mm/day and mm/year)						15-day Averages (mm/day)						7-day Averages (mm/day)						3-day Averages (mm/day)					
Month	no. years	Mean	Std. Dev.	Skew	Kurt.	20% Ex.	80% Ex.	Mean	Std. Dev.	AveHi	20% Ex.	Ave Low	80% Ex.	Mean	Std. Dev.	Ave Hi	20% Ex.	Ave Low	80% Ex.	Mean	Std. Dev.	Ave Hi	20% Ex.	Ave Low	80% Ex.
Alfalfa Reference Evapotranspiration																									
Jan.	30	0.85	0.25	0.43	1.45	0.98	0.72	0.85	0.22	1.04	1.13	0.67	0.57	0.85	0.31	1.31	1.46	0.45	0.29	0.85	0.41	1.62	1.96	0.23	0.03
Feb.	30	1.57	0.44	0.98	3.47	1.63	1.14	1.53	0.49	1.83	2.26	1.27	0.89	1.54	0.60	2.23	2.96	0.97	0.58	1.56	0.72	2.60	3.35	0.67	0.26
Mar.	30	3.00	0.67	0.20	0.58	3.39	2.53	3.04	0.61	3.54	4.11	2.51	2.24	3.02	0.77	4.01	4.52	2.05	1.64	2.99	0.98	4.71	5.43	1.61	1.26
Apr.	30	4.78	0.58	0.30	3.23	5.32	4.25	4.87	0.73	5.41	6.06	4.22	3.68	4.82	1.01	6.20	7.12	3.55	3.20	4.80	1.33	7.27	8.05	2.92	2.47
May	30	5.86	0.89	0.09	0.55	6.40	5.18	5.85	0.89	6.57	7.38	5.19	4.56	5.84	1.21	7.46	8.25	4.36	3.72	5.85	1.51	8.33	9.04	3.49	2.94
June	30	7.09	0.58	-0.23	2.60	7.54	6.57	7.07	0.79	7.81	8.27	6.40	5.82	7.08	1.10	8.46	9.03	5.48	5.04	7.09	1.43	9.24	9.80	4.52	3.84
July	30	7.61	0.67	-0.27	1.07	8.00	7.32	7.64	0.58	8.03	8.28	7.18	6.68	7.63	0.70	8.46	8.77	6.71	6.19	7.62	0.99	9.16	9.35	5.78	4.76
Aug.	30	6.83	0.54	-0.06	0.60	7.11	6.48	6.81	0.57	7.34	7.67	6.29	5.71	6.83	0.76	7.82	8.07	5.80	5.09	6.84	0.95	8.37	8.63	5.10	4.38
Sept.	30	5.44	0.41	-0.17	3.76	5.85	5.16	5.36	0.64	5.97	6.25	4.78	4.29	5.39	0.88	6.64	6.95	4.18	3.72	5.42	1.15	7.36	7.65	3.47	3.02
Oct.	30	3.84	0.56	0.13	0.66	4.09	3.47	3.88	0.64	4.51	4.94	3.22	2.81	3.88	0.91	5.24	5.71	2.66	1.95	3.85	1.17	5.78	6.31	1.99	1.31
Nov.	30	1.69	0.37	0.55	3.81	1.87	1.32	1.69	0.50	2.10	2.41	1.30	0.92	1.68	0.64	2.53	2.94	0.97	0.72	1.68	0.79	3.07	3.51	0.62	0.45
Dec.	30	0.87	0.36	0.37	1.29	1.05	0.66	0.87	0.29	1.06	1.28	0.70	0.53	0.86	0.36	1.31	1.55	0.46	0.29	0.87	0.45	1.62	1.89	0.25	0.06
Annual	30	1504	63	-0.15	2.43	1562	1438																		
Winter Wheat																									
Jan.	30	0.52	0.20	-0.13	1.13	0.60	0.42	0.52	0.16	0.64	0.76	0.40	0.34	0.52	0.22	0.82	1.03	0.26	0.20	0.52	0.29	1.04	1.31	0.12	0.03
Feb.	30	0.89	0.24	-0.25	2.34	1.09	0.61	0.88	0.28	1.07	1.25	0.70	0.50	0.88	0.36	1.33	1.66	0.50	0.28	0.88	0.46	1.66	2.00	0.33	0.18
Mar.	30	1.63	0.59	-0.15	1.14	1.96	1.33	1.60	0.51	1.98	2.30	1.25	0.83	1.62	0.63	2.38	2.87	0.98	0.64	1.62	0.75	2.86	3.36	0.75	0.50
Apr.	30	3.23	0.87	0.42	2.04	4.16	2.32	3.21	0.98	3.85	4.70	2.64	1.80	3.21	1.15	4.51	5.26	2.13	1.42	3.22	1.34	5.47	6.75	1.76	1.08
May	30	5.82	0.91	-0.02	0.73	6.34	5.23	5.83	0.92	6.63	7.53	5.03	4.42	5.82	1.27	7.53	8.24	4.09	3.55	5.82	1.60	8.43	9.22	3.30	2.59
June	30	7.22	0.52	0.12	2.93	7.62	6.80	7.28	0.79	8.00	8.37	6.57	6.08	7.26	1.09	8.72	9.22	5.66	4.96	7.23	1.44	9.52	10.23	4.56	4.08
July	30	3.62	1.97	-0.17	0.51	4.79	2.18	3.54	1.98	5.47	6.97	1.80	0.86	3.58	2.37	6.52	7.94	1.15	0.57	3.61	2.56	7.35	9.13	0.86	0.43
Aug.	30	0.62	0.51	0.64	1.95	0.83	0.34	0.61	0.42	0.88	1.19	0.35	0.16	0.60	0.55	1.32	1.83	0.23	0.12	0.62	0.74	2.11	3.16	0.18	0.08
Sept.	30	0.47	0.34	0.79	3.29	0.71	0.13	0.47	0.47	0.73	1.11	0.22	0.03	0.46	0.57	1.12	1.59	0.09	0.02	0.47	0.67	1.74	2.90	0.06	0.01
Oct.	30	0.64	0.43	0.06	0.57	0.91	0.34	0.64	0.39	0.94	1.34	0.34	0.09	0.64	0.52	1.31	1.86	0.17	0.03	0.64	0.61	1.69	2.48	0.12	0.02
Nov.	30	0.59	0.22	-0.05	3.09	0.76	0.44	0.59	0.29	0.77	1.01	0.42	0.22	0.59	0.34	0.98	1.18	0.29	0.16	0.59	0.39	1.24	1.56	0.19	0.09
Dec.	30	0.46	0.26	0.04	0.65	0.60	0.27	0.46	0.20	0.59	0.75	0.34	0.20	0.46	0.25	0.74	0.98	0.20	0.10	0.46	0.31	0.95	1.30	0.09	0.03
Annual	30	783	30	0.13	4.18	803	757																		
G.Season	30	758	27	-0.28	4.53	773	742																		

Comparison of Crop Evapotranspiration Products with Other Sources

Illustrative comparisons were made between seasonal ET_c calculated for this report and growing season ET_c reported by Allen and Brockway (1983) and by the USBR AgriMet system[4] at the Parma, Twin Falls (7E) and Ashton weather stations. Two types of comparisons were made. The first comparison was for reported periods of record for Allen and Brockway and AgriMet and for 30-year normals from this report. Therefore, the periods of record varied among the three sources. The second comparison was for year 2000 only, where the ET_c product from this report was compared with USBR AgriMet ET_c reported for 2000 and with seasonal ET reported by Allen et al. (2007b) for crops in Magic Valley as determined using the METRIC satellite-based energy balance processing system (Allen et al. 2007a).

Comparisons over multiple years. Descriptions of the periods of record for the three sources used for seasonal ET_c are summarized in Table 10. Although this current report has a substantially longer period of record than the other two sources that is preserved in the daily, monthly and annual ET_c time series, statistics were calculated only for the most current 30 years of complete data (i.e., 30 year normals) in this report. The AgriMet period of record is the shortest since it is a relatively modern system. The Allen-Brockway and AgriMet averages do not share any overlapping period of record. As a consequence of nonsimilar periods of record, one should not expect the seasonal totals to compare precisely. However, similarities in trends and general magnitudes are expected. One additional distinction in regard to growing season length is that the Allen and Brockway totals are for the March-October period whereas the AgriMet and seasonal ET contained in this report are for the actual growing season (emergence to termination for AgriMet and planting to termination here).

Table 10. Periods of record for seasonal ET_c averages from Allen and Brockway (1983), AgriMet and this report.

Source	Parma	Twin Falls 7E	Ashton	Season
Allen and Brockway (1983)	1932-1980	1964-1980	1931-1980	March-October
AgriMet	1990-2005	1991-2005	1990-2005	Variable
Allen and Robison (2007)	1971-2004	1973-2004	1967-2004	Variable

The Allen-Brockway study used the 'FAO-24 Blaney-Criddle' reference ET method converted to an equivalent alfalfa reference ET_r method using data from Kimberly, Idaho and used 'mean' K_c curves from Wright (1981). The AgriMet system uses the 1982 Kimberly Penman method (Wright 1982) for alfalfa reference ET_r and 'mean' K_c curves that are traceable to Wright (1981) for primary southern Idaho crops. This study used the ASCE standardized Penman-Monteith method for alfalfa reference ET_r and the dual $K_{cb} + K_e$ method. The K_{cb} curves are traceable to Wright (1982) for primary southern Idaho crops.

Total seasonal crop evapotranspiration is shown in Figure 8 for Parma, Twin Falls and Ashton locations for major crops common to the three data sets (note that Allen-Brockway and AgriMet do not distinguish between high and low management pasture nor orchards with and without ground-cover, and Allen-Brockway does not distinguish between types of potatoes, thus the single ET_c value was assigned to both classes). The three locations were selected to represent relative extremes for major irrigated crop producing areas of southern Idaho, where Parma, at 680 m (2220 ft) elevation, is near the western edge of the Idaho Snake Plain, Twin Falls, at 1200 m (3960 ft) elevation, is near the center of the Snake Plain, and Ashton, at 1560 m (5110 ft) is near the upper edge of the Snake Plain.

In general, the growing season ET_c is similar among the three data sources for the three locations. For some crops such as field corn, peas, sugar beets, orchards with grassed cover, and high management pasture, the growing season ET_c computed for this report (Allen-Robison) falls near that reported by Allen and Brockway

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[4] http://www.usbr.gov/pn/AgriMet/ETtotals.html

(1983) at all three locations. For some crops such as dry beans, sileage corn, early season and late season potatoes, and low management pasture, the growing season ET_c computed for this report falls a small to moderate amount below the ET_c reported by Allen and Brockway (1983). The growing season ET_c for alfalfa hay and alfalfa seed was equal to or exceeded that by Allen-Brockway. The growing season ET_c for spring and winter grain (including wheat and barley) was less than that by Allen-Brockway at Parma, was equal to that by Allen-Brockway at Twin Falls, and exceeded that by Allen-Brockway at Ashton. Some of the higher ET_c estimated for small grains (spring and winter) at Ashton may stem from the prediction of relatively long growing seasons at high elevations in this study, as summarized in Appendix 8. It is possible that growing season lengths could reduce below that predicted if shorter season varieties are grown.

For alfalfa hay and alfalfa seed, the new estimates for seasonal ET_c lay above those of Allen and Brockway (1983) (by 2% and 11% at Parma, by 10% and 17% at Twin Falls and by 4% at Ashton (hay only)). In the Allen-Brockway report, the ET_c for alfalfa hay was estimated using a smoothed K_c curve representing a blending of cutting effects and representing average evaporation from irrigation and rainfall. In the present report, the ET_c for alfalfa hay was estimated by constructing a basal K_{cb} curve that was reconstructed annually according to air temperature conditions of the specific year and that estimated each cutting event and the associated reduction in K_{cb}. Evaporation from irrigation and rainfall was calculated separately and added to the basal values. In addition, the start of the growing season for alfalfa was estimated annually in the current calculations according to cumulative growing degree days since the start of the calendar year and seasons ran until a hard, killing frost. Thus, on average the lengths of growing seasons for alfalfa hay can be longer than the March-October or April-October periods presented by Allen-Brockway. The average length of growing season for alfalfa hay at the Twin Falls 7E NWS weather station was estimated in this report to be 226 days with a standard deviation of 19 days, whereas the standard April-October period applied by Allen-Brockway for Twin Falls spans only 214 days. These differences may explain some of the increased ET_c estimated for alfalfa hay in this new report. The 'low management' pasture ET_c from this report appears to agree closely with the general pasture ET_c reported by AgriMet and the 'high management' pasture ET_c appears to agree closely with the general pasture ET_c reported by Allen-Brockway.

In most cases, except for alfalfa hay, peas, dry beans and early potatoes, the growing season ET_c estimated by AgriMet fell below that of this report and that of Allen and Brockway (1983) at all three of the weather station locations. This may be caused in part by the particular crop coefficient curves employed by AgriMet and in part by the mechanics of how the start and termination of growing periods is estimated by AgriMet, which may result in a shorter period over which ET_c is computed and integrated.

The substantial differences in periods of coverage and lengths of periods of coverage does not seem to have caused significant separation among the three groups of estimates. It is possible, however, that differences among the periods of coverage do exist, but were masked by other differences in ET_c estimation procedures.

Comparisons with estimates from Sutter and Corey (1970). Figure 9 shows the same information from Figure 8 for the three locations across southern Idaho with the addition of growing season ET_c (consumptive use) estimated and reported by Sutter and Corey (1970). The Sutter-Corey study utilized the SCS 'modified' Blaney-Criddle equation published as USDA Report TR-21 (USDA, 1967). The SCS Blaney-Criddle (BC) method included standard crop coefficient curves intended for use with the BC method only. ET_c estimates for Parma were not available from Sutter-Corey, thus estimates for nearby Caldwell were used instead.

As shown in Figure 9, seasonal ET_c from Sutter-Corey fell below estimates from the three other ET_c sources for alfalfa hay, corn (except at Parma), sugar beets, spring grain, winter grain, pasture, orchards and small vegetables. The Sutter-Corey ET_c estimates for dry beans and late potatoes (Sutter-Corey and Allen-Brockway had only a single potato class) agreed with those from the current study at Parma and Twin Falls. Estimates by Sutter-Corey for field and sileage corn agreed with those from the current study at Parma, but were substantially below new estimates at Twin Falls and Ashton.

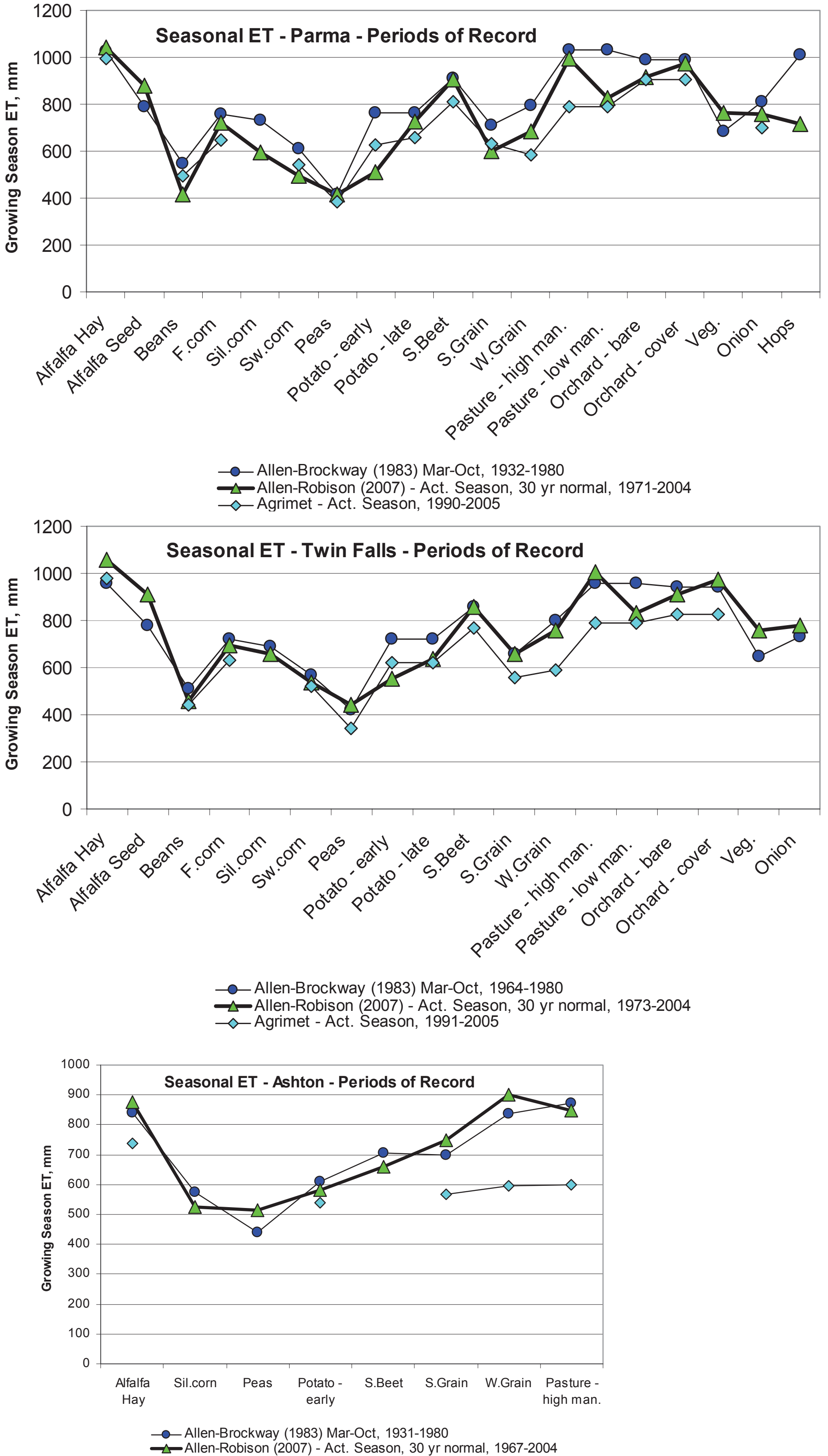


Figure 8. Total growing season ET_c for major crop categories averaged over the periods of record at a) Parma, b) Twin Falls 7E and c) Ashton from reports by Allen and Brockway (1983) *(based on* $K_{c\ mean}\ ET_r$*)*, Allen and Robison (2007 *(this report)*) *(based on* $(K_s K_{cb}+K_e)\ ET_r$*)*, and from AgriMet *(based on* $K_{c\ mean}\ ET_r$*)*.

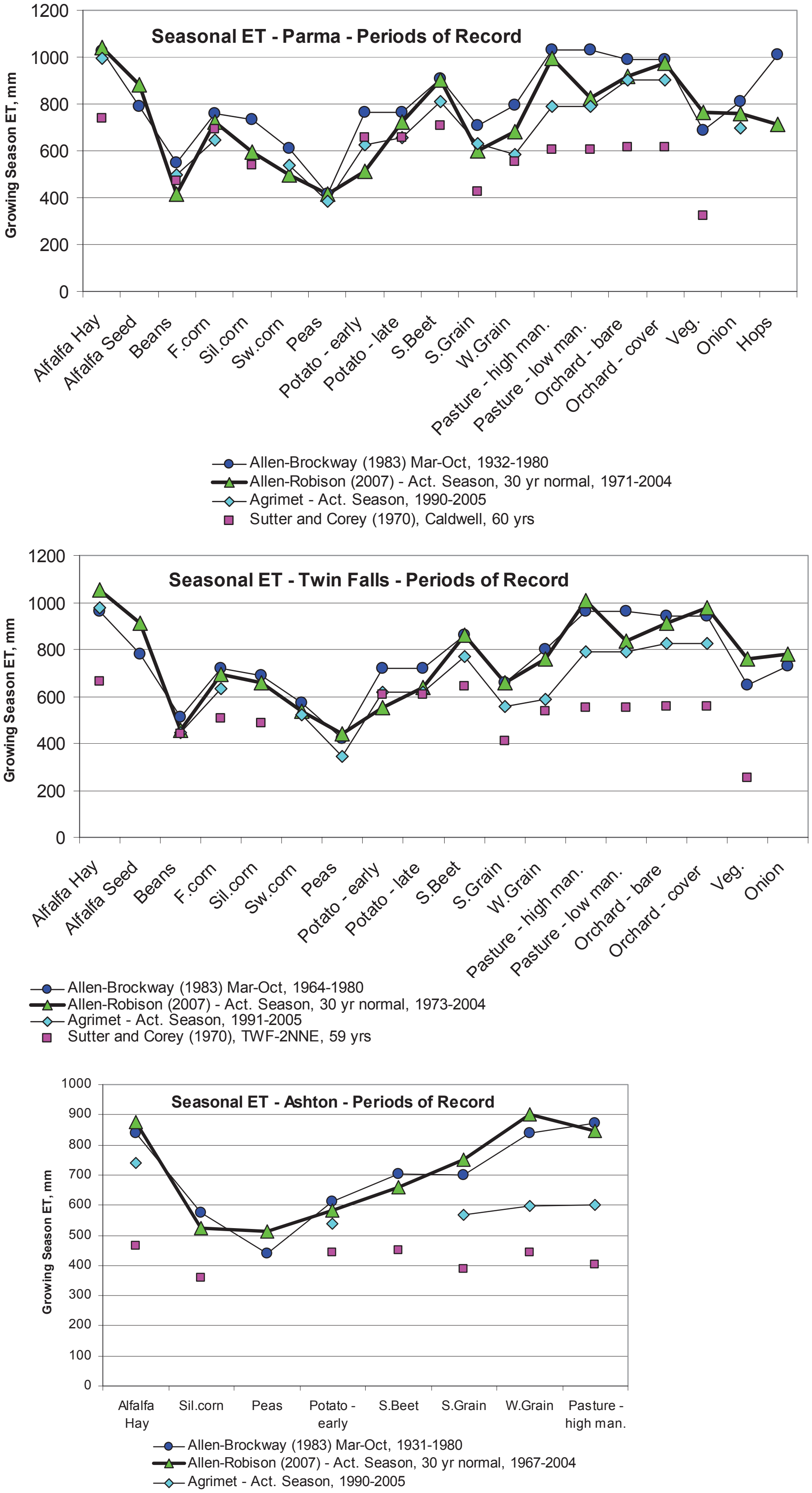


Figure 9. Total growing season ET_c for major crop categories averaged over the periods of record at a) Parma, b) Twin Falls 7E and c) Ashton from reports by Allen and Brockway (1983) *(based on $K_{c\ mean}\ ET_r$)*, Allen and Robison (2007 *(this report)*) *(based on $(K_sK_{cb}+K_e)\ ET_r$)*, from AgriMet *(based on $K_{c\ mean}\ ET_r$)*, and from Sutter and Corey (1970) *(based on the SCS-Blaney-Criddle method)*.

Comparisons for year 2000. Growing season ET$_c$ is compared in Figure 9 for the specific year 2000 for locations near Twin Falls and Jerome. This year was the focus of an intensive application of the METRIC satellite-based energy balance method for estimating ET over large areas. The METRIC procedure and application are described in Allen et al., (2007a and 2007b). 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 9 were sampled from large numbers of fields in the Jerome and Twin falls areas 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). Comparisons of K$_c$ by METRIC with K$_c$ from this study for year 2000 are included in Appendix 14. The METRIC derived images were integrated monthly and over the March 1 – October 31 period. The METRIC process was first applied to the 2000 image data by Tasumi (2003) and monthly results were revised during a second application in 2007 (Burnett and Allen, pers. comm.). The 'Allen-Robison (2007)' entries in Figure 9 represent ET$_c$ determined in this report 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 9 represents growing season ET$_c$ reported by the USBR AgriMet web site.

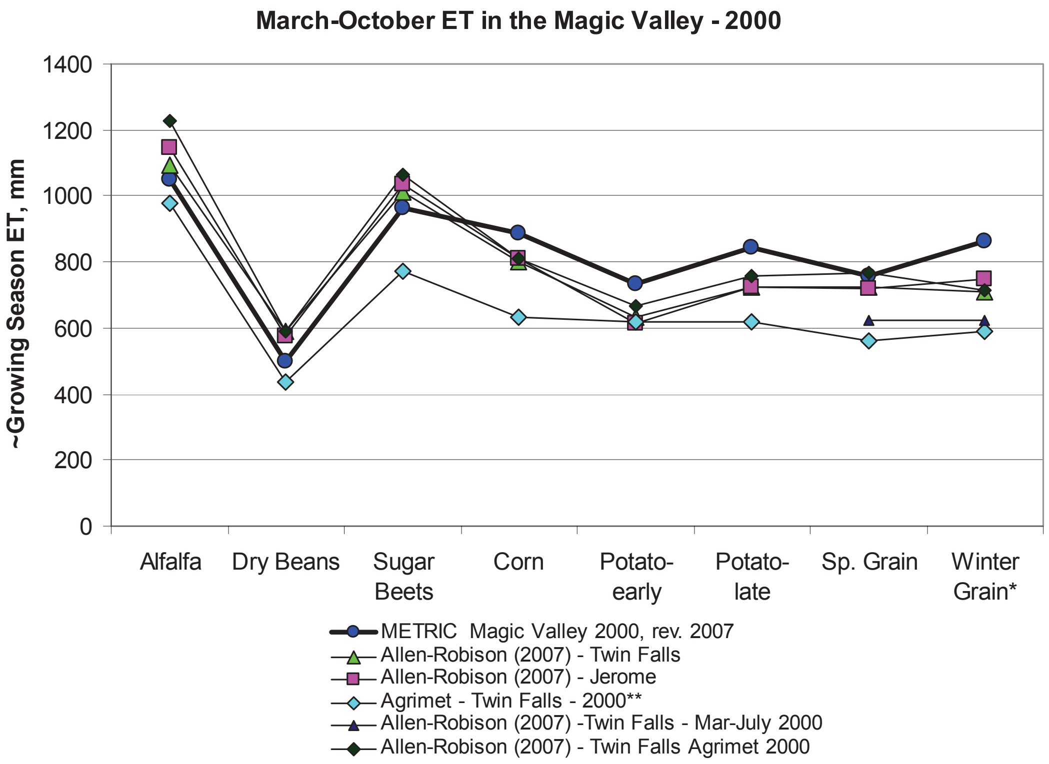


Figure 9. Growing season evapotranspiration during year 2000 for major crops grown in the Twin Falls – Jerome area of Magic Valley from four sources (1. METRIC satellite-based energy balance; 2. this report for Twin Falls 7E and Jerome NWS stations; 3. USBR AgriMet ET reports; and 4. this report using 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.

Differences in ET_c among the Twin Falls (NWS-7E), Jerome and Twin Falls Agrimet calculations from this report (Allen-Robison) indicate the general impact of weather station environment and weather data simulation (solar radiation, dewpoint and wind speed at Jerome and Twin Falls NWS-7E were estimated) on the ET_c estimates. In general, impacts were small and generally less than differences between the Allen-Robison estimates and ET_c from the other sources (METRIC and AgriMet).

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. Some uncertainty in METRIC-derived ET over the growing season stems from the fact that K_c was determined only 12 times during the 2000 growing season. K_c on intervening days was interpolated between Landsat image dates using a spline function and daily K_c values were multiplied by daily reference ET. Thus, some assumptions regarding monotonically increasing or decreasing K_c between satellite-image dates was made during the interpolations as well as during extrapolation of K_c from the first image date back in time to March 1 and during extrapolation of K_c from the last image date to October 31. However, METRIC estimates may be more accurate than K_c ET_r-based estimates produced by this study because some error and bias enters into K_c ET_r estimates due to uncertainty in estimated lengths of growing periods, planting and harvest dates, and uncertainty in the estimated K_{cb} and K_e curves and estimates themselves. It is difficult to determine whether METRIC or the Allen-Robison estimates are the ‘more accurate’ estimate.

The moderately higher estimates for growing season ET_c for alfalfa hay by the new procedure (7% based on a Jerome-Twin Falls 7E average and 10% based on a - Jerome-Twin Falls 7E-Twin Falls AgriMet average) gives cause for closer examination. The METRIC and Allen-Robison ET_c estimates represent the March 1 – Oct 31 period. The Allen-Robison estimates are averages for the two cutting frequency conditions computed for alfalfa hay. The 2000 growing season for alfalfa began earlier than normal, with greenup at Twin Falls estimated to occur on March 11 and the killing frost (-7 ^{o}C for alfalfa) not occurring until November 10. This longer than average growing season supported an estimated five ‘high-frequency’ cuttings of hay for dairy consumption and nearly four ‘lower-frequency’ cuttings of hay for beef cattle consumption during year 2000, which are greater than the four and three cuttings historically obtained, respectively.

Comparisons of K_c curves observed by METRIC and those simulated in this study (Appendix 14) show the simulated K_c by Allen-Robison to typically range higher than that from METRIC during periods of full alfalfa cover. One can speculate that the METRIC ‘observations’ of actual ET via energy balance, that were averaged over 325 fields (Tasumi et al., 2005; Burnett and Allen, 2007, pers. comm..), may reflect the impact of including ET from some fields that had reduced ET due to water shortage or poor water management or that might have suffered from disease or insect damage. One may also speculate that reductions in ET observed by METRIC may have been caused by influences of retarded alfalfa regrowth following cuttings caused by delays in removing windrows. This impact is real, but speculative in this case, since no ground evidence is available for 2000 for the region to indicate that windrow removal might have been delayed and ET thus impacted. The K_{cb} curves used in calculations for this new report are based on the alfalfa K_{cb} curves of Wright (1982) (see Appendix 3) that were fitted to ET_c by Ranger variety alfalfa. Wright (1988) noted that field harvests of alfalfa (from the field surrounding the lysimeters) averaged about 5% lower than that for the lysimeter. Some of the reduction was attributed to effects of machine harvesting on regrowth of the crop and delay of regrowth for areas under windrow because of shading and concentration of insects. Wright speculated that the ET from the field, if it followed the same ET-yield relationship for the lysimeters, to be about 5% less than that measured by the lysimeter. Wright (1988) noted that more recent alfalfa varieties tend to have finer stems and are more prone to lodging, thus, one could speculate that ET from more modern varieties is a small amount less than for Ranger variety due to aerodynamic effects. However, no direct ET measurements are available to support this (a Wright 1988 data set for the finer stemmed alfalfa was impacted by soil texture, soil chemical and soil water availability effects). Differences caused by the reduction in aerodynamic roughness caused by lodging of mature crops are estimated to be a few percent or less. Allen (pers. commun. Univ. Idaho 2002) found estimated alfalfa ET_r to decline by about 5% for a 25% reduction in alfalfa height (and aerodynamic roughness). The reduction in height was associated with a 10% reduction in leaf area, which would not occur with lodging only.

Reasons for the lower ET_c estimation by Allen-Robison (this report) 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. Differences in timing between K_c curves from the two processes can be observed in Appendix 14. The later extension of the growing period into July, as observed by METRIC, resulted in higher ET_c than was estimated in this study for year 2000 due to high ET_r rates in July.

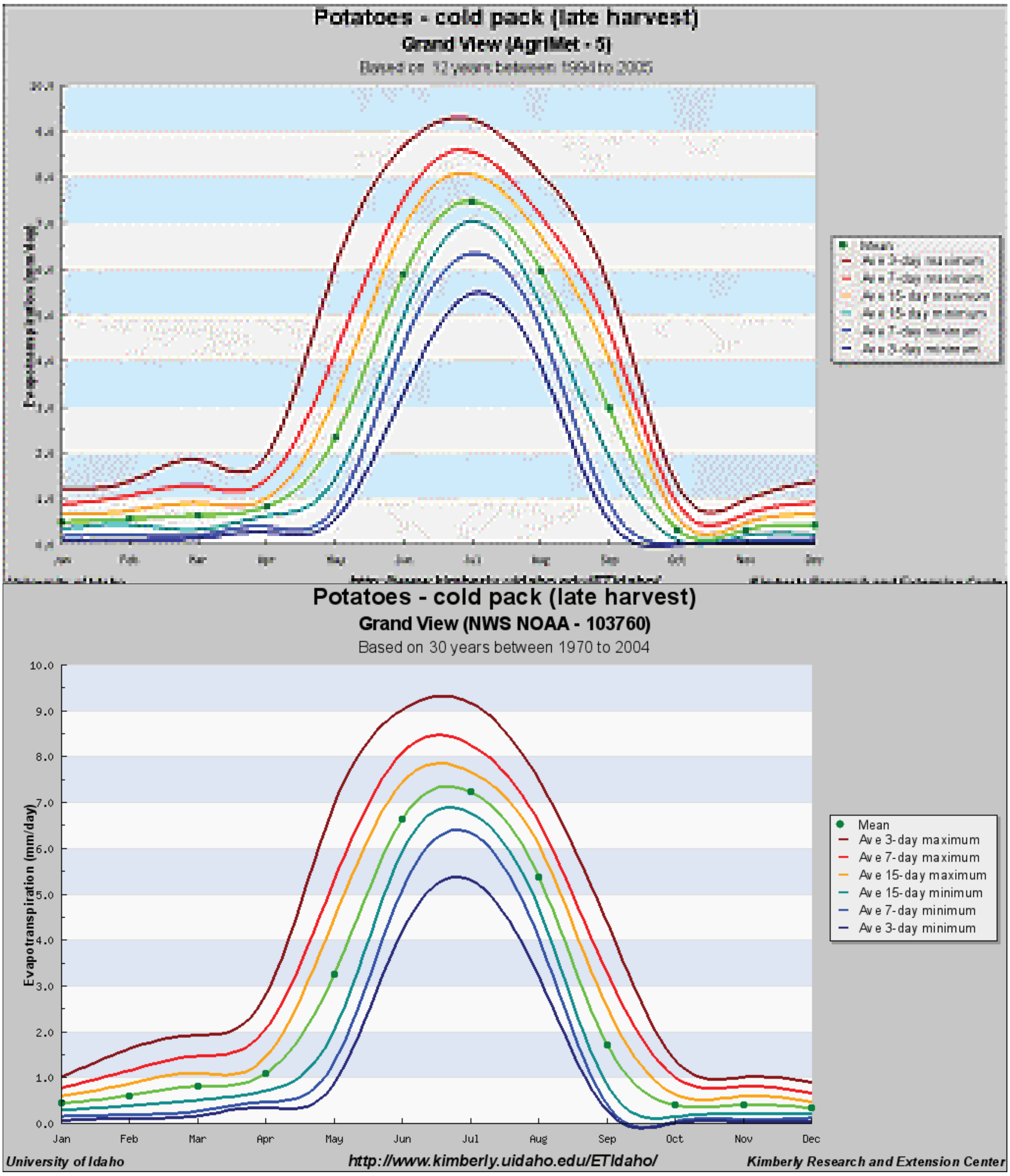
The AgriMet ET_c by USBR-AgriMet estimated about 7% below METRIC-derived growing season ET_c for alfalfa hay and 13-15% below METRIC for dry bean and early potato crops. AgriMet ET_c estimated 20-30% below METRIC for the balance of crops (sugar beets, corn, late potatoes, spring grain, winter grain). Agrimet estimated shorter growing periods for sugar beets and field corn, as reflected in the K_c curves (Appendix 14) 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.

In conclusion the new calculations of ET_c for primary agricultural crops tend to follow growing season totals presented by Allen and Brockway (1983) and as observed by the METRIC satellite-based ET procedure.

Impacts of Estimating Solar Radiation, Humidity and Wind Speed. As illustrated in the preceeding section and Figure 9, the impact of using estimated solar radiation and dewpoint temperature based on daily air temperature and using long term monthly averages for wind speed does not appear to have impacted the general accuracy of the ET_c estimates. This is further illustrated in Figure 10, which was created by the ETIdaho web site, where monthly values (smoothed using a cubic spline) for actual crop ET (ET_{act}) are shown for seven types of monthly means calculated for a long-season potato crop at Grand View. The various means represent the true monthly mean ('mean') and the 'aveHi' and 'aveLo' values for each of the 3-, 7- and 15-day periods. The 'aveHi' and 'AveLo' values represent the long-term averages for the highest and lowest 3-, 7- or 15-day period per month and are defined in Appendix 11. The top figure of Figure 10 shows data computed using AgriMet weather data from 1994-2005 (full data set for daily solar radiation, dewpoint temperature, wind speed and air temperature), but using K_c and ET_r computed during this study, and the bottom figure shows data computed using the Grand View NWS station for the 1970-2004 (30-year normal) period where only air temperature and precipitation were measured and solar radiation, dewpoint temperature and wind speed were estimated.

The shapes and magnitudes of the various mean curves are very similar between the two data sets during both the growing periods for the potatoes and during the nongrowing periods. This close agreement indicates that the methods used to estimate (simulate) solar radiation, dewpoint temperature and wind speed at the NWS stations produced relatively accurate estimates for reference ET_r and subsequently ET_c. The close agreement is surprisingly good considering the shorter period for the Agrimet data (1994-2005) as opposed to 1970-2004 for the NWS station).

Figure 11 is similar to Figure 10, except that the precipitation deficit, P_{def}, is shown rather than ET_{act}. The P_{def} is defined as $ET_{act} - P_{inf}$ where P_{inf} is precpitation that has infiltrated and resided within the root zone. Negative values for P_{inf} indicate precipitation in excess of ET for the period length within the month. The agreement between the P_{inf} for the AgriMet and NWS data sets is not as good as with ET_{act}. This is primarily due to differences in reported precipitation at the two Grand View weather stations caused by differences in periods of record (1994-2005 vs. 1970-2004) and due to the means for measuring precipitation, where the AgriMet stations generally use automatic tipping bucket rain gauges and the NWS stations use manually read standard NWS precipitation gauges. In general, however, agreement is relatively good and gives cause for confidence in the ET_c calculations for the National Weather Service (NWS) stations.



Potatoes - cold pack (late harvest)

Grand View (AgriMet - 5)

Based on 12 years between 1994 to 2005

Potatoes - cold pack (late harvest)

Grand View (NWS NOAA - 103760)

Based on 30 years between 1970 to 2004

Figure 10. Monthly values (smoothed) for actual crop ET (ET_{act}) for seven types of monthly means calculated for a long-season potato crop at Grand View, where the top figure shows data computed using AgriMet weather data from 1994-2005 (full data set for daily solar radiation, dewpoint temperature, wind speed and air temperature), and where the bottom figure shows data computed using the Grand View NWS station for the 1970-2004 (30-year normal) period where only air temperature and precipitation were measured and solar radiation, dewpoint temperature and wind speed were estimated. The means represent the true monthly mean ('mean') and the 'aveHi' and 'aveLo' values for 3-, 7- and 15-day periods. The 'aveHi' and 'AveLo' values are defined in Appendix 11.

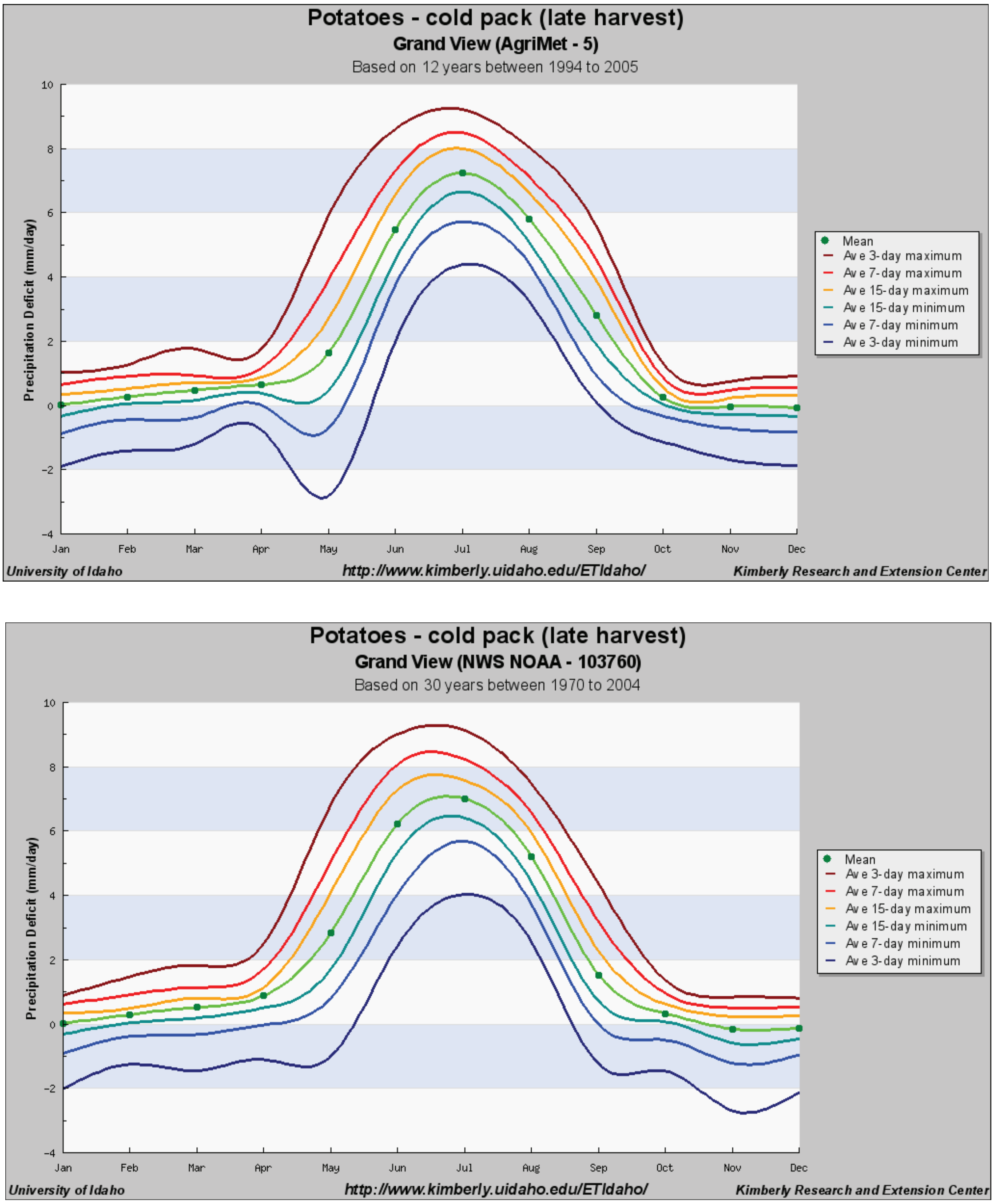


Figure 11. Monthly values (smoothed) for precipitation deficit (P_{def}) for seven types of monthly means calculated for a long-season potato crop at Grand View, where the top figure shows data computed using AgriMet weather data from 1994-2005 (full data set for daily solar radiation, dewpoint temperature, wind speed and air temperature), and where the bottom figure shows data computed using the Grand View NWS station for the 1970-2004 (30-year normal) period where only air temperature and precipitation were measured and solar radiation, dewpoint temperature and wind speed were estimated. The means represent the true monthly mean ('mean') and the 'aveHi' and 'aveLo' values for 3-, 7- and 15-day periods. The 'aveHi' and 'AveLo' values are defined in Appendix 11.

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SUMMARY AND CONCLUSIONS

Evapotranspiration and net irrigation water requirement estimates have been updated in this report for agricultural areas in Idaho. New ET calculation procedures have been employed including an updated type of reference equation (the ASCE standardized Penman-Monteith method) and using an updated procedure to calculate crop coefficients that considers the impact of surface wetting by irrigation and precipitation on total evapotranspiration. ET has been calculated for daily, monthly and annual timesteps for 123 weather station locations across Idaho for complete, available periods of record. These ET calculations supersede calculations previously made for Idaho by Allen and Brockway (1983). The ET estimates represent 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 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 affecting evapotranspiration and are located primarily in the southern part of the state. Calculations have been made through December 31, 2004 for the NWS stations and through December 31, 2005 for the AgriMet stations.

The ASCE standardized Penman-Monteith reference evapotranspiration equation is a highly regarded method (ASCE-EWRI 2005) and serves as a reproducible index approximating the climatic demand for water vapor. Reference ET is the ET rate from an extensive surface of reference vegetation having a standardized uniform height and that is actively growing, completely shading the ground, has a dry but healthy and dense leaf surface, and is not short of water. The ASCE Penman-Monteith (PM) equation was recently standardized by ASCE-EWRI (2005) for application to a full-cover alfalfa reference and to a clipped cool season grass reference.

Because only maximum and minimum air temperature are observed at the National Weather Service 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. 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 high 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.

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 according to growing degree days following the start of season. Growing seasons were terminated by predicted maturation of the crop or by a killing frost. The base K_{cb} curves were expressed on relative time scales or relative thermal unit scales to allow K_{cb} curves to be 'stretched' differently each year, according to weather conditions. Four different methods were used to express the base K_{cb} curves, depending on the crop or land-use type: 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 organized or developed for forty-two crop and land-cover types.

The FAO-56 method for estimating evaporation from bare, wet soil, was utilized where a daily water balance was computed for the top 10 cm of soil as a means for reducing evaporation losses as the soil surface dries. Irrigations were simulated for irrigated crops for purposes of estimating evaporation from wet soil surfaces. Scheduling of irrigations was made using a root-zone water balance assuming a nonresistricted root zone and depletion of soil water to an allowable depletion level. Simulated irrigation schedules were typically like those practiced with surface irrigation and with hand-move or wheel-line sprinkler systems (i.e., 'low frequency' irrigation).

Available water holding capacity and texture of soil for each station was determined using information from the National StatsGo soils information data base using a GIS analysis of the national soil data base for the area assigned to each station. Precipitation runoff was estimated using the NRCS Curve Number method where antecedent moisture was computed from the daily surface soil water balance. The curve number was determined from soil texture based on the StatsGo soils data base.

Snow cover data as observed at many of the NWS stations were used to modify winter time estimates of evaporation caused by high albedo of snow and energy required for heat of fusion and was also used during adjustment of cumulative growing degree days for winter wheat during winter.

Besides the daily, monthly and annual time series of ET_c that have been compiled, tables of statistics describing long-term mean values 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.

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.

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APPENDIX 1

CALCULATION OF REFERENCE EVAPOTRANSPIRATION

This appendix is largely excerpted from ASCE-EWRI (2005) and describes data requirements, equations, and procedures necessary for calculating the ASCE-Penman-Monteith ET_r on a daily calculation time step. A daily time step has historically been commonly used in the calculation of ET_r.

Required Data for the Standardized Reference Equation

The calculation of ET_r using the ASCE-PM method requires measurements or estimates for air temperature, humidity, solar radiation, and wind speed. When humidity, solar radiation or wind speed measurements are not available, substitute values for daily and longer time periods can be estimated using procedures described in Appendix E of ASCE-EWRI (2005).

Calculations Required for Daily Time-steps

Psychrometric and Atmospheric Variables[5]

Mean Air Temperature (T)

For the standardized method, the mean air temperature, T, for a daily time step is preferred as the mean of the daily maximum and daily minimum air temperatures rather than as the average of hourly temperature measurements to provide for consistency across all data sets.

$$T = \frac{T_{max} + T_{min}}{2} \tag{1.1}$$

where:

T = daily mean air temperature [°C]
T_{max} = daily maximum air temperature [°C]
T_{min} = daily minimum air temperature [°C]

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[5] Many of the equations presented here are the same as those reported in ASCE Manual 70 (Jensen et al., 1990) and in FAO-56 (Allen et al., 1998).

Atmospheric Pressure (P)

The mean atmospheric pressure at the weather site is predicted from site elevation using a simplified formulation of the Universal Gas Law[6]:

$$P = 101.3\left(\frac{293 - 0.0065\,z}{293}\right)^{5.26} \tag{1.2}$$

where:

P = mean atmospheric pressure at station elevation z [kPa], and
z = weather site elevation above mean sea level [m].

Psychrometric Constant (γ)

The standardized application using latent heat for vaporization $\lambda = 2.45$ MJ kg^{-1} results in a value for the psychrometric constant, γ, that is proportional to the mean atmospheric pressure:

$$\gamma = 0.000665\ \text{P} \tag{1.3}$$

where P has units of kPa and γ has units of kPa $^{\circ}\text{C}^{-1}$.

Slope of the Saturation Vapor Pressure-Temperature Curve (Δ)

The slope of the saturation vapor pressure-temperature curve[7], Δ, is computed as:

$$\Delta = \frac{2503\ \exp\left(\frac{17.27\,\text{T}}{\text{T} + 237.3}\right)}{(\text{T} + 237.3)^2} \tag{1.4}$$

where:

Δ = slope of the saturation vapor pressure-temperature curve [kPa $^{\circ}\text{C}^{-1}$], and
T = daily mean air temperature [°C].

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[6] Reference: Burman et al. (1987)

[7] References: Tetens (1930), Murray (1967)

Saturation Vapor Pressure (e_s)

The saturation vapor pressure[8] (e_s) represents the capacity of the air to hold water vapor.

For calculation of daily standardized ET_r , e_s is given by:

$$e_s = \frac{e^o(T_{max}) + e^o(T_{min})}{2} \tag{1.5}$$

where:
$e^o(T)$ = saturation vapor pressure function (Eq. 1.6) [kPa]

The function to calculate saturation vapor pressure is:

$$e^o(T) = 0.6108 \exp\left(\frac{17.27\,T}{T + 237.3}\right) \tag{1.6}$$

where vapor pressure is in units of kPa and temperature is in °C.

Actual Vapor Pressure (e_a)

Actual vapor pressure (e_a) is used to represent the water content (humidity) of the air at the weather site. The actual vapor pressure can be measured or it can be calculated from various humidity data, such as measured dew point temperature, wet-bulb and dry-bulb temperature, or relative humidity and air temperature data.

Preferred procedures for calculating e_a
When multiple types of humidity or psychrometric data are available for estimating e_a, the preferences listed in Table A.1 are recommended by ASCE-EWRI (2005) for the calculation method. These recommendations are based on the likelihood that the data will have integrity and that estimates for e_a will be representative. The availability and quality of local data, as well as site conditions, may justify a different order of preference.

When humidity and psychrometric data are missing or are of questionable integrity, dew point temperature can be estimated from daily minimum air temperature as described in Appendix E of ASCE-EWRI (2005). This estimation process should be verified locally. The assessment of weather data integrity is discussed in Appendix D of ASCE-EWRI (2005).

e_a from measured dew point temperature
The dew point temperature (T_{dew}) is the temperature to which the air must cool to reach a state of saturation. For daily calculation time steps, average dew point temperature can be computed by averaging over hourly periods or, for purposes of estimating ET_r, it can be determined by an early morning measurement (generally at 0700 or 0800 hours). The value for e_a is calculated by substituting T_{dew} into Eq. 1.6 resulting in:

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[8] Reference: Jensen et al. (1990) and Tetens (1930)

$$e_a = e^o\left(T_{dew}\right) = 0.6108\ exp\left[\frac{17.27\ T_{dew}}{T_{dew} + 237.3}\right] \tag{1.7}$$

Table A.1. Preferred method for calculating e_a for daily ET_r

Method No.	Method	Preference Ranking
1	e_a averaged over the daily period (based on hourly or more frequent measurements of humidity)[a,b]	1
2	Measured or computed dew point temperature averaged over the daily period	1
3	Wet-bulb and dry-bulb temperature averaged over the daily period	2
4	Measured or computed dew point or measured wet-bulb and dry-bulb temperature at 7 or 8 am	2
5	Daily maximum and minimum relative humidity	2
6	Daily maximum relative humidity	3
7	Daily minimum relative humidity	3
8	Daily minimum air temperature	4
9	Daily mean relative humidity	4

e_a from daily minimum air temperature

When humidity data are not measured or are of poor quality, ASCE-EWRI (2005) suggested estimating T_{dew} by subtracting an offset from T_{min}:

$$T_{dew} = T_{min} - K_o \tag{1.8}$$

where T_{min} is daily minimum air temperature (°C) and K_o is an offset that can vary monthly. Determination of values for K_o is described in Appendix 2. The value for T_{dew} from Equation 1.8 is used with Equation 1.7 to produce an estimate for e_a.

Net Radiation (R_n)

Net radiation (R_n) is the net amount of radiant energy available at a vegetation or soil surface for evaporating water, heating the air, or heating the surface. R_n includes both short and long wave radiation components [9]:

$$R_n = R_{ns} - R_{nl} \tag{1.9}$$

where:

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[9] Reference: Brutsaert (1982), Jensen et al., (1990), Wright (1982), Doorenbos and Pruitt (1975,1977), Allen et al., (1998).

R_{ns} = net short-wave radiation, [MJ m^{-2} d^{-1}] (defined as being positive downwards and negative upwards),

R_{nl} = net outgoing long-wave radiation, [MJ m^{-2} d^{-1}] (defined as being positive upwards and negative downwards),

R_{ns} and R_{nl} are generally positive or zero in value.

Net radiation is difficult to measure because net radiometers are problematic to maintain and calibrate. There is good likelihood of systematic biases in R_n measurements. Therefore, R_n is often predicted from observed short wave (solar) radiation, vapor pressure, and air temperature. This prediction is routine and generally highly accurate.

Net Solar or Net Short-Wave Radiation (R_{ns})

Net short-wave radiation resulting from the balance between incoming and reflected solar radiation is given by:

$$R_{ns} = R_s - \alpha R_s = (1 - \alpha) R_s \tag{1.10}$$

where:

R_{ns} = net solar or short-wave radiation [MJ m^{-2} d^{-1}],

α = albedo or canopy reflection coefficient, is fixed at 0.23 for the standardized short and tall reference surfaces [dimensionless], and

R_s = incoming solar radiation [MJ m^{-2} d^{-1}].

The calculation of ASCE-PM ET_r uses the constant value of 0.23 for albedo for daily and hourly periods.

Net Long-Wave Radiation (R_{nl})

R_{nl}, net long-wave radiation, is the difference between upward long-wave radiation from the standardized surface (R_{lu}) and downward long-wave radiation from the sky (R_{ld}), so that $R_{nl} = R_{lu} - R_{ld}$. The following calculation for <u>daily</u> R_{nl} follows the method of Brunt (1932, 1952) of using vapor pressure to predict net emissivity:

$$R_{nl} = \sigma \ f_{cd} \left(0.34 - 0.14 \sqrt{e_a}\right) \left[\frac{T_{K\ max}^4 + T_{K\ min}^4}{2}\right] \tag{1.11}$$

where:

R_{nl} = net long-wave radiation [MJ m^{-2} d^{-1}],

σ = Stefan-Boltzmann constant [4.901 x 10^{-9} MJ K^{-4} m^{-2} d^{-1}],

f_{cd} = cloudiness function [dimensionless] (limited to $0.05 \le f_{cd} \le 1.0$),

e_a = actual vapor pressure [kPa],

$T_{K\,max}$ = maximum absolute temperature during the 24-hour period [K] (K = °C + 273.16),
$T_{K\,min}$ = minimum absolute temperature during the 24-hour period [K] (K = °C + 273.16).

The superscripts “4” in Eq. 1.11 indicate the need to raise the air temperature, expressed in Kelvin units, to the power of 4. For daily and monthly calculation timesteps, f_{cd} is calculated as[10]:

$$f_{cd} = 1.35\frac{R_s}{R_{so}} - 0.35 \tag{1.12}$$

where:

R_s/R_{so} = relative solar radiation (limited to $0.3 \le R_s/R_{so} \le 1.0$),
R_s = measured or calculated solar radiation [MJ m^{-2} d^{-1}], and
R_{so} = calculated clear-sky radiation [MJ m^{-2} d^{-1}].

The ratio R_s/R_{so} in Eq. 1.12 represents relative cloudiness and is limited to $0.3 < R_s/R_{so} \le 1.0$ so that f_{cd} has limits of $0.05 \le f_{cd} \le 1.0$.

Clear-Sky Solar Radiation (R_{so})

Clear-sky solar radiation (R_{so}) is used in the calculation of net radiation (R_n) and is used during quality assessment and control of solar radiation measurements. Clear-sky solar radiation is defined as the amount of solar radiation (R_s) that would be received at the weather measurement site under conditions of clear-sky (i.e., cloud-free). The ratio of R_s to R_{so} in the equation for R_n is used to characterize the impact of cloud-cover on the downward emission of thermal radiation to the earth’s surface. Daily R_{so} is a function of the time of year and latitude. R_{so} is also impacted by station elevation (affecting atmospheric thickness and transmissivity), the amount of water vapor in the atmosphere (affecting the absorption of some short-wave radiation), and the amount of dust or aerosols in the air.

R_{so} is generally estimated as some fraction of exoatmospheric radiation (R_a) that passes through the atmospheric and to the earth’s surface. Exoatmospheric radiation, also known as extraterrestrial radiation, is the amount of solar radiation that would be received at the earth’s surface in the absense of any atmosphere. R_a serves as a relatively accurate means for determining a theoretical R_{so}envelope as illustrated in Figure 1.1. The envelope can be expressed in tabular form or as an equation. In this section, a simple procedure[11] is demonstrated for estimating R_{so} for purposes of predicting net radiation. A more involved procedure, used for evaluating R_s data integrity, is described in Appendix 2.

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[10] Jensen et al., (1990); Allen et al., (1998)

[11] Reference: Allen (1996)

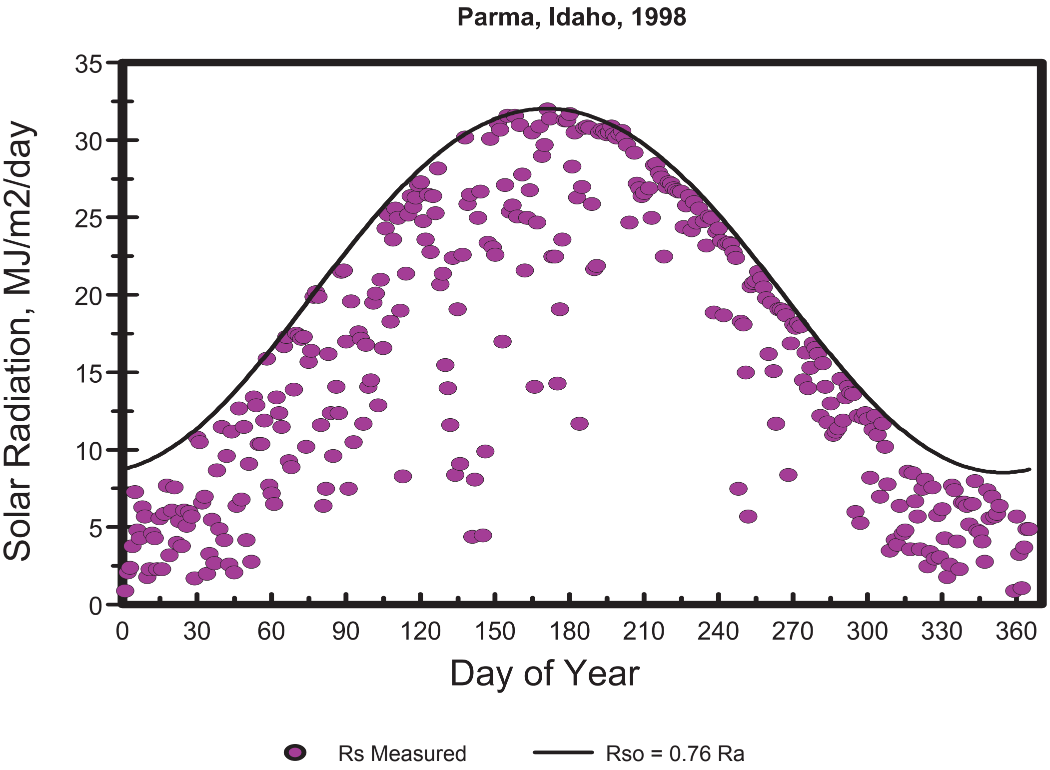

Figure 1.1. Daily solar radiation (R_s) at Parma, Idaho during 1998 (elevation 703 m, Lat. 43.8°) and clear sky (R_{so}) envelope (from ASCE-EWRI, 2005).

R_{so}, for purposes of calculating R_n, is computed as:

$$R_{so} = \left(0.75 + 2\,x\,10^{-5}\,z\right) R_a \tag{1.13}$$

where:

z = station elevation above sea level [m].

Eq. 1.13 estimates progressively higher levels of clear sky radiation with increasing elevation, and is the basis for the "0.76" factor for the R_{so} curve drawn in Figure 1.1. Elevation serves as a surrogate for total air mass and atmospheric transmissivity above the measurement site.

Exoatmospheric Radiation For 24-Hour Periods (R_a)[12]

Exoatmospheric radiation, R_a, is defined as the short-wave solar radiation in the absence of an atmosphere, and is a well-behaved function of the day of the year, time of day, and latitude. It is needed for calculating R_{so}, which is in turn used in calculating R_n. For daily (24-hour) periods, R_a is estimated from the solar constant, the solar declination, and the day of the year:

$$R_a = \frac{24}{\pi} G_{sc}\, d_r \left[\omega_s \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s)\right] \tag{1.14}$$

where:

R_a = exoatmospheric radiation [MJ m^{-2} d^{-1}],
G_{sc} = solar constant [4.92 MJ m^{-2} h^{-1}],
d_r = inverse relative distance factor (squared) for the earth-sun [unitless],
ω_s = sunset hour angle [radians],
φ = latitude [radians], and
δ = solar declination [radians].

The latitude, φ, is positive for the Northern Hemisphere and negative for the Southern Hemisphere. The conversion from decimal degrees to radians is given by:

$$Radians = \frac{\pi}{180}\left(decimal\ degrees\right) \tag{1.15}$$

and d_r and δ are calculated as:

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365} J\right) \tag{1.16}$$

$$\delta = 0.409 \sin\left(\frac{2\pi}{365} J - 1.39\right) \tag{1.17}$$

where:

J is the number of the day in the year between 1 (1 January) and 365 or 366 (31 December). J is calculated as[13]:

$$J = D_M - 32 + Int\left(275\frac{M}{9}\right) + 2\ Int\left(\frac{3}{M+1}\right) + Int\left(\frac{M}{100} - \frac{Mod(Y,4)}{4} + 0.975\right) \tag{1.18}$$

where:

D_M = the day of the month (1-31),

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[12] Reference: Duffie and Beckman (1980).

[13] Reference: Allen (2000).

M = the number of the month (1-12), and
Y = the number of the year (for example 1996 or 96).

The "Int" function in Eq. 25 finds the integer number of the argument in parentheses by rounding downward. The "Mod(Y,4)" function finds the modulus (remainder) of the quotient Y/4.

The sunset hour angle, ω_s, is given by:

$$\omega_s = arccos\left[-tan(\varphi)tan(\delta)\right] \tag{1.19}$$

The "arccos" function is the arc-cosine function and represents the inverse of the cosine. This function is not available in all computer languages, so that ω_s can alternatively be computed using the arc-tangent (inverse tangent) function:

$$\omega_s = \frac{\pi}{2} - arctan\left[\frac{-tan(\varphi)tan(\delta)}{X^{0.5}}\right] \tag{1.20}$$

where:

$$X = 1 - \left[tan(\varphi)\right]^2\left[tan(\delta)\right]^2 \tag{1.21}$$

$$and\ \ X = 0.00001\ if\ \ X \le 0$$

Soil Heat Flux Density (G)

Soil heat flux density is the thermal energy utilized to heat the soil. G is positive when the soil is warming and negative when the soil is cooling. The magnitude of the daily, weekly or ten-day soil heat flux density, G, beneath a fully vegetated grass or alfalfa reference surface is relatively small in comparison with R_n. Therefore, in calculation of alfalfa reference ET_r for daily timesteps, the ASCE standardization sets G to zero:

$$G_{day} = 0 \tag{1.22}$$

where:

G_{day} = daily soil heat flux density [MJ m^{-2} d^{-1}].

Wind Profile Relationship

Wind speed varies with height above the ground surface. For the calculation of ET_r, the standardized Penman-Monteith method requires an equivalent wind speed at 2 meter height above the surface. Therefore, wind measured at other heights must be adjusted. To adjust wind speed data to the 2-m height, Eq. 1.23 is used for measurements taken above a short grass (or similar) surface, based on the full logarithmic wind speed profile relationship given in Appendix B of ASCE-EWRI (2005):

$$u_2 = u_z \frac{4.87}{ln(\ 67.8\ z_w - 5.42)} \qquad (1.23)$$

where:

u_2 = wind speed at 2 m above ground surface [m s^{-1}],

u_z = measured wind speed at z_w m above ground surface [m s^{-1}], and

z_w = height of wind measurement above ground surface [m].

For wind measurements above surfaces other than clipped grass, the user should apply the full logarithmic equation B.14 of Appendix B of ASCE-EWRI (2005).

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APPENDIX 2

ESTIMATION OF SOLAR RADIATION, HUMIDITY AND WIND DATA FOR HISTORICAL PERIODS AND THE IMPACT OF ESTIMATES ON REFERENCE EVAPOTRANSPIRATION CALCULATION

Procedure

Application of a Penman type equation, including the Penman-Monteith equation (Eq. 1 in the text), requires measurement or estimation of air temperature, solar radiation, humidity and wind speed. For the National Weather Service (NWS) cooperative stations, where only daily maximum and minimum air temperature and precipitation (along with snow fall) are measured, solar radiation, humidity and wind speed need to be approximated. The alternative is to use an empirical reference ET equation, such as the 1985 Hargreaves equation (Hargreaves et al., 1985) or the outdated Blaney-Criddle method that require only air temperature. However, use of air-temperature based ET_r equations leaves the 'knowledge' of background levels of wind speed, humidity and solar radiation in the hands of the empirical equation itself and thus embedded in generally constant empirical coefficients. The general consensus among the ET estimation community today is that it is preferable to utilize a physically based and generally accurate equation such as the Penman-Monteith method for all applications and to estimate for missing or unmeasured data using tested, standardized procedures (see FAO, 1998; ASCE-EWRI, 2005, appendix D, for example).

Solar Radiation

FAO-56 (Allen et al, 1998) and the ASCE-EWRI (2005) standardization recommended estimating solar radiation from daily air temperature extremes using an equation such as the Hargreaves-Samani (1982) equation:

$$R_s = 0.16\,(T_{max} - T_{min})^{0.5}\,R_a \tag{2.1}$$

where R_s is estimated daily solar radiation, MJ m^{-2} d^{-1}, R_a is exoatmospheric radiation (also known as exoatmospheric radiation), MJ m^{-2} d^{-1}, T_{max} is daily maximum air temperature, ^oC and T_{min} is daily minimum air temperature, ^oC. The value for R_s estimated by Eq. (2.1) must be limited to less than or equal to the value R_s that would occur under clear sky conditions.

Comparisons between estimates by Eq. (2.1) and measured R_s from AgriMet stations across southern Idaho have indicated that Eq. 2.1 tends to produce upward biases in estimated R_s at many locations with the amount of bias varying from location to location. This is shown in some of the following figures and table. As a result, following the completion of the September 2006 report, an R_s estimation procedure by Thornton and Running (1999) was explored and tested at a number of AgriMet locations. The Thornton and Running procedure was found to produce more consistent and accurate estimation of R_s than the Hargreaves method. The Thornton and Running (T-R) method is similar to the Hargreaves-Samani approach in that the difference between T_{max} and T_{min} is used as the primary estimator. However, the exponent on T_{max}-T_{min} is 1.5 in the Thornton and Running method rather than 0.5, as in Eq. (2.1), and an exponential transformation is employed. The form of the Thornton-Running equation is:

$$R_s = R_{so}\left[1 - 0.9\ exp\left(- B\left(T_{max} - T_{min}\right)^{1.5}\right)\right] \tag{2.2}$$

where R_{so} is theoretical solar radiation on a clear day, B is an empirical fitting coefficient, 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. In the Thornton-Running (1999) paper, a 'universal' function for B for use across the U.S. was presented as:

$$B_{T-R} = 0.031 + 0.201\ exp\left(- 0.185\ \Delta T_{month}\right) \tag{2.3}$$

where the subscript 'T-R' indicates the use of the original Thornton-Running coefficients in the Eq. for parameter B. Parameter ΔT_{month} in Eq. 2.3 and 2.4 functions as a local fitting term and is computed as the difference in long term average values for T_{max} and T_{min} on a monthly basis, ^oC. Parameter ΔT_{month} in effect normalizes the estimation equation (Eq. 2.2) so that deviations of $T_{max} - T_{min}$ above or below ΔT_{month} tend to represent more standardized amounts of relative cloudiness, or R_s/R_{so}. Twelve values for ΔT_{month} (one for each month) are required for each location of application.

Equation 2.2 with B from Eq. 2.3 tended to overestimate R_s at AgriMet stations. Therefore, improved coefficients were fitted to the form of Eq. 2.3 to improve accuracy of R_s estimates across southern Idaho. The improved coefficients were developed by fitting Eq. 2.3 to specific data from Thornton-Running that were identified as western U.S. stations (namely Portland and Eugene, Oregon). The resulting equation for B is:

$$B = 0.023 + 0.1\ exp\left(- 0.2\ \Delta T_{month}\right) \tag{2.4}$$

Figure 2.1 shows estimates of R_s from Eq. 2.2 with B from Eq. 2.3 (left figure) and with B from Eq. 2.4 (right figure), where R_s has been normalized by dividing by R_{so}. The figures include estimates of R_s (normalized to R_{so}) by the Hargreaves-Samani equation (Eq. 2.1) for comparison. The series of curves in the figures represent R_s/R_{so} calculated over a range of ΔT_{month} in Eq. 2.3 or 2.4 to demonstrate the sensitivity to ΔT_{month}. In general, the use of the fitted equation for B (Eq. 2.4) produces lower estimates for R_s for a given $T_{max} - T_{min}$ difference as compared to the general B_{T-R} function. Comparison of the various ΔT_{month} curves in Figure 2.1 reveals that R_s from Eq. 2.2 collapses toward a lower boundary on R_s/R_{so} as ΔT_{month} approaches or exceeds approximately $\Delta T_{month} \sim 20^oC$.

The Hargreaves-Samani estimates for R_s/R_{so} calculated by dividing Eq. 2.1 by R_{so} agree closely with estimates from the Eq. 2.2 + Eq. 2.4 combination (right hand figure) when T_{max}-$T_{min} > 10^oC$ for $\Delta T_{month} > 15^oC$ (i.e., during summer). Eq. 2.1 agrees with the Eq. 2.2 + 2.4 combination when T_{max}-T_{min} is in the range of 2 to 10^oC when $10 < \Delta T_{month} < 15^oC$ (i.e., during spring and fall).

Besides improved accuracy of the Eq. 2.2 + Eq. 2.4 combination over Eq. 2.1, an added advantage of Eq. 2.2 over the Hargreaves-Samani equation is that it is self limiting to a maximum value for R_s represented by R_{so}. Estimates of R_s from Eq. 2.1 that exceed R_{so} must be 'clipped' to R_{so}.

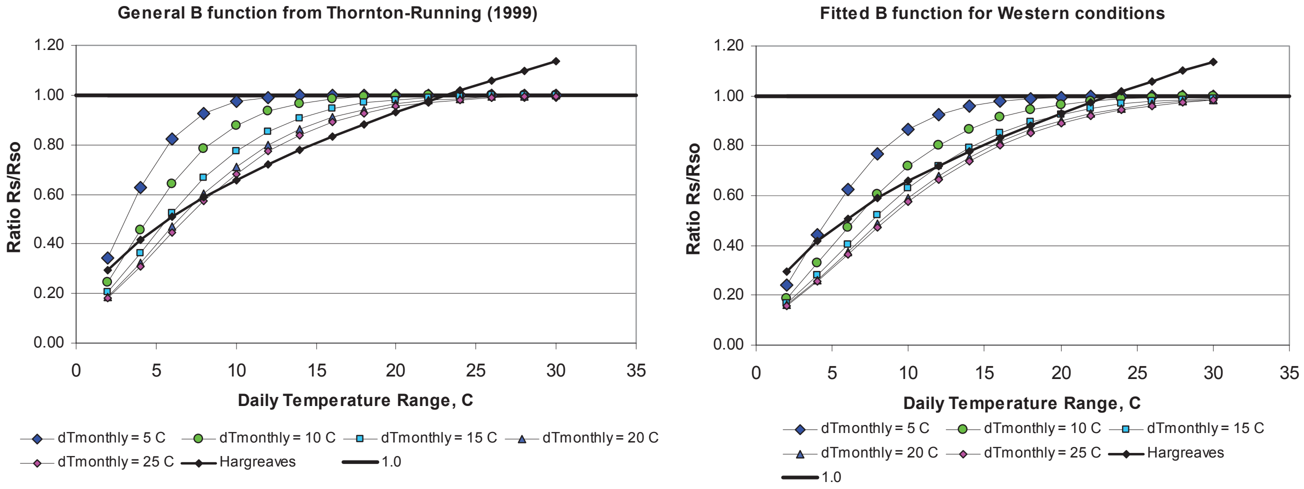


Figure 2.1. Comparison of R_s estimated from Eq. 2.2 (Thornton-Running equation) using the original Thornton-Running coefficients for B (left) and using coefficients for B (Eq. 2.4) derived during this study for western US stations identified in the paper (right). Estimates for R_s are normalized in the figure by dividing by R_{so} and are expressed as a function of the $T_{max} - T_{min}$ difference. (dTmonthly represents ΔT_{month}).

Clear Sky Solar Radiation for use in Eq. 2.2 R_{so} in Eq. 2.2 was computed in this study as the product of exoatmospheric radiation, R_a, computed as a function of latitude and date and atmospheric transmissivity, K_T:

$$R_{so} = K_T \, R_a \tag{2.5}$$

where the units for R_{so} and R_a are the same (generally MJ m^{-2} d^{-1} or W m^{-2}). The ASCE-EWRI (2005) report, Appendix D, provides an accurate procedure for estimating K_T that considers the effects of sun angle and water vapor on absorption of short wave radiation and that separates K_T into components representing absorption and scattering of beam and diffuse radiation, so that:

$$K_T = K_B + K_D \tag{2.6}$$

where K_B is a clearness index for direct beam radiation [unitless] and K_D is a transmissivity index for diffuse radiation [unitless]. The ASCE-EWRI (2005) equation for K_B is:

$$K_B = 0.98 \, exp\left[\frac{-0.00146\,P}{K_{tb}\,sin\,\beta} - 0.075\left(\frac{W}{sin\,\beta}\right)^{0.4}\right] \tag{2.7}$$

where K_{tb} is a turbidity coefficient [unitless], $0 < K_{tb} \leq 1.0$ where $K_{tb} = 1.0$ for clean air and $K_{tb} \leq 0.5$ for extremely turbid, dusty or polluted air, P is atmospheric pressure at the site elevation [kPa], β is the angle of the sun above the horizon [radians], and W is precipitable water in the atmosphere [mm]. A value of K_{tb} = 1.0 is recommended in Eq. 2.7 and represents relatively clean air. The "sin β" in Eq. 2.7 is limited to ≥ 0.01 for computational stability.

Precipitable water is estimated as:

$$W = 0.14 e_a P + 2.1 \tag{2.8}$$

where W is precipitable water in the atmosphere [mm], e_a is actual vapor pressure of the air [kPa] and P is atmospheric pressure at the site elevation [kPa].

The diffuse radiation index is estimated from K_B following ASCE-EWRI (2005):

$$\begin{aligned} K_D &= 0.35 - 0.36 K_B \quad for\ K_B \geq 0.15 \\ K_D &= 0.18 + 0.82 K_B \quad for\ K_B < 0.15 \end{aligned} \tag{2.9}$$

For daily (24-hour) time periods, the average value of β in Eq. 2.7, weighted according to R_a, is approximated following Allen (1996) as:

$$sin\,\beta_{24} = sin\left[0.85 + 0.3\varphi\, sin\left(\frac{2\pi}{365}J - 1.39\right) - 0.42\varphi^2\right] \tag{2.10}$$

where β_{24} is average β during the daylight period, weighted according to R_a [radians], φ is latitude [radians] and J is day of the year [unitless].

More information on computation of R_{so} and its accuracy is given in Allen (1996) and ASCE-EWRI (2005). The ASCE-EWRI (2005) report contains updated coefficients as used in Eq. 2.7 and 2.9. Computation of R_a as a function of latitude and day of year follows standard procedures as described in Allen (1996) and ASCE-EWRI (2005).

Comparisons at AgriMet stations. AgriMet weather stations are located throughout southern Idaho and are operated by the U.S. Bureau of Reclamation primarily for purposes of irrigation scheduling and other water management programs. These stations employ electronic sensors and are operated remotely. The stations measure solar radiation, humidity, air temperature, wind speed and direction, soil temperature and precipitation. Other measurements are made at some stations. Figure 2.2 shows a location map for AgriMet stations in the Pacific Northwest.

Eight AgriMet stations were selected for evaluating accuracy of the estimated R_s from Eq. 2.2 with Eq. 2.4, where National Weather Service (NWS) volunteer weather stations were located near the AgriMet station. These stations are listed in Table 2.1 and were spread from near the Oregon border in the west (Parma) to near Grand Teton National Park in the east (Ashton).

Annual ratios of estimated solar radiation to measured solar radiation at eight AgriMet stations over their periods of record are listed in Table 2.1, where estimated solar radiation was based on air temperature data from a nearby NWS station. Air temperature from the nearby NWS station was used to preserve any biases in T_{max} or T_{min} existing between NWS and AgriMet. Included in Table 2.1 are root mean square error (RMSE) for monthly and daily time periods, where RMSE is computed as

$$RMSE = \sqrt{\frac{\sum\left(X_{est} - X_{meas}\right)^2}{n}} \tag{2.11}$$

where X_{est} is the value for the estimate and X_{meas} is the value for the measurement and n is the number of observations.

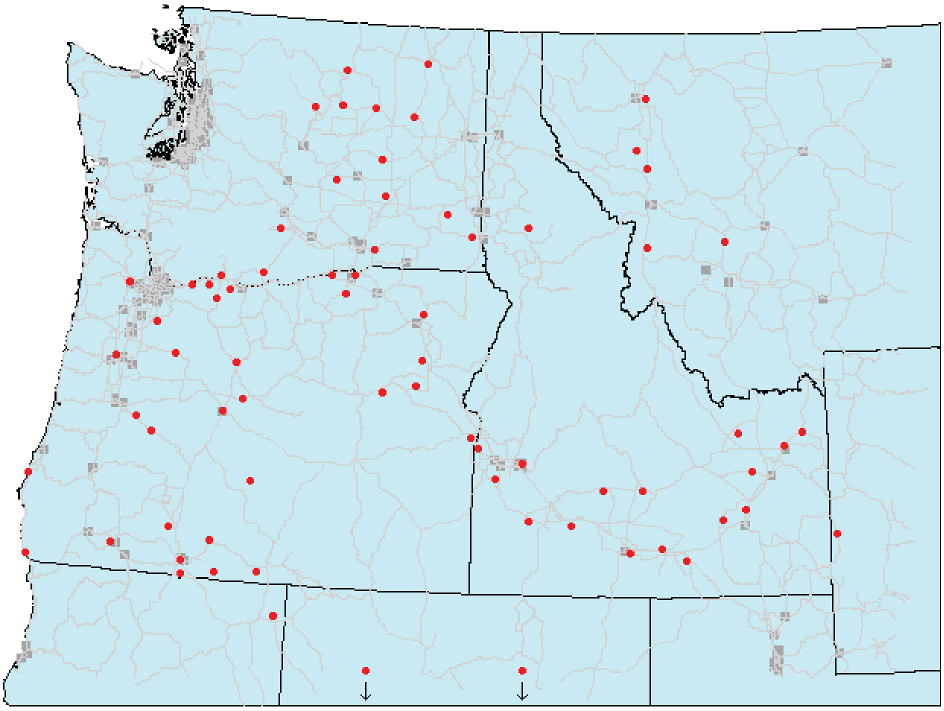


Figure 2.2. Locations of AgriMet weather stations in the Pacific northwest. Taken from http://www.usbr.gov/pn/agrimet/agrimetmap/agrimap.html.

Table 2.1. Annual ratios of estimated solar radiation to measured solar radiation at eight AgriMet stations over their periods of record, where estimated solar radiation was based on air temperature data from nearby NWS stations. Results for the Hargreaves-Samani (Eq. 2.1) and Thornton-Running (Eq. 2.2 + 2.4) are shown. Included are root mean square error (RMSE) for monthly and daily time periods.

Station	Ratio of est. R_s to measured		Mean ΔT_{month} for August, °C	RMSE for monthly average R_s, MJ $m^{-2}d^{-1}$		RMSE for daily estimated R_s, MJ $m^{-2}d^{-1}$	
	Hargreaves	T-R, Eq. 2,2+2.4		Hargreaves	T-R, Eq. 2.2+2.4	Hargreaves	T-R, Eq. 2.2+2.4
Aberdeen	1.10	1.05	22.3	2.16	1.56	4.49	4.26
Ashton	1.04	1.02	19.8	1.90	1.86	4.30	4.34
Malta	1.12	1.06	22.6	2.43	1.71	4.41	4.08
Parma	1.08	0.98	21.0	1.69	1.39	4.61	4.44
Picabo	1.06	1.01	21.9	1.50	1.22	4.18	4.02
Rexburg	1.09	1.05	20.9	1.84	1.62	4.09	4.04
Rupert	1.07	1.02	20.7	1.61	1.33	4.09	4.09
TwinFalls	1.00	0.98	18.3	1.19	1.40	4.13	4.17
-- Average	1.07	1.02	20.9	1.8	1.5	4.3	4.2
-- Std. Dev.	0.04	0.03	1.4	0.4	0.2	0.2	0.2

Table 2.2 summarizes RMSE for reference ET_r calculated from NWS data using estimated R_s, dewpoint temperature and wind speed as compared against ET_r calculated from the full complement of weather data from AgriMet stations (measured T_{max}, T_{min}, R_s, T_{dew}, wind speed). The average error introduced by estimating weather data averaged about 0.6 mm d^{-1} for ET_r averaged over monthly periods and 1.5 mm d^{-1} for any specific day. Ratios of the two ET_r estimates averaged 1.02, ranging from –4% to +12% at specific stations, and with standard deviation of 0.07 among the ratios. This error is considered to be acceptable.

Table 2.2. Annual root mean square error (RMSE) and ratios of reference ET_r calculated using estimated solar radiation (and estimated humidity and wind) based on air temperature data from NWS stations to ET_r calculated using measured solar radiation (and measured humidity and wind) at eight nearby AgriMet stations over their common periods of record.

Station	RMSE for monthly average ET_r, mm d^{-1}	RMSE for daily estimated ET_r, mm d^{-1}	Ratio of Annual ET_r for NWS station to Annual ET_r for AgriMet
Aberdeen	0.58	1.32	1.10
Ashton	0.54	1.22	1.05
Malta	0.92	1.75	0.96
Parma	0.47	1.18	1.01
Picabo	0.41	2.60	1.01
Rexburg	0.63	1.23	1.12
Rupert	0.69	1.40	0.94
TwinFalls	0.47	1.20	0.96
-- Average	0.59	1.49	1.02
-- Std. Dev.	0.16	0.49	0.07

Annual ratios of estimated to measured R_s are shown in Figure 2.3 where they are plotted vs. the mean August ΔT_{month}. The estimates from the Hargreaves-Samani method tended to increase above ratios of 1.0 with increased ΔT_{month}, whereas the estimates by the Thornton-Running method using Eq. 2.4 for B do not show as large an increase with ΔT_{month} and are within 5% of a ratio of 1.00 (a ratio of 1.00 indicates perfect estimation on an annual basis) for all but one location.

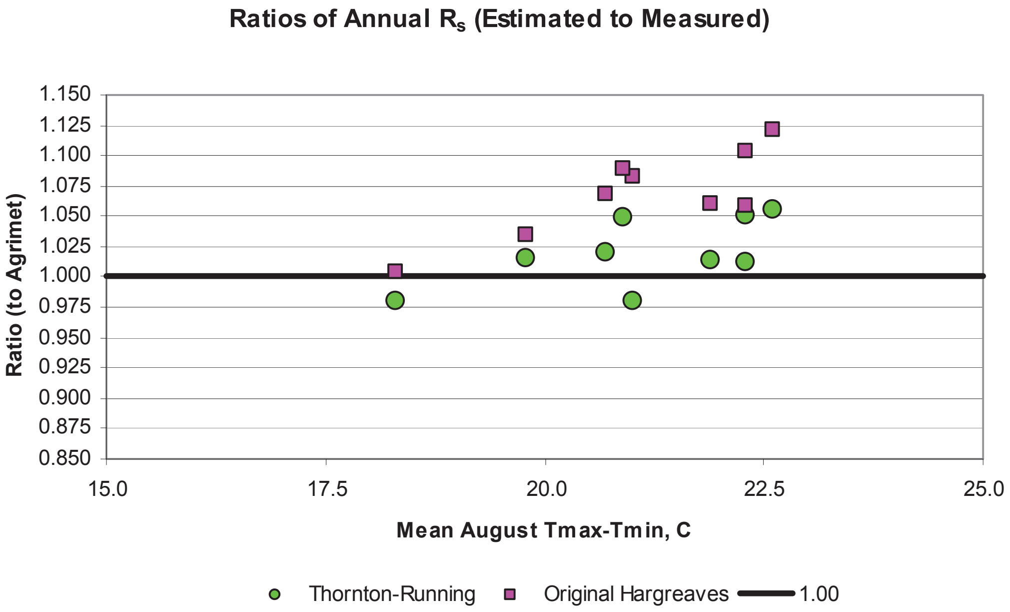
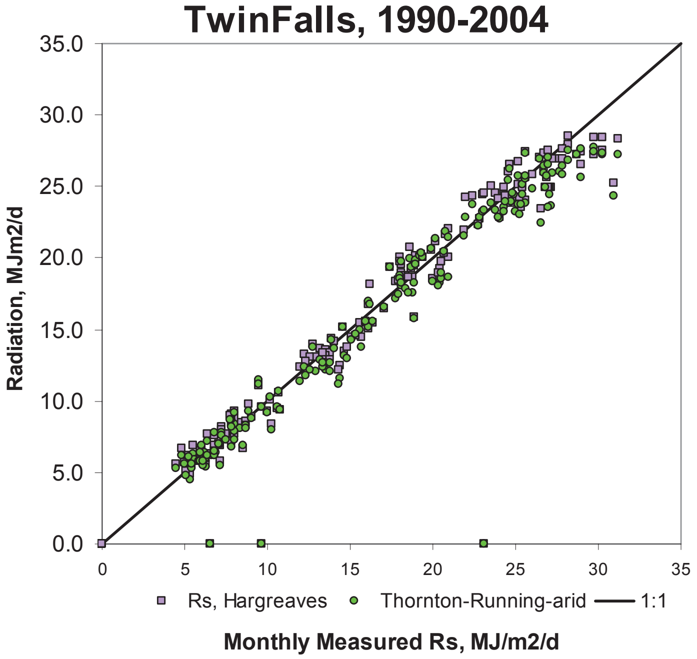


Figure 2.3. Annual ratios of estimated to measured R_s vs. the mean August ΔT_{month} for the eight AgriMet-NWS weather statation pairs listed in Tables 2.1 and 2.2 plus a ratio for the stations at Fairfield.

Comparisons at individual locations. The following sets of figures show estimated R_s vs. measured R_s for five AgriMet stations that span southern Idaho. These stations provide an indication of the relatively good agreement between the R_s estimated using the T-R approach and the advantage that it has, in accuracy, over the Hargreaves-Samani equation. Figures are shown for monthly periods averaged over all years of record common to the NWS-AgriMet pairs, for individual months over the periods of record, and for individual days over the periods of record.

In general, the T-R method estimates well over the ranges of R_s experienced and during all months of the year. The accuracy is somewhat more consistent than that of the Hargreaves-Samani method. Some scatter exists between daily estimated R_s and measured, which is expected, since the estimates are based on only T_{max} and T_{min}. However, over all, estimated daily R_s follows a close, linear relationship with measured R_s at all locations.



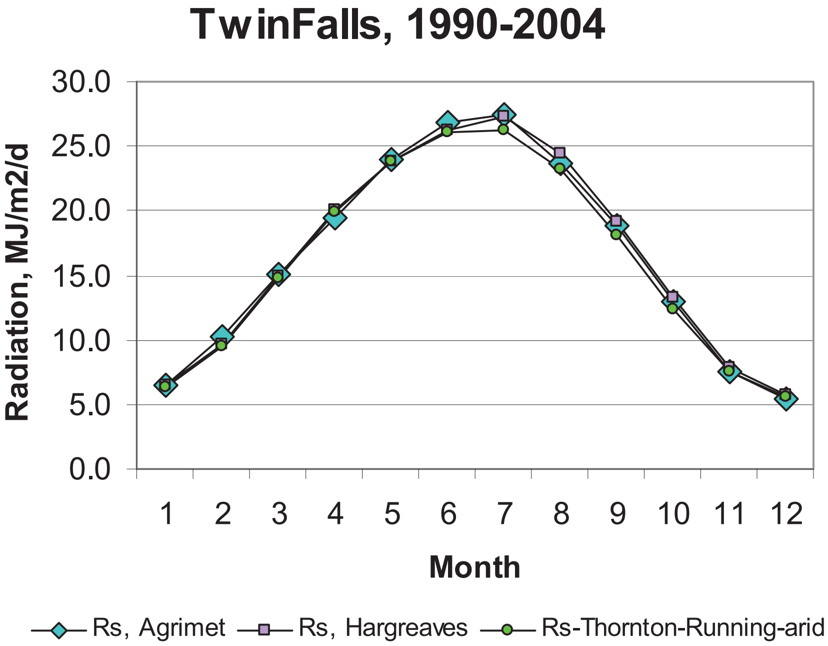


Figure 2.4. Monthly estimated R_S (using the Thornton-Running (with Eq. 2.4 for B) and using the Hagreaves-Samani methods) vs. measured R_S from a nearby AgriMet station at Twin Falls, ID for averages over each month over the common period of record (top) and long-term averages for individual months over the period of record (bottom).

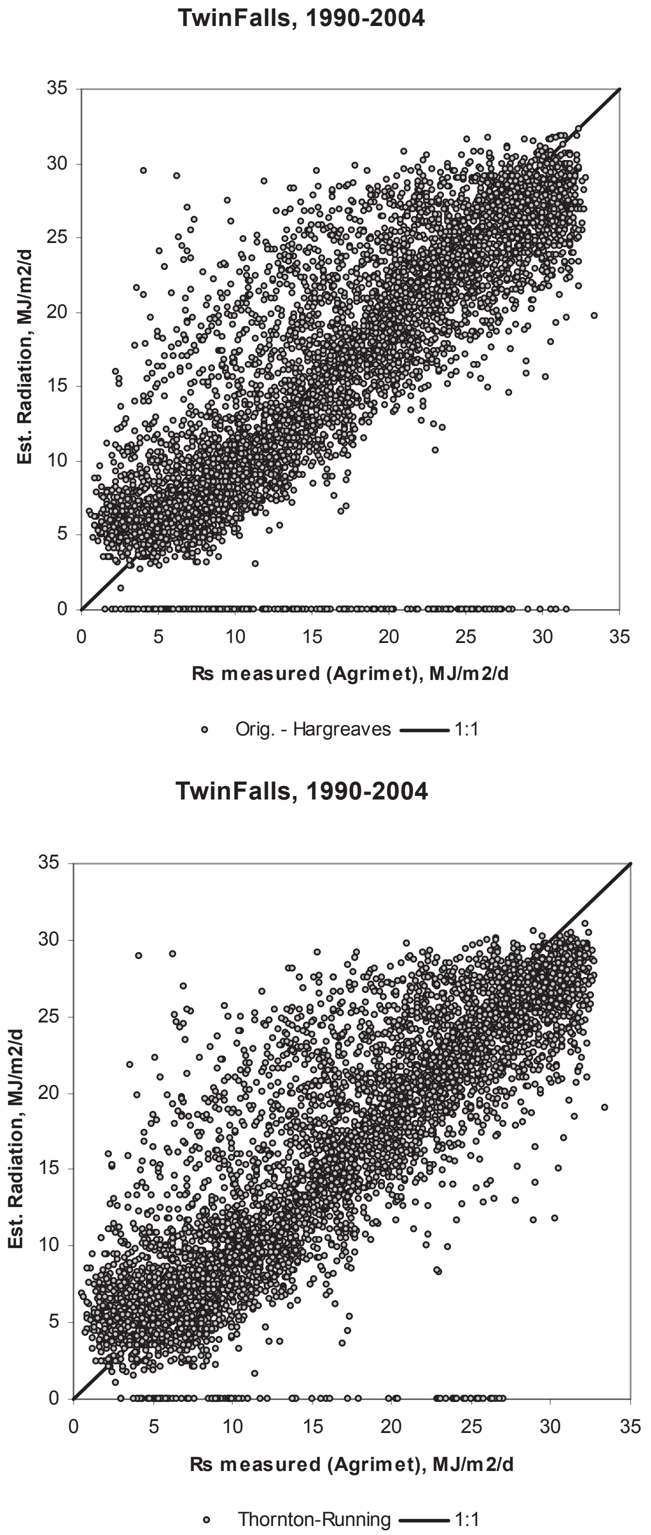
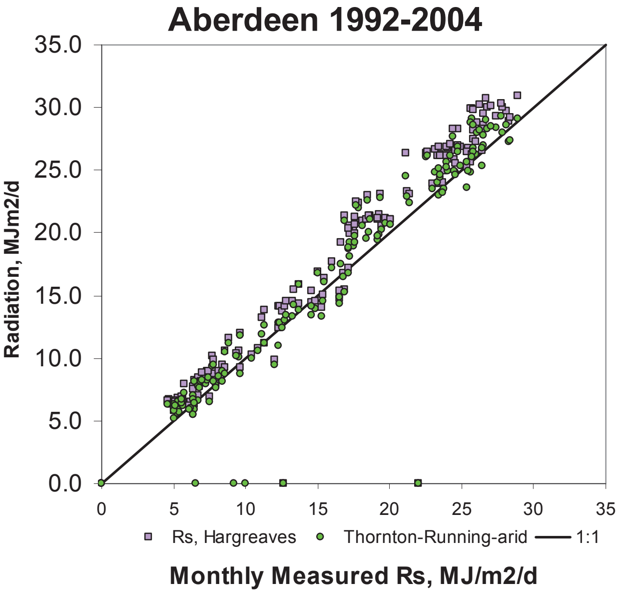


Figure 2.5. Daily estimated R_S (using the Hagreaves-Samani method (top) and the Thornton-Running (with Eq. 2.4 for B) (bottom)) vs. measured R_S from a nearby AgriMet station at Twin Falls, ID over the period of record (bottom).



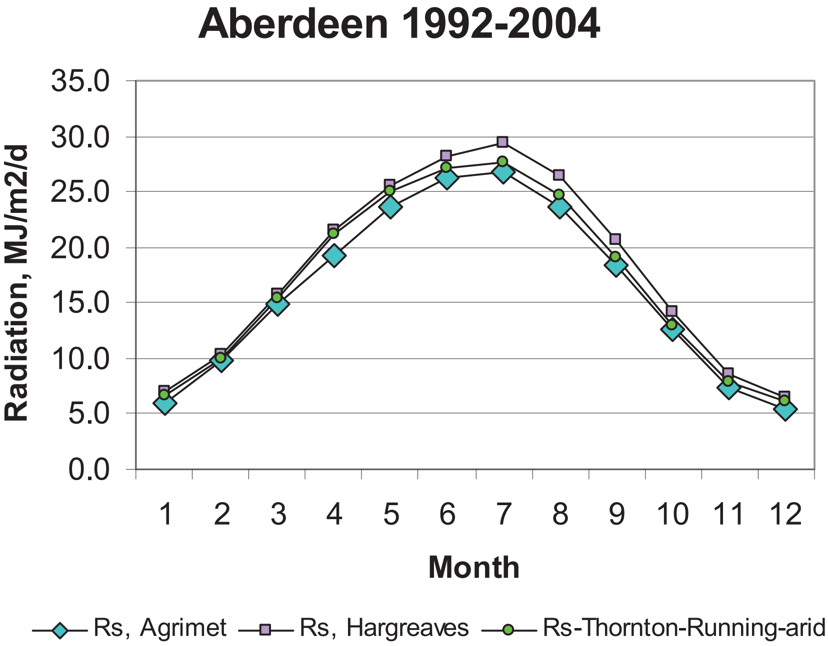


Figure 2.6. Monthly estimated R_S (using the Thornton-Running (with Eq. 2.4 for B) and using the Hagreaves-Samani methods) vs. measured R_S from a nearby AgriMet station at Aberdeen, ID for averages over each month over the common period of record (top) and long-term averages for individual months over the period of record (bottom).

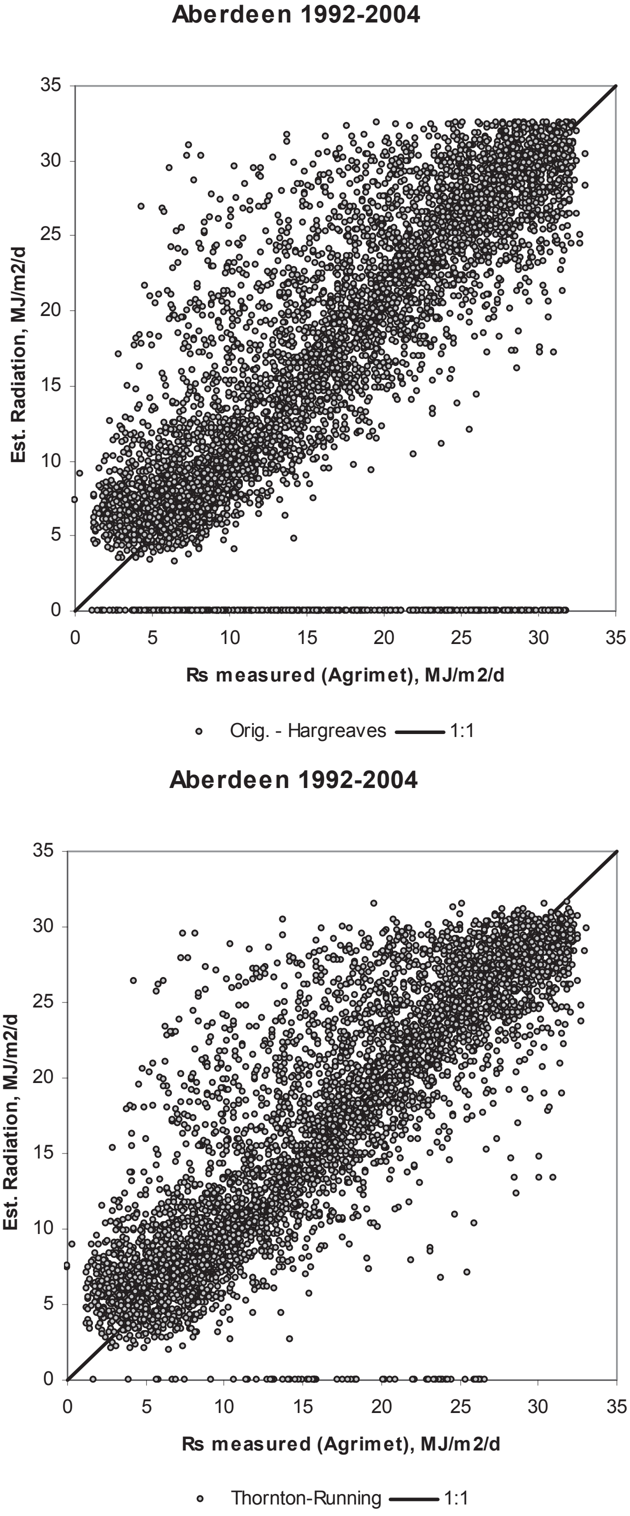


Figure 2.7. Daily estimated R_S (using the Hagreaves-Samani method (top) and the Thornton-Running (with Eq. 2.4 for B) (bottom)) vs. measured R_S from a nearby AgriMet station at Aberdeen, ID over the period of record (bottom).

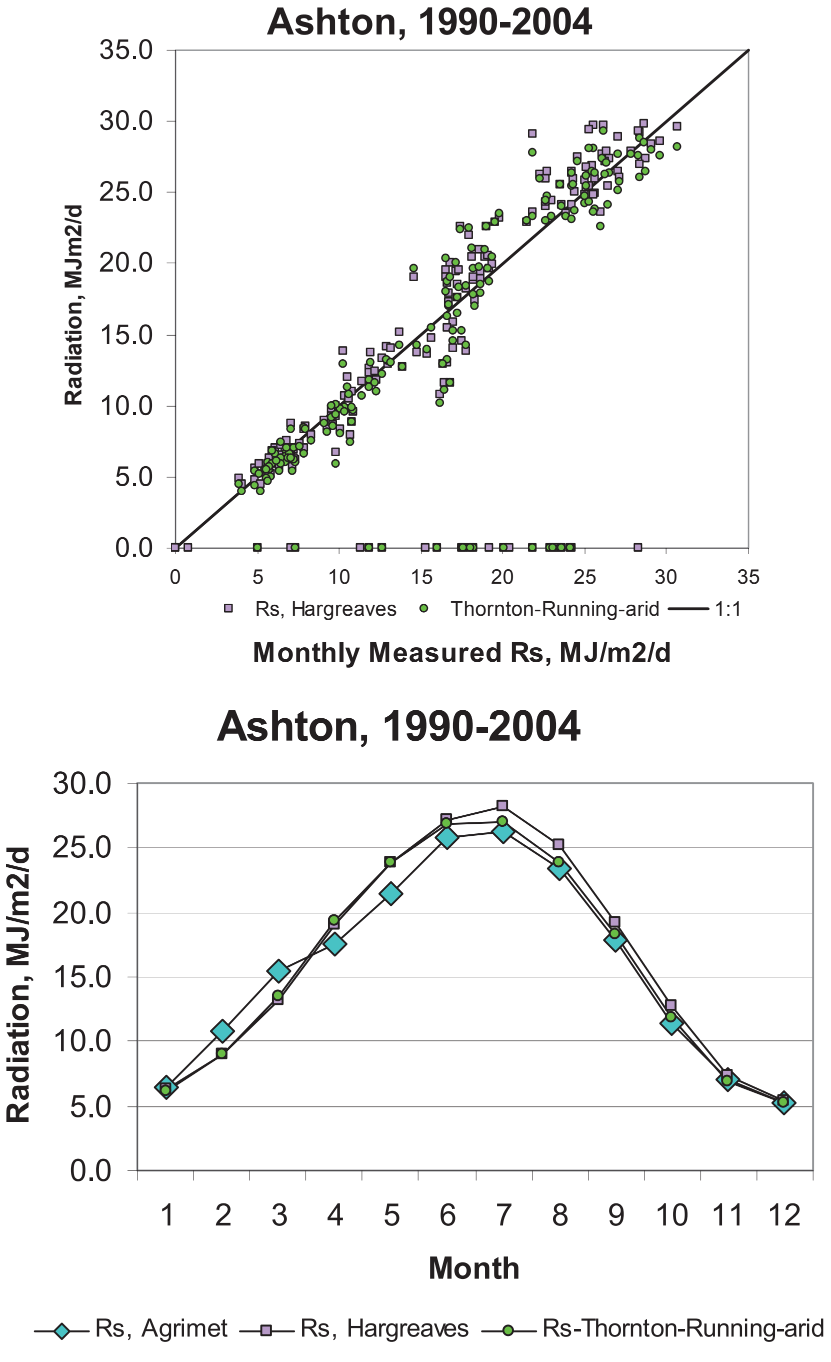


Figure 2.8. Monthly estimated R_S (using the Thornton-Running (with Eq. 2.4 for B) and using the Hagreaves-Samani methods) vs. measured R_S from a nearby AgriMet station at Ashton, ID for averages over each month over the common period of record (top) and long-term averages for individual months over the period of record (bottom).

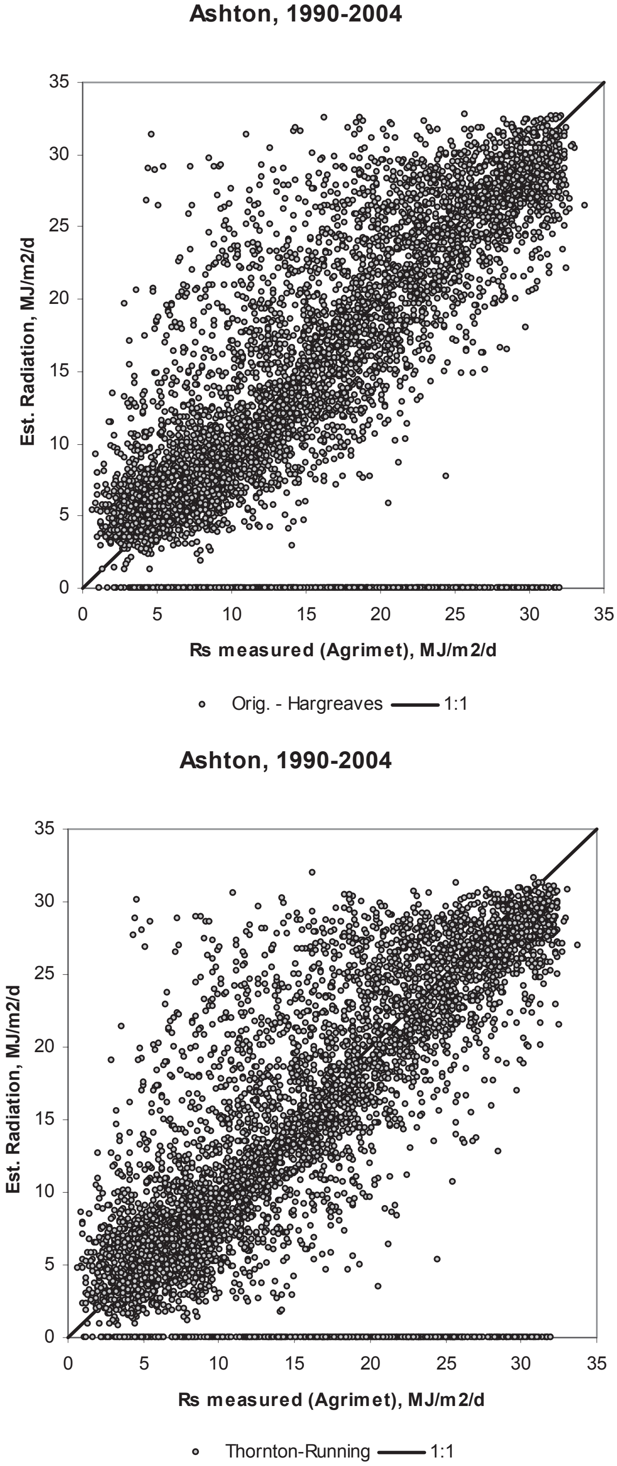
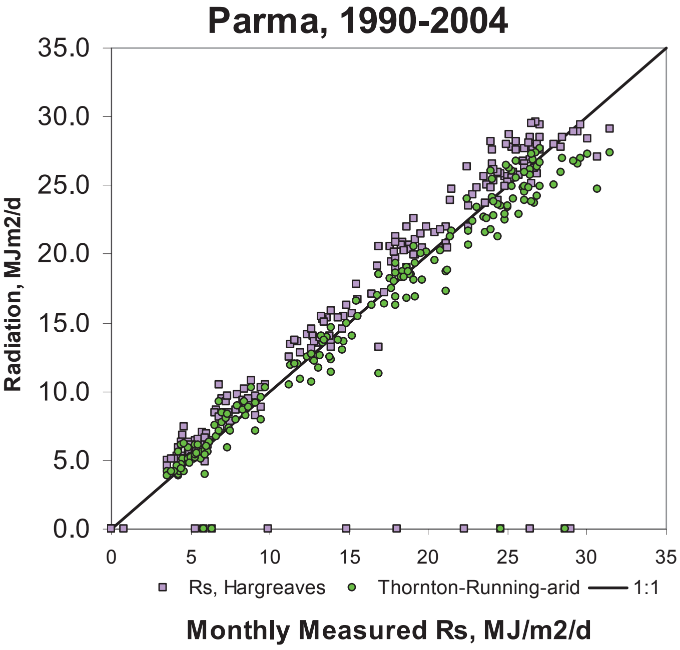


Figure 2.9. Daily estimated R_S (using the Hagreaves-Samani method (top) and the Thornton-Running (with Eq. 2.4 for B) (bottom)) vs. measured R_S from a nearby AgriMet station at Ashton, ID over the period of record (bottom).



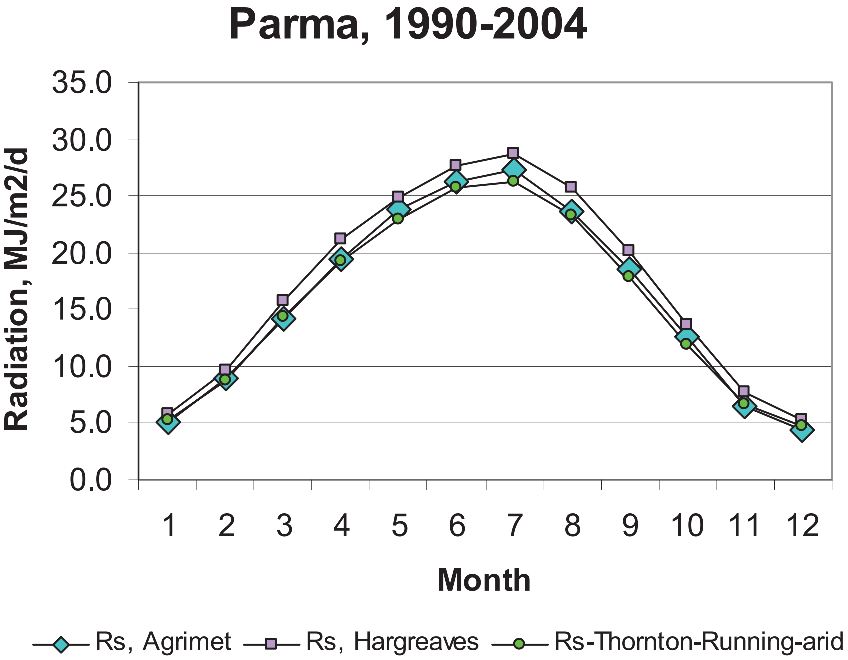


Figure 2.10. Monthly estimated R_S (using the Thornton-Running (with Eq. 2.4 for B) and using the Hagreaves-Samani methods) vs. measured R_S from a nearby AgriMet station at Parma, ID for averages over each month over the common period of record (top) and long-term averages for individual months over the period of record (bottom).

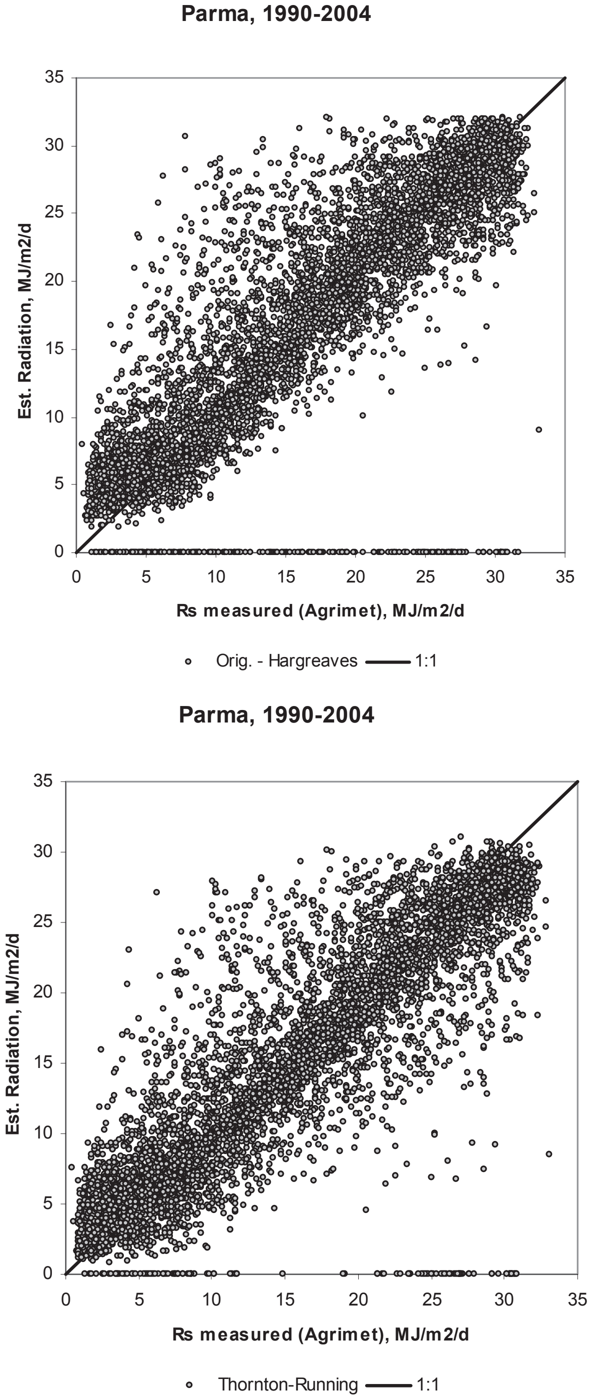
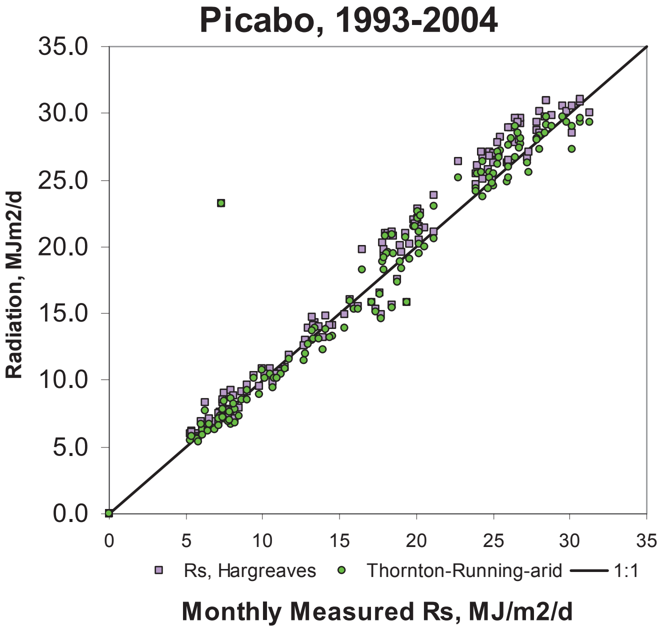


Figure 2.11. Daily estimated R_S (using the Hagreaves-Samani method (top) and the Thornton-Running (with Eq. 2.4 for B) (bottom)) vs. measured R_S from a nearby AgriMet station at Parma, ID over the period of record (bottom).



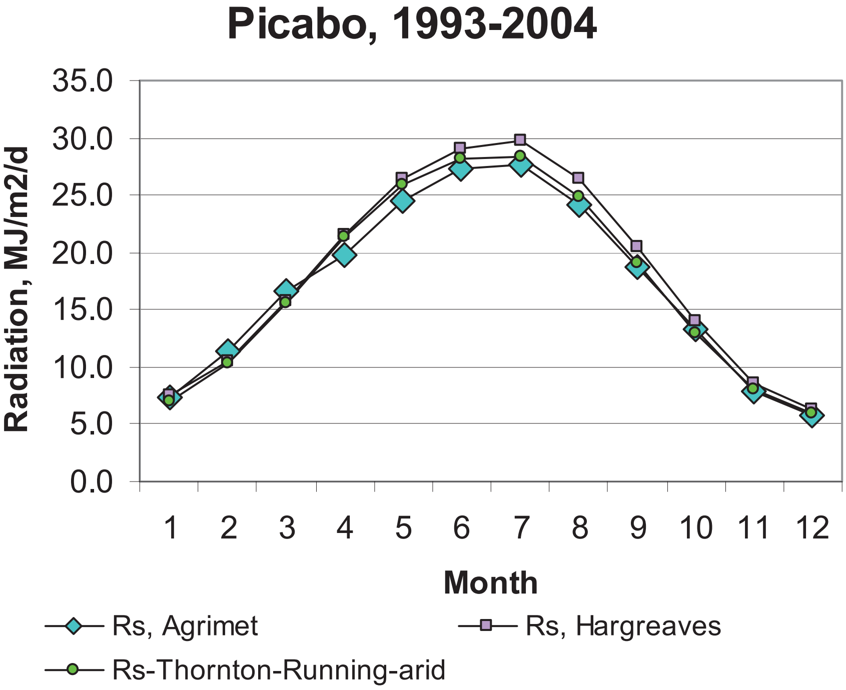
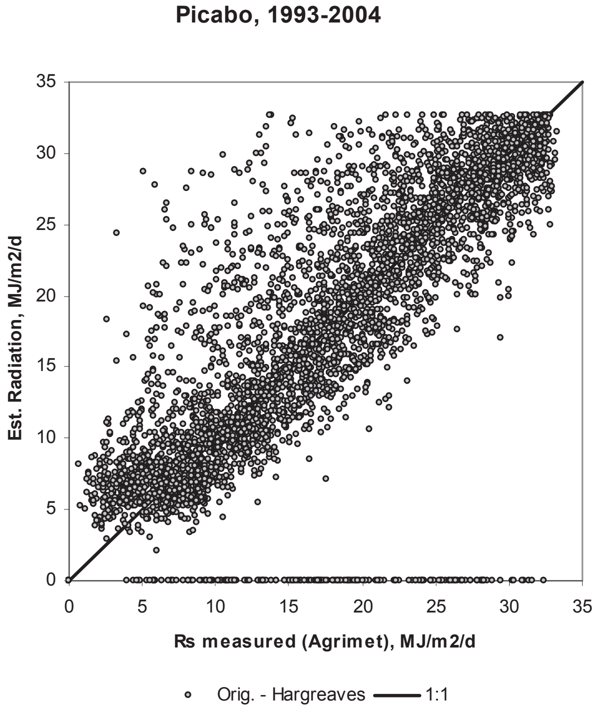


Figure 2.12. Monthly estimated R_S (using the Thornton-Running (with Eq. 2.4 for B) and using the Hagreaves-Samani methods) vs. measured R_S from a nearby AgriMet station at Picabo, ID for averages over each month over the common period of record (top) and long-term averages for individual months over the period of record (bottom).



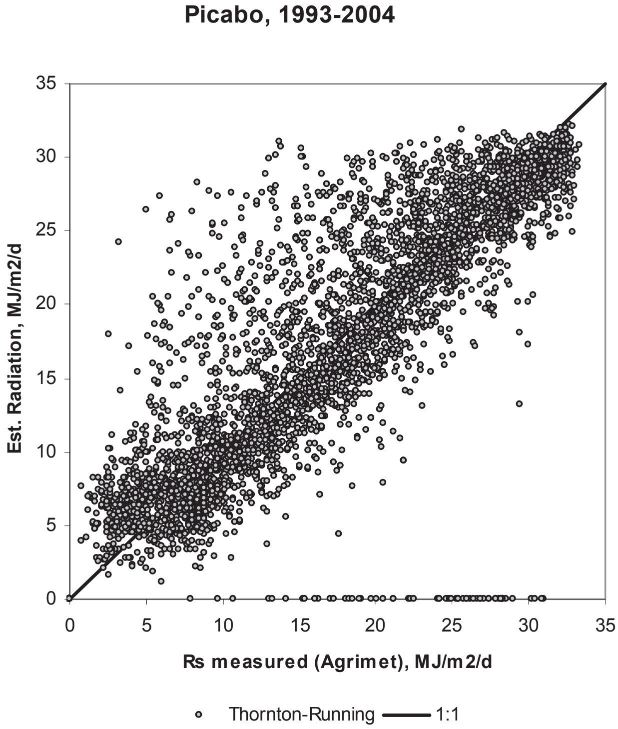


Figure 2.13. Daily estimated R_S (using the Hagreaves-Samani method (top) and the Thornton-Running (with Eq. 2.4 for B) (bottom)) vs. measured R_S from a nearby AgriMet station at Picabo, ID over the period of record (bottom).

Dewpoint temperature

Dewpoint temperature, T_{dew}, can be used to represent the humidity content of the lower air layer. The dewpoint is defined as the temperature at which air, when cooled, becomes saturated with water vapor, and condensation occurs, forming dew. The relative humidity, RH, is at 100% when the air temperature is at the dewpoint. Dewpoint temperature was estimated for the NWS stations by applying mean monthly offsets between daily minimum air temperature, T_{min}, and T_{dew} that were developed from analyses of AgriMet weather data sets. The T_{dew} measurement commonly approaches air temperature during nighttime as the earth's surface cools by radiative or evaporative cooling. This is especially the case in irrigated regions where water for nighttime evaporation is available from vegetation or a moist soil surface. Therefore, typically strong relationships exist between T_{min} and T_{dew}. Saturation of air during nighttime, as air cools, tends to prohibit cooling below T_{min}, and thus, T_{min} often lingers near or slightly above the T_{dew} temperature. The daily dewpoint temperature is often an average measurement across the day or is a measurement taken during early morning (for example, at the Twin Falls WSO station). In these cases, the daily T_{dew} value can sometimes exceed T_{min} by a few degrees, especially during the nongrowing season.

Exceptions to consistent relationships between T_{min} and T_{dew} can occur on days that feature a change in air mass (e.g., frontal passage), or that have high winds and/or cloudiness at night. Generally, it is common in arid and semiarid regions to have T_{dew} 2 to 5 °C lower than T_{min} under reference conditions and well below T_{min} if the measurement site is subjected to local aridity.

Figure 2.14 shows a plot of T_{dew} and T_{min} for 375 days near Kimberly during 1969-1971. The plot shows that T_{dew} is generally distributed near or a few degrees below the T_{min} . The relationship is relatively consistent during the year.

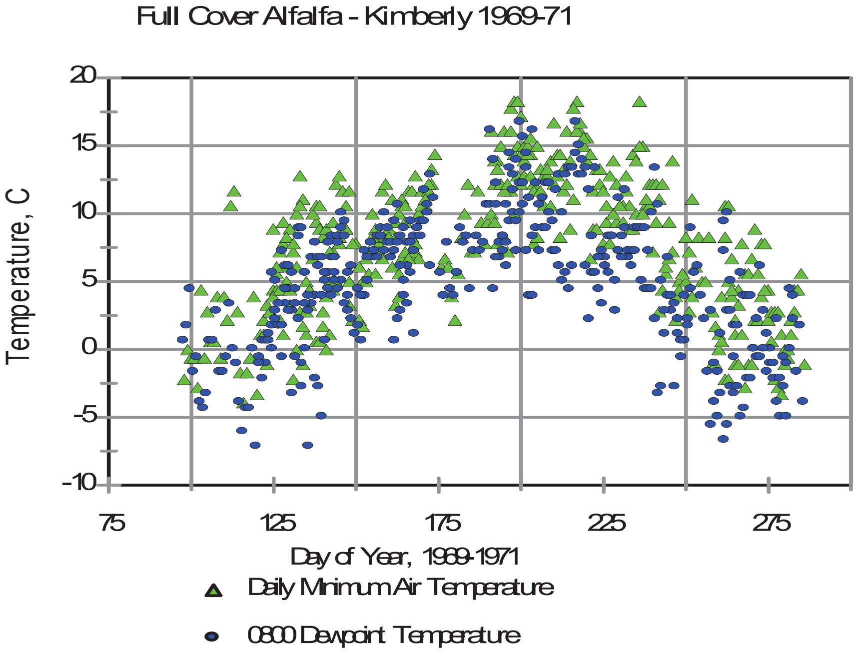


Figure 2.14. Measured daily minimm air temperature and dewpoint temperature measured at 0800 at the Twin Falls 7E weather station on days when the alfalfa lysimeter near Kimberly, Idaho durng 1969-1971 was at "full-cover."

ASCE-EWRI (2005) suggested estimating T_{dew} by subtracting an offset from T_{min}:

$$T_{dew} = T_{min} - K_o \tag{2.12}$$

where T_{min} is daily minimum air temperature (°C) and K_o is an offset that varies monthly as shown in the following Table 2.3:

Table 2.3. Mean monthly values for the K_o offset for use in Eq. 2.12 for estimating daily dewpoint temperature at National Weather Service weather stations in Idaho for their periods of record, °C.

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

The offsets in Table 2.3 were determined using long-term records of dewpoint and T_{min} collected at AgriMet weather stations listed in Table 2.1. Mean monthly values at individual AgriMet stations are shown in Figure 2.15, where T_{min} from the AgriMet station was used to calculate K_o (left) and where T_{min} from the associated NWS station was used to calculate K_o (right).

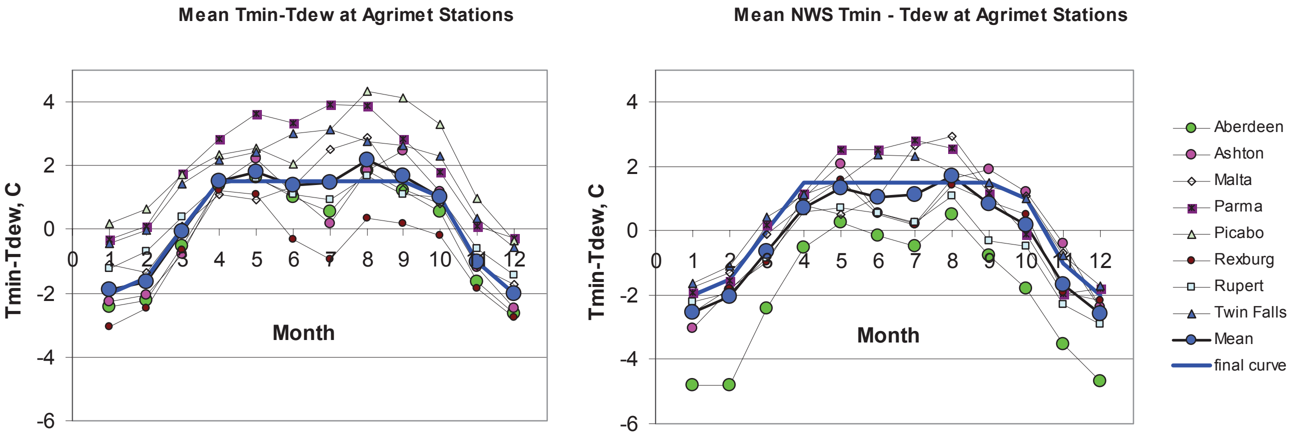


Figure 2.15. Mean monthly $K_o = T_{min} - T_{dew}$ offsets from AgriMet stations in southern Idaho during the AgriMet periods of record, using T_{min} from Agrimet (left) and using T_{min} from NWS (right).

Some station to station variation existed in K_o, however, differences from the mean curve presented in Table 2.3 were generally less than 2 °C. The winter to summer trend in K_o, where values tend to be negative during winter (i.e., mean daily T_{dew} tends to exceed T_{min}), is present for all AgriMet stations. The $T_{min} - T_{dew}$ calculated using T_{min} from the Aberdeen NWS station plotted several degrees lower than for the other stations (right figure) and even for its AgriMet counterpart (left figure). This departure was caused by T_{min} at the Aberdeen NWS station running about 2°C cooler than its AgriMet counterpart during nearly all months, even though the separation between the two stations is less than 100 m. No explanation for the bias is made, save the possibility of calibration bias in the NWS liquid minimum thermometer. The AgriMet sensors are checked annually. In general, T_{min} for the NWS stations ran an average 0.5-1 °C cooler than their AgriMet counterparts. The liquid NWS sensors were housed in wooden, ventilated shelters and the electronic AgriMet thermal sensors were housed in small plastic naturally-ventilated, plated radiation shields.

The 2° C range in mean K_o among AgriMet stations is similar to ranges to be expected among the 107 NWS stations throughtout Idaho for which ET has been estimated. Some of the variation in K_o among AgriMet stations may be caused by sensor error and effects of the relative amounts of green, transpiring vegetation in the near vicinity of the station. No trend in the K_o relationships with general location in Idaho nor with elevation was found. Therefore, the mean ("final") K_o curve shown in Figure 2.14 and Table 2.3 was adopted at all NWS locations.

A sensitivity analysis of the impact of K_o on the ET_r estimate was made for the Twin Falls (Kimberly Research Center) AgriMet location over the 1990-2005 period of record. Results are shown in Table 2.4. In general, the impact of lowering the K_o offset by 2°C would be to increase the ET_r estimate by 0.3 to 0.4 mm day^{-1} over all months. This is equivalent to an increase in ET_r by about 125 mm (5 inches) per calendar year or by about 80 mm (three inches) during April-October. These potential biases are considered to be smaller than those that would occur over the 107 NWS stations had a general, empirical reference ET equation, such as the Blaney-Criddle or Hargreaves (1985) method had been applied.

Table 2.4. Sensitivity of the alfalfa reference ET_r estimates to an increase in the value for K_o (i.e., lowering of the T_{dew} estimate) by 2°C over all months at the Twin Falls AgriMet station, averaged over the 1990-2005 period.

Month	1	2	3	4	5	6	7	8	9	10	11	12
ET_r difference, mm/day	0.30	0.32	0.36	0.40	0.41	0.40	0.35	0.32	0.33	0.34	0.31	0.29
ET_r ratio	1.19	1.15	1.10	1.09	1.07	1.06	1.04	1.05	1.06	1.09	1.14	1.20

Wind Speed

Wind speed was estimated for each NWS station by substituting a mean monthly value for wind speed derived for a nearby AgriMet station in southern Idaho or from a regional airport station or other data set in northern and central Idaho. The regions of the state assigned to each mean monthly weather data set is shown in Figure 5 of the main report.

$$U = U_{mean\ monthly_i} \tag{2.13}$$

where U is estimated daily wind speed and $U_{\text{mean monthly i}}$ is mean monthly wind speed for the region for the month. The following Table 2.5 lists the monthly wind speed values that were assigned to the NWS stations.

Table 2.5. Long-term monthly wind speed values from Agrimet and other stations that were assigned to the NWS stations.

Wind Sta. No.	**Agrimet and NOAA Station name**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
1	Aberdeen	3.05	2.93	3.01	3.25	2.92	2.60	2.13	1.98	2.11	2.74	2.71	2.77
2	Ashton	2.28	2.99	2.86	3.49	3.56	3.07	2.28	2.32	2.42	2.80	2.66	2.41
3	Fairfield	2.55	2.57	2.51	3.13	2.95	2.48	2.05	1.93	2.02	2.39	2.28	2.25
4	Glenns Ferry	2.93	3.23	3.19	3.39	3.01	2.84	2.72	2.54	2.54	2.82	2.72	3.01
5	Grand View	1.86	2.36	2.54	2.67	2.37	2.31	2.10	1.76	1.71	1.88	1.85	1.95
6	Malta	3.17	3.03	2.99	3.30	2.54	2.34	2.08	1.85	2.01	2.70	2.90	2.95
7	Monteview	1.39	1.55	2.04	2.38	2.23	1.98	1.77	1.60	1.59	1.94	1.72	1.68
8	Nampa	2.74	3.44	3.47	3.56	3.24	2.86	2.37	2.21	2.41	2.75	2.68	2.80
9	Parma	1.51	1.80	2.23	2.30	2.15	1.71	1.43	1.36	1.39	1.51	1.57	1.57
10	Picabo	1.33	1.52	1.61	1.96	2.01	1.80	1.54	1.56	1.52	1.58	1.33	1.14
11	Rexburg	2.27	2.22	2.94	3.36	3.02	2.45	1.87	2.02	2.14	2.44	2.16	2.18
12	Rupert	4.50	3.43	3.58	3.89	3.48	2.86	2.21	2.13	2.32	2.98	3.12	3.35
13	Twin Falls	3.07	3.03	2.92	3.26	2.84	2.60	2.23	2.12	2.32	2.72	2.76	2.88
14	Afton, WY	1.16	1.22	1.41	1.81	1.85	1.72	1.56	1.46	1.40	1.39	1.20	1.09
15	Logan, UT-USU Drn. Farm	0.97	1.10	1.43	1.98	1.89	1.83	1.73	1.83	1.69	1.52	1.20	0.99
16	Challis Airport	1.04	1.26	1.71	1.97	2.04	1.97	1.82	1.78	1.52	1.48	1.19	1.15
17	Coeur d'alene Airport	2.73	2.80	2.59	2.59	2.56	2.39	2.22	2.36	2.29	2.22	2.42	2.56
18	Elk City (KP69)	0.51	0.59	0.51	0.55	0.59	0.55	0.59	0.55	0.51	0.40	0.44	0.48
19	Lewiston-Nez Perce Cnty Aairport (KLWS)	2.01	1.95	2.05	2.05	1.91	1.95	1.95	1.91	1.67	1.60	1.88	2.15
20	McCall Airport (KMYL)	1.20	1.45	1.38	1.70	2.07	1.85	1.60	1.52	1.52	1.45	1.09	0.94
21	Mullan Pall VOR	1.81	2.42	2.53	2.49	2.42	2.63	2.32	2.36	2.49	2.63	2.66	1.78
22	Salmon-Lemhi Cnty AP	0.67	0.94	1.53	1.80	1.72	1.61	1.50	1.46	1.16	1.09	0.97	0.82
23	Stanley Ranger Sta.	1.05	1.53	1.31	1.31	1.50	1.50	1.53	1.46	1.16	1.05	1.05	0.82

Comparisons of ET_r calculated using estimated solar radiation, humidity and wind speed vs. using measured data for Kimberly during 1969-1971

A question that arises when an empirical ET_r equation is applied or when some weather parameters are estimated is whether the variance of the population of ET_r or ET_c estimates is reduced to less than that of the true underlying population (Allen and Brockway 1983, Allen and Pruitt 1986). To address this question, the following analysis was conducted early in this study to evaluate the relative impact of estimating solar radiation, dewpoint and wind speed on ET_r and the relative effect on population variance. The analysis was made using precision lysimeter data collected by Dr. James L. Wright of the USDA-ARS research center near Kimberly, Idaho. The lysimeter data set was comprised of daily measurements of ET from alfalfa for days when the crop was considered to be at 'full cover'. The full cover days were selected by Wright as days when the height of the alfalfa crop was 0.3 m or greater. The lysimeter data were collected by Wright during 1969-1971 when the alfalfa variety was 'Ranger.' The measured ET from the lysimeter over the three year period is shown in Figure 2.16. The variance of the lysimeter measurements is likely a good representation of the true population variance of daily ET. A total of 375 days of data were evaluated.

The following series of figures indicate the ability of the estimates for R_s, T_{dew} and wind speed to estimate ET_r. Because this study was done early in this project, the Hargreaves equation (Eq. 2.1) was applied rather than the Thornton-Running equation (Eq. 2.2 plus 2.4) and a fixed $K_o = T_{min} - T_{dew} = 2^oC$ was applied, rather than the K_o values in Table 2.3 that vary monthly. However, impacts in the use of Eq. 2.1 rather than 2.2 + 2.4 and in using $K_o = 2^oC$ rather than Table 2.3 are small, due to the similarity in estimation by the two R_s equations and the similarity between K_o in Table 2.3 and 2^oC during the April-October periods when lysimeter data were collected.

Figure 2.16 shows measured and estimated R_s plotted vs. time of year. The solid lines in the figures are theoretical curves of R_{so} that describe the expected R_s on cloud-free days. The estimation of R_s is relatively good and exhibits similar variation within the population. Figure 2.17 shows a plot of estimated R_s vs. measured R_s from the same data set where R_s was estimated using Eq. 2.1. The RMSE over the period of record averaged 4.2 MJ m^{-2} d^{-1} for the daily values which is similar to the RMSE = 4.13 and 4.17 MJ m^{-2} d^{-1} calculated for Eq. 2.2 + 2.4 applied to the AgriMet data set as summarized in Table 2.1.

Figure 2.18 shows a plot of T_{dew} estimated as $T_{min} - 2^oC$ vs. measured T_{dew} within the Kimberly lysimeter data set. Some scatter in the plots exists. However, the root mean square error (RMSE) was 2.9 ^oC, which is considered to represent relatively good estimation. About 70% percent of all estimates were within the RMSE of the true observation if the distribution of errors is considered to be normally distributed.

Figure 2.19 compares alfalfa reference ET_r calculated by the ASCE-EWRI standardized Penman-Monteith method to the lysimeter measurements at Kimberly where the ET_r calculations were applied to the original full weather data set. The distribution of daily values for ET_r are similar between measured and calculated ET_r, although the calculated values show a tendancy to bunch more than measured values in middle ranges.

Figures 2.20 through 2.25 are a series of comparisons of estimated alfalfa reference ET_r to the lysimeter measurements at Kimberly for the ASCE-PM with full weather data set and for applications of the ASCE-PM with estimated weather parameters. Also shown are comparisons with estimates by the 1982 Kimberly Penman equation (Wright, 1982) and by the 1985 Hargreaves equation (Hargreaves et al, 1985) multiplied by 1.35 to convert this equation from a grass to alfalfa reference. The last figures show comparisons for 5-day averages. Variation between estimated and measured ET were substantially reduced when averaged over the 5-day periods. Typical irrigation intervals are five days or longer in lengths, so that the estimation error for the 5-day periods is of more relevance when evaluating accuracy for irrigation system design and operation. The Hargreaves method is included to show the relative estimation accuracy of this empirical ET equation that does not require estimation of R_s, T_{dew} or wind speed, but operates soley on daily maximum and minimum air temperature. The 1982 Kimberly Penman calculations are included to provide an idea of the performance of this equation that has been used extensively in the past in the Pacific Northwest. Statistics summarizing the application of the various methods are given in Table 2.6.

Table 2.6 Statistics describing the population of measured and estimated ET from full-cover alfalfa on the Kimberly lysimeter system during 1969-1971.

ET_r Observation or Equation	Mean mm/day	Ratio to Observed	Std. Dev. mm/day	Coef. Variation	Skew	RMSE, mm/day
Lysimeter Measurement	6.36	1.000	1.99	0.31	-0.22	--
ASCE Penman-Monteith	6.41	1.009	1.77	0.28	-0.27	0.97
1982 Kimberly Penman	6.31	0.993	1.69	0.27	-0.24	0.80
1985 Hargreaves x 1.35	6.29	0.990	1.98	0.32	-0.22	1.51
ASCE PM w/ est. R_s	6.43	1.016	1.77	0.28	-0.23	1.16
ASCE PM w/ est T_{dew}	6.30	0.988	1.56	0.25	-0.31	1.07
ASCE PM w/ monthly wind	6.59	1.036	1.80	0.27	-0.52	1.34
ASCE PM w/ est R_s, T_{dew}, monthly wind speed	6.52	1.025	1.76	0.27	-0.33	1.67
5-day Lysimeter Measurement	6.38	1.000	1.58	0.25	-0.47	--
5-day ASCE Penman-Monteith	6.45	1.012	1.38	0.21	-0.36	0.65
5-day Hargreaves x 1.35	6.32	0.990	1.71	0.27	-0.26	0.80
5-day ASCE PM w/ est. R_s, T_{dew}, monthly wind speed	6.53	1.024	1.28	0.20	-0.41	0.90

The figures and statistical summary show that the application of the ASCE Penman-Monteith equation estimated, on average, within 1% of the lysimeter over the 3 year period and the coefficient of variation was within 10% of that for the lysimeter measurements. The closeness of the two coefficients of variation (defined as the standard deviation of estimates or measurements divided by the mean) indicates similar population variance. This implies that estimates of ET_r or ET_c representing the highest 20% of the population or lowest 20% will have values similar to those in the underlying population. The values for skew are similar also, indicating similar shape of the measurement and estimation distributions. These results indicate that the ASCE standardized PM method provides a good representation of daily ET for full cover (i.e., reference) alfalfa as measured by the Kimberly lysimeter system.

Estimation ratios to the measurements remained near 1.00 when R_s, T_{dew}, U or a combination of the three parameters were estimated and coefficients of variation remained close to that for the lysimeter measurements. RMSE values increased from about 1.0 mm d^{-1} for the ASCE-PM with full data to 1.67 mm d^{-1} when R_s, T_{dew} and wind speed were estimated. This represented a 60% increase in the estimation error for individual days. Monthly wind speed was summarized from the same three-year period. When estimates were averaged over five day periods to simulate typical irrigation intervals, RMSE dropped significantly for the ASCE-PM, with estimated R_s, T_{dew} and wind, to 0.90 mm/day. The coefficient of variation in this case was 20% less than that for the lysimeter for the 5-day average observations, however, the skew was similar between estimates and measurements.

The 1982 Kimberly Penman had somewhat better estimation accuracy than the ASCE-PM, having an RMSE of 0.80 mm d^{-1} as opposed to 0.97 mm/day for the ASCE-PM. The coefficient of variation for the Kimberly Penman was 3% further from that of the lysimeter estimates than the ASCE-PM. Additional comparisons between the 1982 Kimberly Penman and ASCE-PM are given in Appendix 9. The 1985 Hargreaves equation, multiplied by 1.35 to convert from a grass reference to ET_r, had an RMSE that was 10% smaller than that for the ASCE-PM method applied using estimated weather parameters. This is impressive for a fully empirical method. The ASCE-PM method with estimated weather is still preferred for application across Idaho since it enables wind speed to be varied monthly for areas that have chronically high or low wind speeds. In addition, the application of ASCE-PM at NWS stations is congruent to the application of the same equation to AgriMet weather data sets where full sets of solar radiation, humidity and wind speed are available.

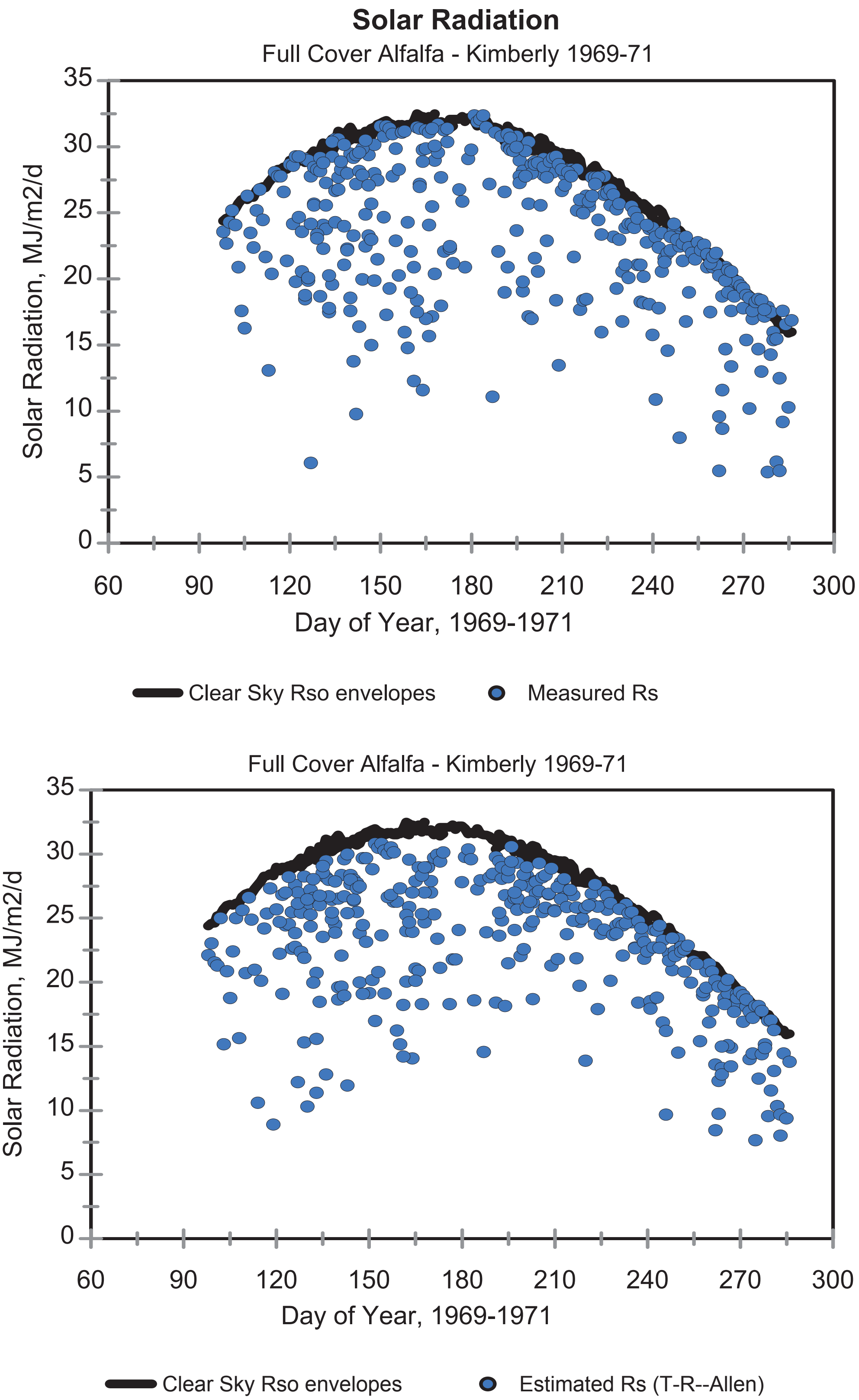


Figure 2.16a,b. Plots of measured R_S vs. time and estimated R_S vs. time using Eq. 2.2+Eq. 2.4 (Thornton-Running) for days at Kimberly, Idaho during 1969-1971 when the lysimeter system had full-cover alfalfa.

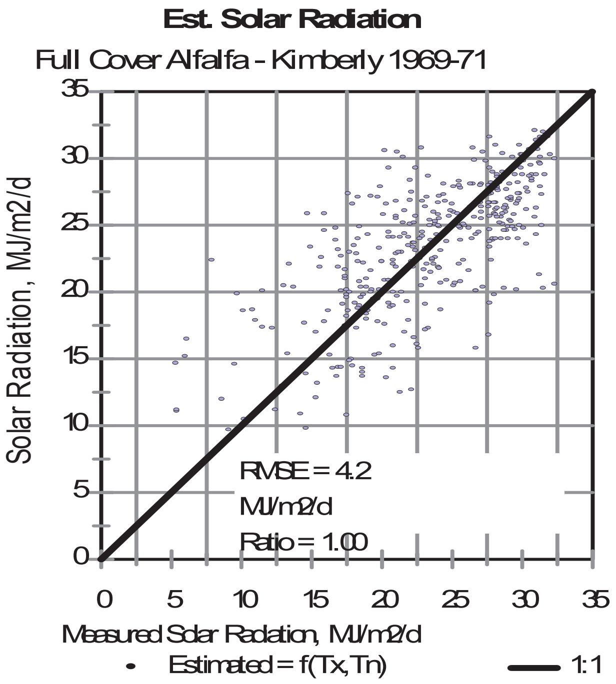


Figure 2.17 Plots of Estimated vs. Measured R_s at Kimberly, Idaho during 1969-1971 when the lysimeter system had full-cover alfalfa, where R_s was estimated using Eq. 2.1.

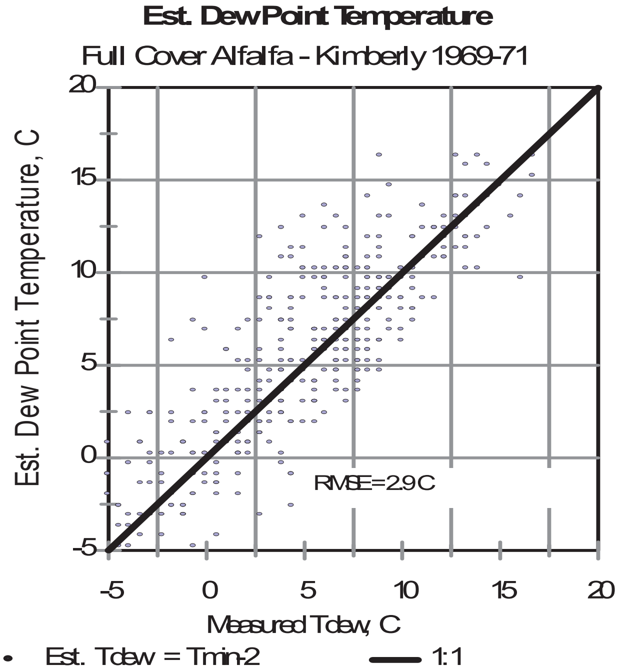


Figure 2.18 Plots of Estimated Dewpoint temperature (bottom) vs. Measured Dewpoint temperature where Estimated $T_{dew} = T_{min} - 2$ for days at Kimberly, Idaho during 1969-1971 when the lysimeter system had full-cover alfalfa (ratio for T_{dew} is 0.99).

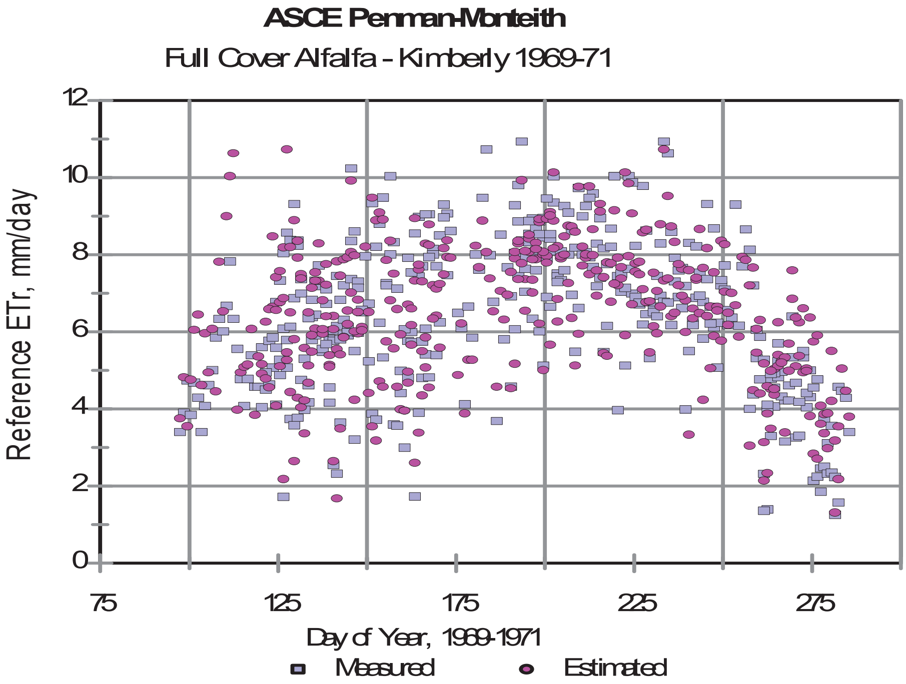
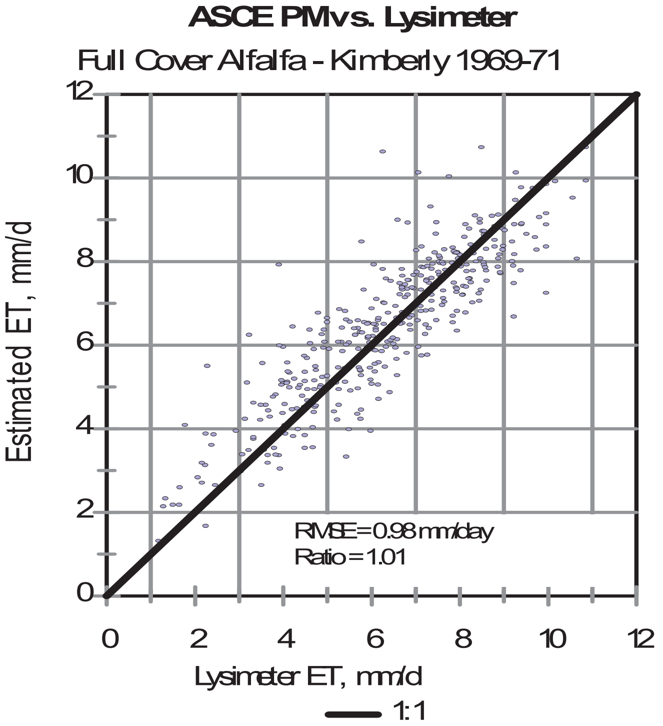


Figure 2.19 Measured ET from 'full-cover' alfalfa near Kimberly, Idaho during 1969 through 1971 vs. day of the year and alfalfa reference ET_r estimated by the ASCE standardized Penman-Monteith equation. Lysimeter data are from Dr. James L. Wright, USDA-ARS, Kimberly.



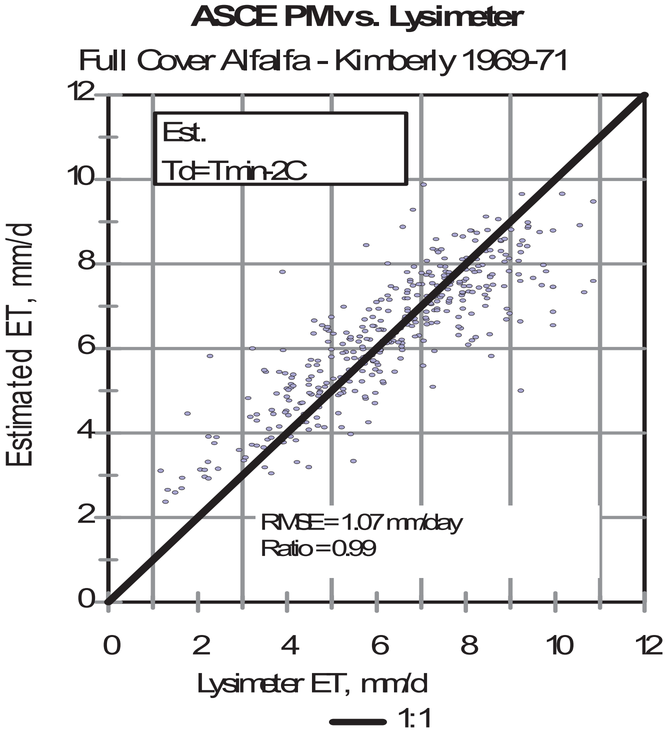


Figure 2.20 Plots of Reference ET_r by the ASCE-EWRI Penman-Monteith equation vs. ET measured by precision lysimeter for days at Kimberly, Idaho during 1969-1971 when the lysimeter system had full-cover alfalfa. The bottom plot shows estimated ET_r when dewpoint was estimated.

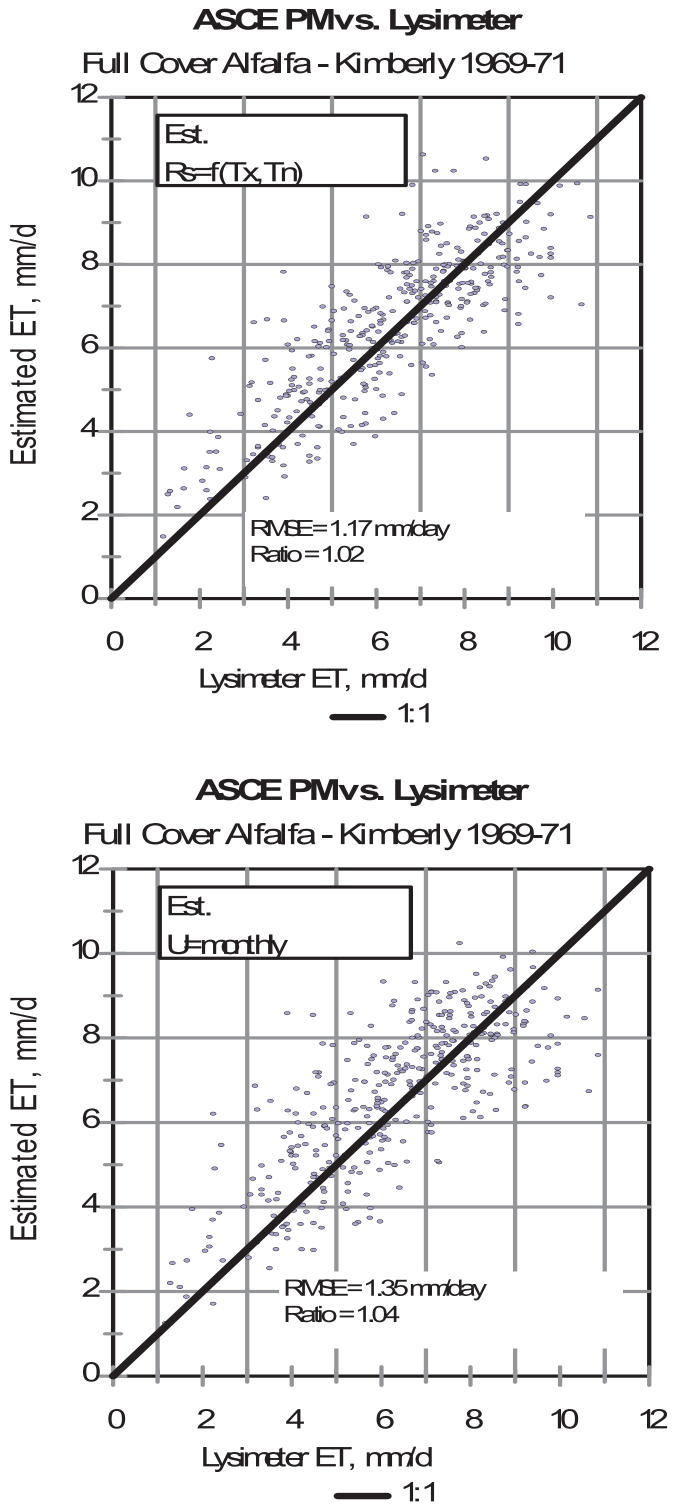
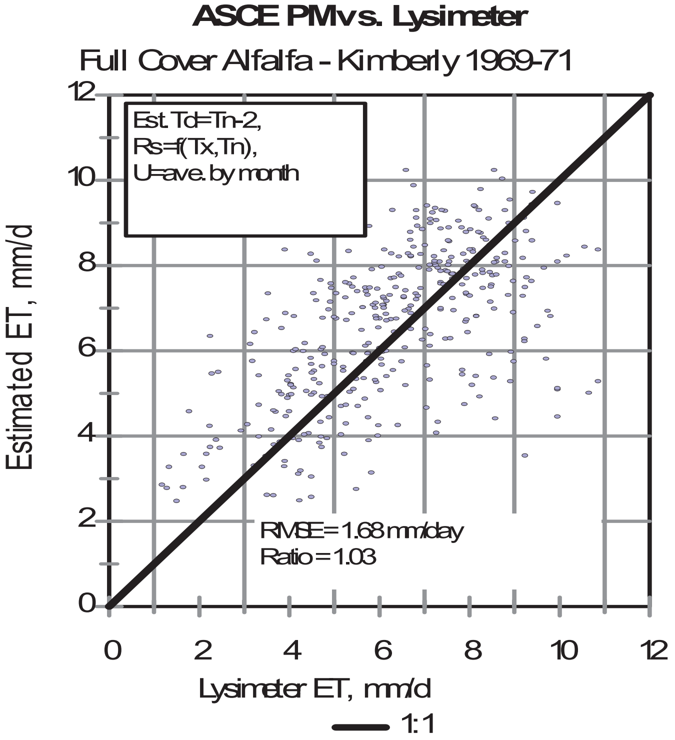


Figure 2.21 Plots of Reference ET_r by the ASCE-EWRI Penman-Monteith equation vs. ET measured by precision lysimeter for days at Kimberly, Idaho during 1969-1971 when the lysimeter system had full-cover alfalfa. The top plot shows estimated ET_r when solar radiation is estimated and the bottom plot shows estimated ET_r when monthly average wind speed is used.



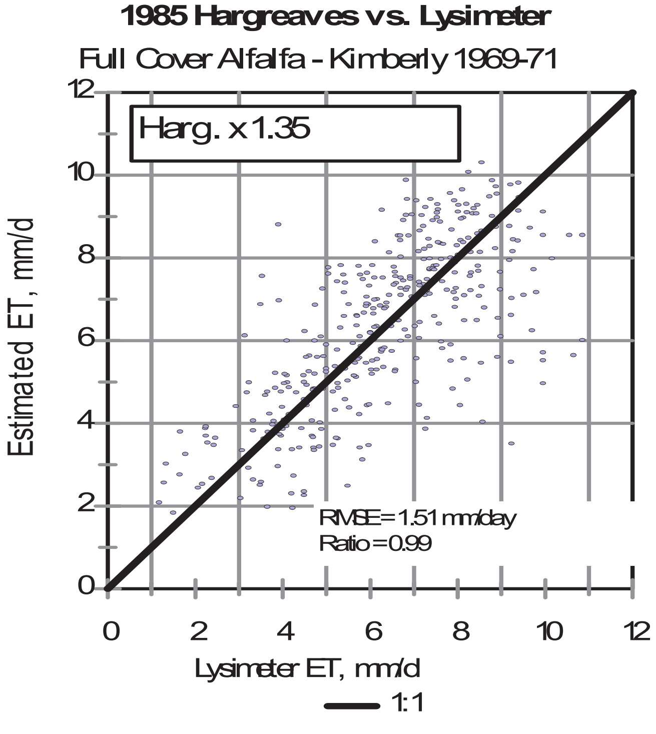


Figure 2.22 Plots of Reference ET_r by the ASCE-EWRI Penman-Monteith equation vs. ET measured by precision lysimeter for days at Kimberly, Idaho during 1969-1971 when the lysimeter system had full-cover alfalfa when dewpoint and solar radiation are estimated wind speed is average monthly (top) and reference ET estimated by the 1985 Hargreaves equation multiplied by 1.35 vs. measured ET.

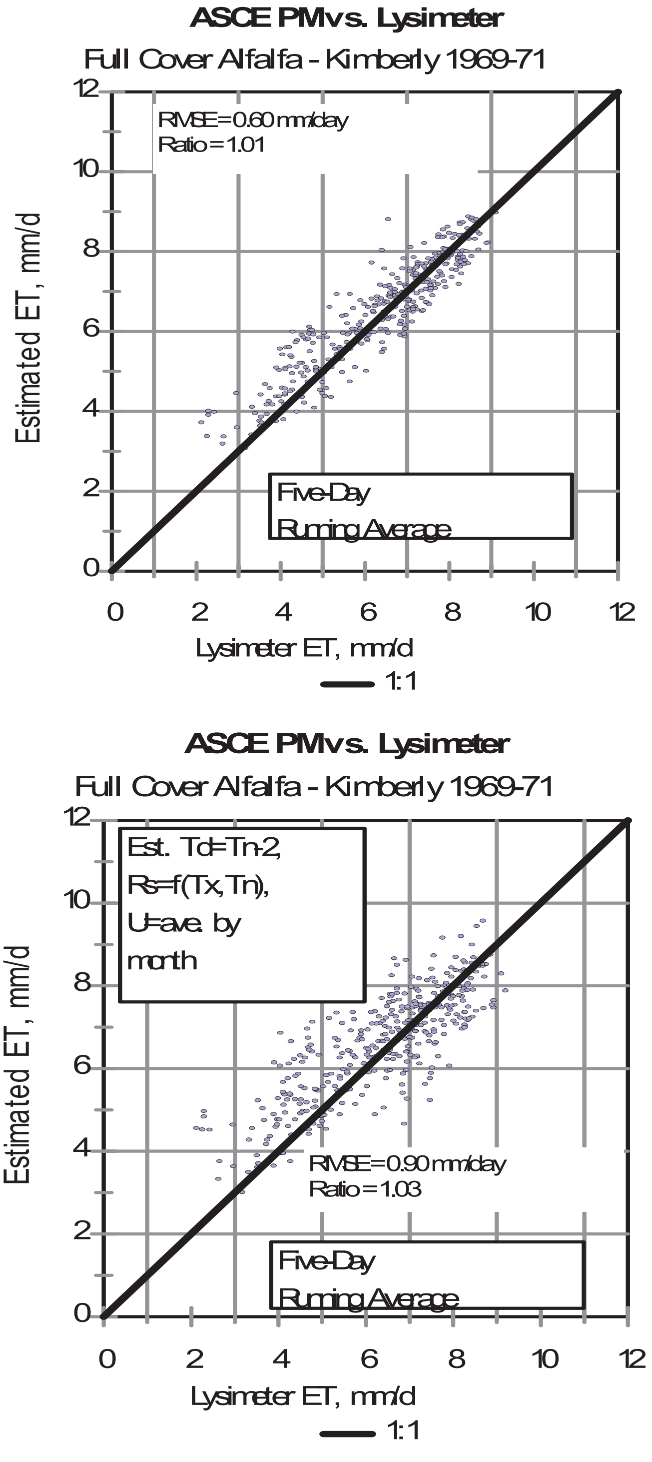
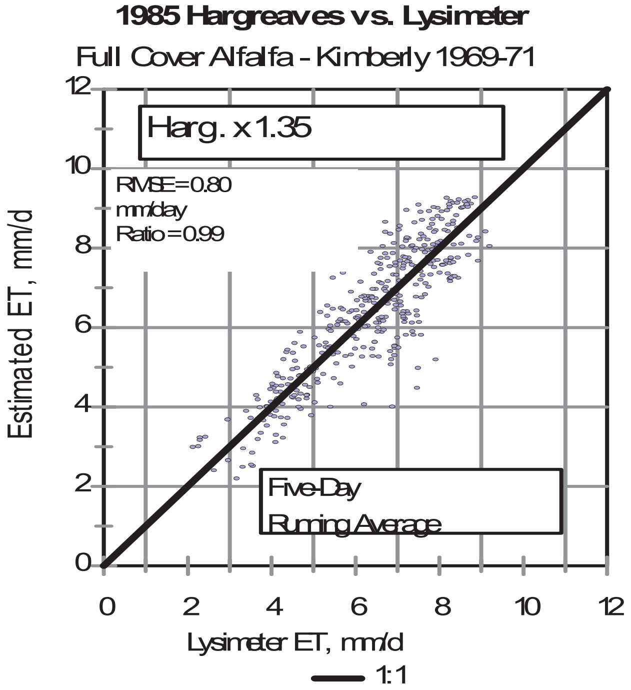


Figure 2.23 Plots of 5-day average Reference ET_r by the ASCE-EWRI Penman-Monteith equation vs. ET measured by precision lysimeter for days at Kimberly, Idaho during 1969-1971 when the lysimeter system had full-cover alfalfa. The bottom plots shows estimated 5-day ET_r when dewpoint and solar radiation are estimated wind speed is average monthly.



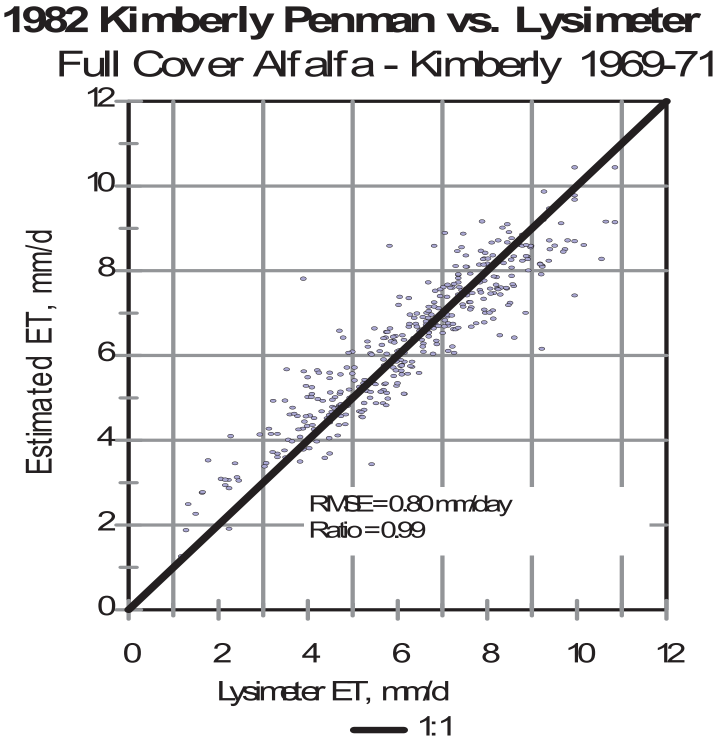


Figure 2.24 Plots of 5-day average Reference ET_r by the 1985 Hargreaves equation vs. ET measured by precision lysimeter for days at Kimberly, Idaho during 1969-1971 when the lysimeter system had full-cover alfalfa (top) and daily average Reference ET_r by the 1982 Kimberly-Penman equation (bottom).

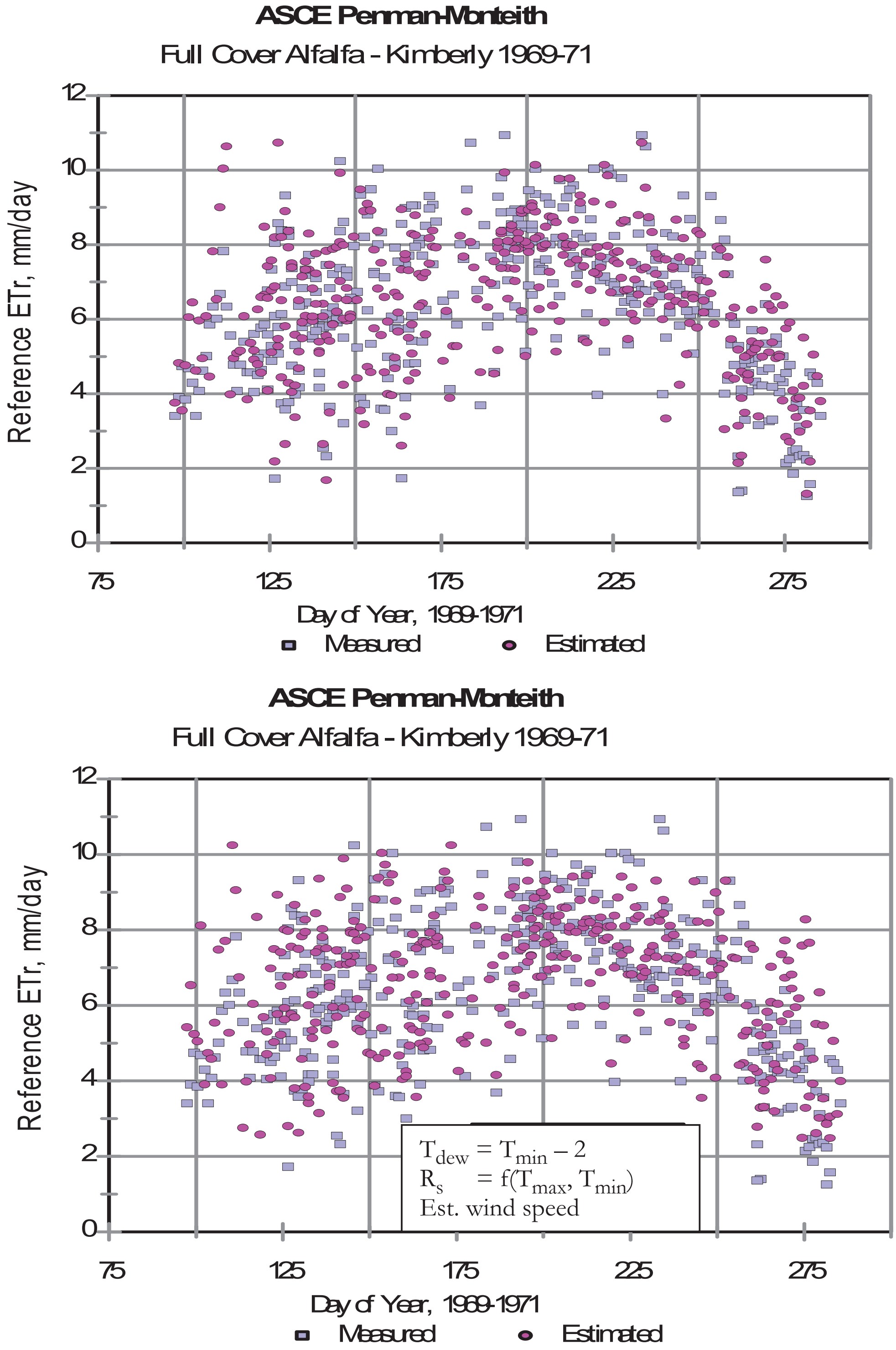


Figure 2.25 Plots of daily Reference ET$_r$ by the ASCE-PM equation with measured weather data vs. ET measured by precision lysimeter for days at Kimberly, Idaho during 1969-1971 when the lysimeter system had full-cover alfalfa (top) and estimates made using estimated dewpoint and solar radiation and mean monthly wind speed (bottom).

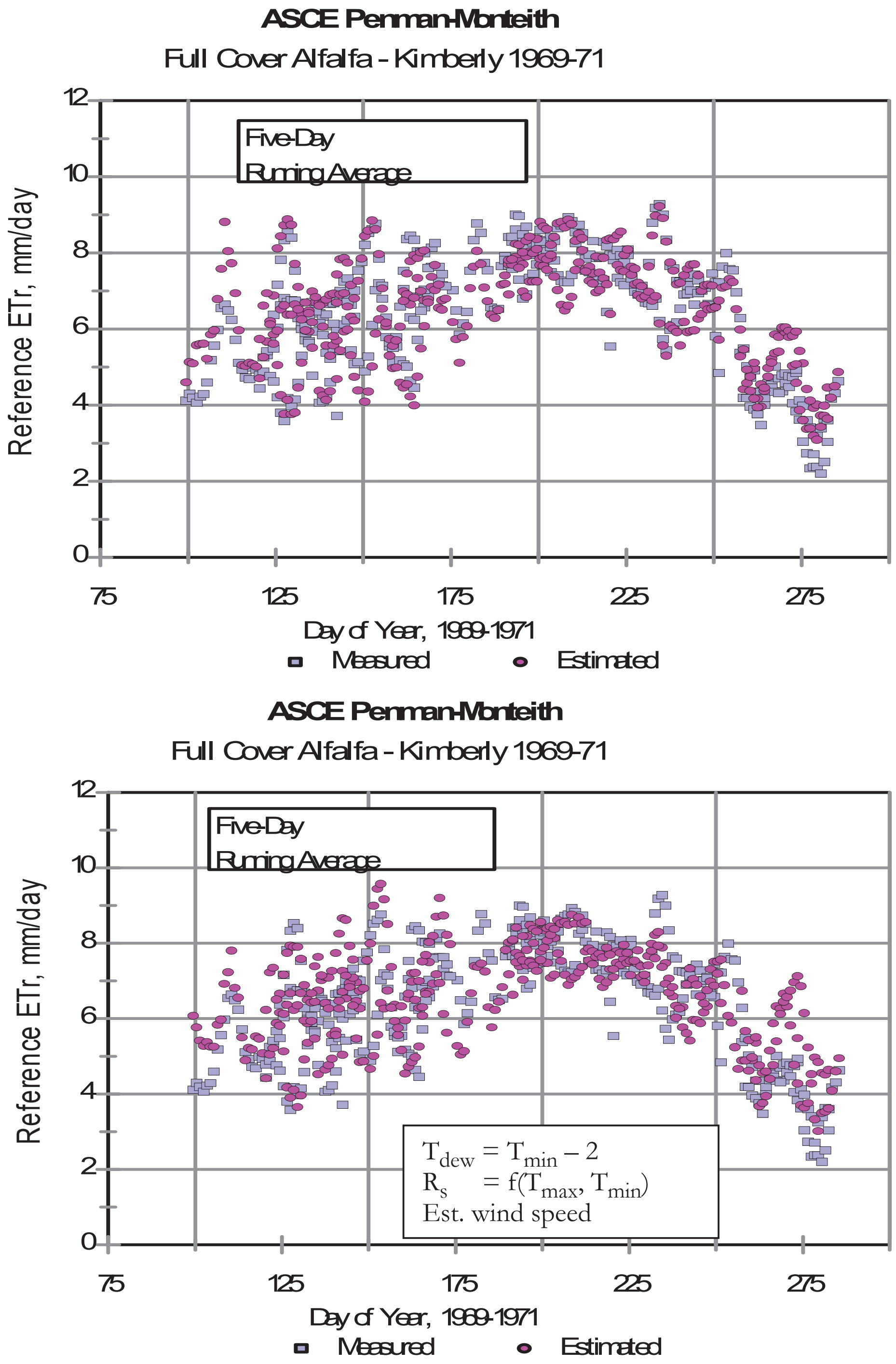


Figure 2.26 Plots of 5-day average Reference ET_r by the ASCE-PM equation with measured weather data vs. ET measured by precision lysimeter for days at Kimberly, Idaho during 1969-1971 when the lysimeter system had full-cover alfalfa (top) and estimates made using estimated dewpoint and solar radiation and mean monthly wind speed (bottom).

Comparisons between ET_r at neighboring NWS and AgriMet weather stations

Graphical comparisons of reference ET_r by the ASCE-PM equation applied with NWS data sets using estimated solar radiation, humidity and wind speed are compared against reference ET_r by the ASCE-PM equation applied at a nearby AgriMet weather data using a full measured data set are shown in Figures 2.27-2.30 for Twin Falls, Aberdeen, Ashton and Parma locations. Parma and Ashton are located at opposite ends of the southern Idaho plain and represent relatively extreme elevations on the plain. Twin Falls and Aberdeen are located in the middle and east-center of the plain. These four locations have both AgriMet and NWS weather stations. The figures include plots of ET_r averaged over monthly periods (NWS vs. AgriMet) and plots of daily ET_r. The NWS and AgriMet data sets are fully independent, since the air temperature measurements were made using different instruments and locations.

Corresponding statistics summarizing ratios and RMSE among the estimates are presented in Table 2.2 for the four stations graphed as well as for four additional station pairs in southern Idaho. RMSE for monthly ET_r estimates at the NWS stations averaged about 0.6 mm d^{-1} over all months and periods of common record (among each station pair). RMSE averaged about 1.5 mm d^{-1} for individual days. Ratios of ET_r for NWS stations vs. ET_r for AgriMet stations averaged 1.02 over the eight station pairs investigated, with a standard deviation of 0.07 (Table 2.2).

Overall, the estimates of ET_r made with the NWS data sets using estimated solar radiation, dewpoint temperature and monthly average wind speed are considered to be accurate for application over complete periods of record at the NWS stations and for use in irrigation systems design and management, land application of waste water, hydrologic studies, and water transfers.

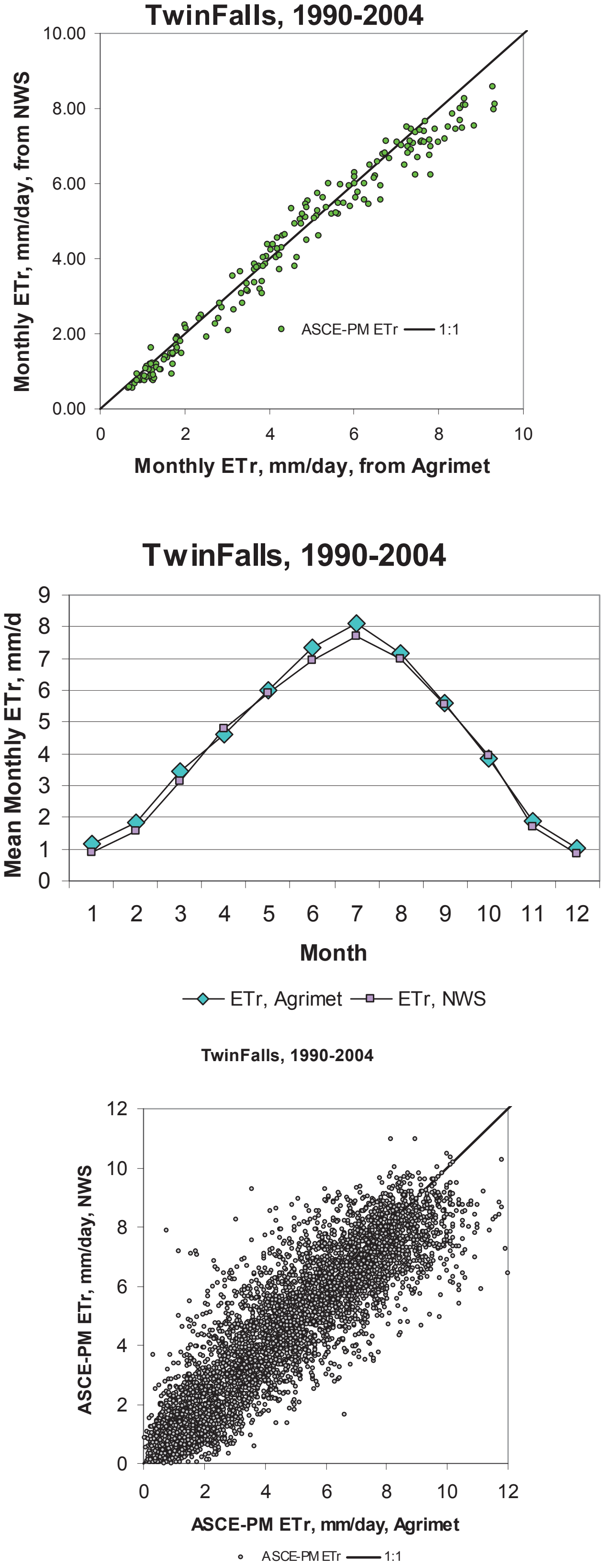


Figure 2.27. Monthly mean ET_r estimated for the Twin Falls 7E NWS station vs. monthly mean ET_r estimated from the Twin Falls AgriMet weather data set over the period of record (top), mean monthly ET_r estimated for the two stations vs. month of year (middle), and daily ET_r estimated for the Twin Falls 3SE NWS station vs. daily ET_r estimated from the Twin Falls AgriMet weather data set over the period of record (bottom)

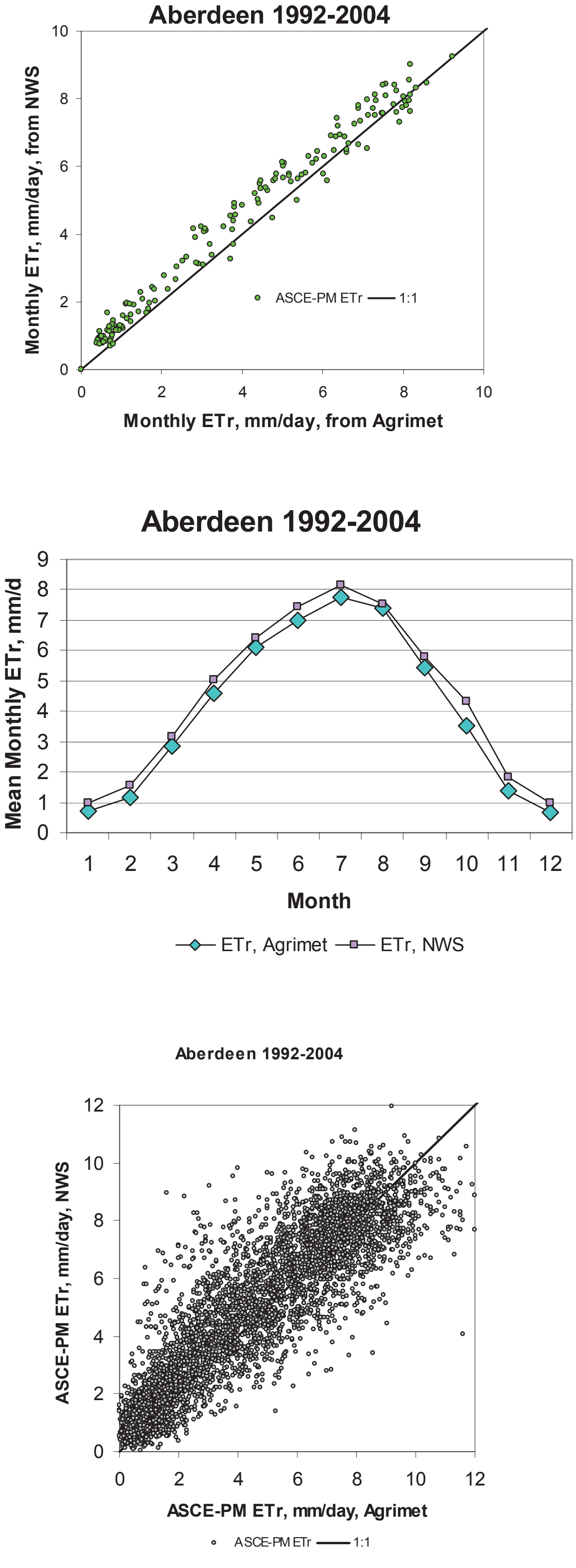
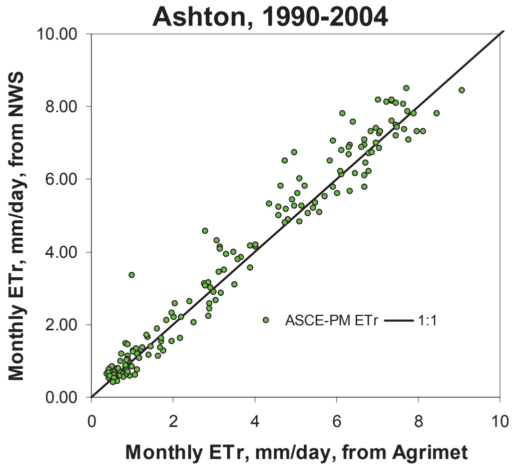
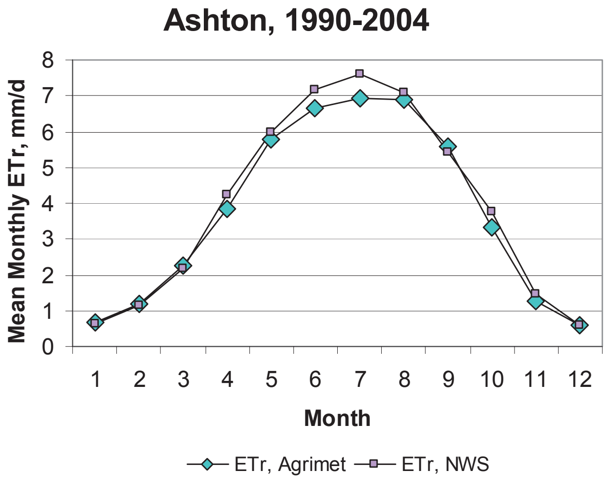


Figure 2.28. Monthly mean ET_r estimated for the Aberdeen NWS station vs. monthly mean ET_r estimated from the Aberdeen AgriMet weather data set over the period of record (top), mean monthly ET_r estimated for the two stations vs. month of year (middle), and daily ET_r estimated for the Aberdeen NWS station vs. daily ET_r estimated from the Aberdeen AgriMet weather data set over the period of record (bottom).





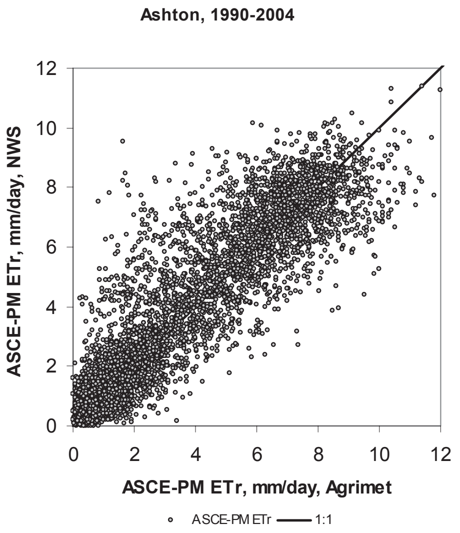


Figure 2.29. Monthly mean ET_r estimated for the Ashton NWS station vs. monthly mean ET_r estimated from the Ashton AgriMet weather data set over the period of record (top), mean monthly ET_r estimated for the two stations vs. month of year (middle), and daily ET_r estimated for the Ashton NWS station vs. daily ET_r estimated from the Ashton AgriMet weather data set over the period of record (bottom).

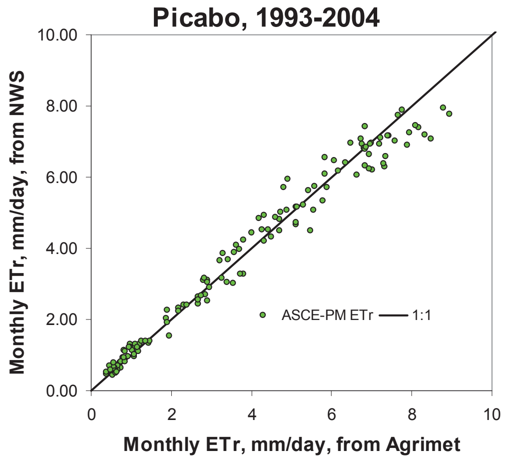
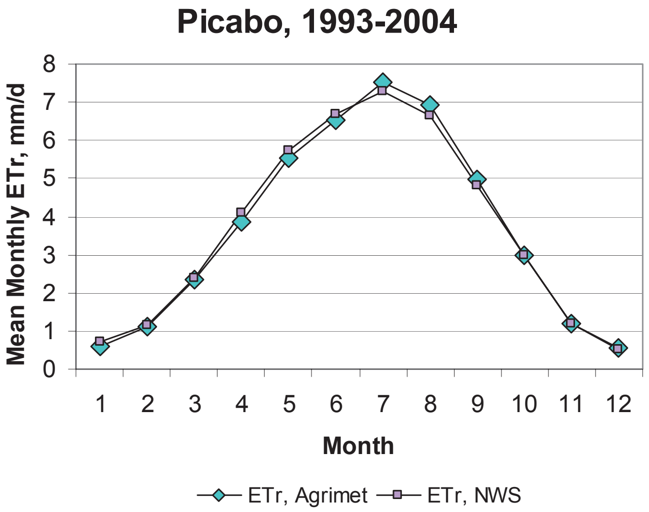
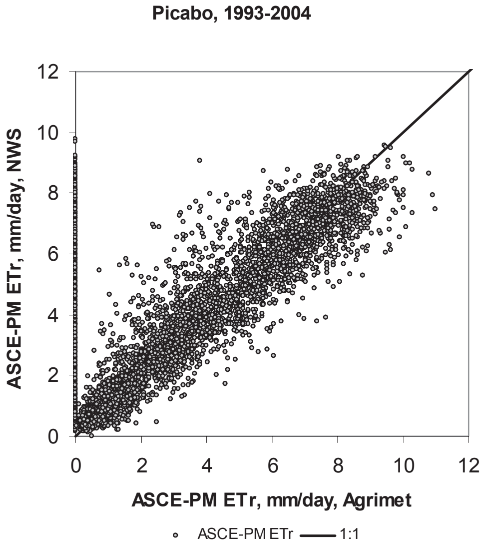


Figure 2.30. Monthly mean ET_r estimated for the Picabo NWS station vs. monthly mean ET_r estimated from the Picabo AgriMet weather data set over the period of record (top), mean monthly ET_r estimated for the two stations vs. month of year (middle), and daily ET_r estimated for the Picabo NWS station vs. daily ET_r estimated from the Picabo AgriMet weather data set over the period of record (bottom).





References to Appendix 2

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

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APPENDIX 3

DEVELOPMENT OF CROP COEFFICIENTS.

Basal crop coefficient curves were developed or organized for forty-two crop and land-cover types. These crops are listed in Table 2 of the main report body, along with the basic type of curve, the primary source and the type of normalizing basis used to scale the curve.

K_{cb} curves for the first 15 crop types are traceable to time based K_{cb} curves derived by Wright (1982) based on lysimeter measurements at Kimberly, Idaho. These time based curves were converted to a normalized cumulative growing degree base as explored by Wright (2001). The description of this conversion, which also included adjustment for using the ASCE Penman-Monteith ET_r in place of the 1982 Kimberly Penman is provided by Allen and Wright (2006). The following section is excerpted from that publication.

This section describes the conversion of basal crop coefficients of Wright (1982), as reported in ASCE Manual 70, for equivalent function with the ASCE Standardized Reference Evapotranspiration equation (ASCE-EWRI, 2005) for an alfalfa reference (ET_{rs}). The Wright (1982) coefficients were originally derived for use with the 1982 Kimberly Penman equation and small differences exist between the two reference calculations.

In addition to conversion of K_{cb} values by Wright (1982) to the ASCE-PM method, coefficients have also been converted for use with a normalized cumulative growing degree day basis following earlier work by Wright (2001). The normalized cumulative growing degree day basis has been applied in this report.

The ASCE Standardized Penman-Monteith ET_r method, which is standardized for a 0.5 m tall vegetation reference for all times of the year, tends to estimate higher than the 1982 Kimberly Penman equation during early spring and fall months (Wright et al., 2000) and to estimate slightly below the 1982 Kimberly Penman method during the peak summer period. Conversion of the Wright (1982) coefficients to the standardized ET_r basis provides for equivalent calculation of crop ET_c for a southern Idaho type of climate using the ASCE standardized Penman-Monteith method.

Conversion of crop coefficients was made using Kimberly weather data for the same year as used for the original coefficient determination (Table 3.1). This was done to reproduce the same ET_c values that were created using the smoothed K_c curves of Wright (1982) used during development of the original K_c and K_{cb} tables and to utilize the same weather patterns as went into the original determinations. The resulting converted K_c curves reproduce the cumulative ET_c vs. time curves for the Kimberly crops as obtained using the original coefficients and the 1982 Kimberly Penman method. This procedure retains all decision-making and original curve shaping decisions by Wright (1982). It is expected that the converted K_c curves will produce applicable and representative ET_c for other temperate climates similar to Kimberly, Idaho having cold winters with defined dormant periods.

In the conversion work, standardized ET_r, denoted as ET_{rs}, was computed daily using Kimberly weather data for air temperature, humidity and wind speed collected by the National Weather Service and solar radiation data collected by the USDA-ARS and the ASCE standardized Penman-Monteith equation. The weather data were quality checked and controlled using procedures from ASCE Standardized Report Appendix D, including comparison of measured solar radiation data with a theoretical clear sky curve and comparison of daily dewpoint temperature with daily minimum air temperature. Solar radiation for portions of some years required adjustment.

Crop ET_c for the original crop coefficient data set was computed daily as $ET_{c\ KP} = K_{c\ Wright} \times ET_{r\ KP}$ where $ET_{c\ KP}$ represents ET_c as predicted using crop coefficients ($K_{c\ Wright}$) by Wright (1981) or Wright (1982), as reported in ASCE Manual 70, Tables 6.6 and 6.9, with some adjustment to some crops by Wright (1995). $ET_{r\ KP}$ represents alfalfa reference ET calculated using the 1982 Kimberly Penman equation and associated equations (Wright, 1982). ET_c for the Standardized Penman-Monteith was computed as $ET_{c\ s} = K_{c\ s} \times ET_{rs}$ where $ET_{c\ s}$ denotes crop ET computed with the standardized ASCE procedure, and $K_{c\ s}$ represents the crop coefficients of Wright converted for use with ET_{rs}. In the conversion work, cumulative $ET_{c\ s}$ vs. time was set equal to cumulative $ET_{c\ KP}$ vs. time.

The same crop coefficient tabular format as used by Wright (1982) is presented for the converted coefficients, where K_c from planting to effective full cover is expressed as a function of percent time from planting to effective full cover, in multiples of 10%, and K_c after effective full cover is expressed as a function of days after full cover in multiples of 10 days. Basal crop coefficients of Wright (1982) as reported in ASCE Manual 70 and refined by Wright (1995) are summarized in Tables 3.3. The planting, effective full cover and harvest dates summarized in ASCE Manual 70 Table 6.7 are listed in Table 3.2.

During conversion of the K_c tables, computed ET_c were expressed as cumulative ET_c since planting, in mm. This was done by summing ET_c computed daily over the growing period using both methods. Each decadal (i.e., 10% or 10 day) K_c entry for the constructed $K_{cm\ s}$ or $K_{cb\ s}$ tables was adjusted for each crop until the cumulative ET_c vs. time curves by the two methods coincided. A root mean square difference, RMSD, was computed for each crop based on the differences in prediction during each decade (10% or 10 day period). The conversions caused the two cumulative ET_c curves to graphically coincide, created a relatively smooth and continuous evolution in K_c vs. time, and minimized the total RMSD for the $K_{cm\ s}$ or $K_{cb\ s}$.

Winter wheat was modeled from the date of planting in fall until estimated dormancy in early winter and then again from greenup in spring until harvest following Wright (1982). Alfalfa was modeled and converted for each of the four growth cycles as done by Wright (1981, 1982) and for a mean seasonal curve that smoothed impacts of reduced K_c following cuttings. Three years of weather and lysimeter data had been used by Wright to construct the alfalfa curves (1969, 1970, 1971). Therefore, a combined daily series for ET_r was created by averaging the daily ET_r for these three years. Similarly, two years, 1973 and 1974 were averaged to construct the daily ET_r curve for the snap bean crop since these two years were used in defining the original K_c curves (Wright, 1982).

The clipped ryegrass crop was not reported by Wright (1981) or Wright (1982), but was included in ASCE Manual 70, and was therefore converted here. This crop represented 1983 and 1984, so that the ET_r for these two years was averaged to produce a single daily time series.

Because the second and third growth cycles for alfalfa at Kimberly use the same single curve (Tables 3.3 and 3.4), this curve was converted so that each of the two growth cycles shared any "error" in the curve conversion.

Converted $K_{cb\ s}$ coefficient tables are shown in Table 3.4 for use with the ASCE Standardized Penman-Monteith method. Standard errors of estimate between cumulative ET_c by the two methods vs. percent time to full cover and days after cover were generally less than 1 mm per decadal period. This translates into less than about 0.2 mm/day RMSD in most cases.

Graphs showing daily K_{cm} and K_{cb} vs. time and graphs showing cumulative ET_c vs. time are included at the back of this report.

Table 3.1. Years of original lysimeter and weather data collection reported by Wright (1981) and Wright (1982) and RMSD of crop coefficient conversion.

Crop	Year of data	RMSD of K_{cm} conversion for use with the ASCE Standardize Penman-Monteith Reference ET method, mm/decadal[1] period
Spring grain	1979	1.1
Peas	1977	1.0
Sugar Beets	1975	0.9
Potatoes	1972	0.7
Field Corn	1976	0.9
Sweet Corn	1976	0.9
Snap Beans	1973, 1974 (ave)	0.3
Winter Wheat	1977-78	1.4
Alfalfa	1969, 1970, 1971 (ave)	0.7 (season) 0.4, 1.3, 1.3, 0.4 for cuttings 1, 2, 3, 4
Ryegrass	1983, 1984	0.7

[1] A decadal period represents 10% of the planting to effective full cover period or each 10 days following effective full cover until harvest.

TABLE 3.2. Dates of Various Crop Growth Stages Identifiable for Crops Studied at Kimberly, Idaho 1968-1979 (after Wright, 1982, and Table 6.7 of ASCE Manual 70)

	Date of Occurrence (Month/Day)							Days		
Crop	Planting	Emer-gence	Rapid Growth	Full Cover	Heading or Bloom	Ripening	Harvest	Planting to Full Cover	Full Cover to Harvest	Growing Period Length, Days
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	
Spring grain[1]	04/01	04/15	05/10	06/10	06/10	07/20	08/10	70	61	131
Peas	04/05	04/25	05/10	06/05	06/15	07/05	07/25	61	50	111
Sugar Beets	04/15	05/10	06/01	07/10			10/15	86	97	183
Potatoes	04/25	05/25	06/10	07/10	07/01	09/20	10/10	76	92	168
Field Corn	05/05	05/25	06/10	07/15	07/30	09/10	09/20	71	67	138
Sweet Corn	05/05	05/25	06/10	07/15	07/20		08/15	71	31	102
Beans	05/22	06/05	06/15	07/15	07/05	08/15	08/30	54	46	100
Winter Wheat[2]	(2/15)	(3/1)	03/20	06/05	06/05	07/15	08/10	(110)	66	304
Alfalfa (1st)[3]	04/01		04/20				06/15			75
Alfalfa (2nd)[3]	06/15		06/25				07/31			46
Alfalfa (3rd)[3]	07/31		08/10				09/15			46
Alfalfa (4th)[3]	09/15		10/01				10/30			45

[1] Spring grain includes barley and wheat.

[2] Effective dates in parentheses, Crop was planted on 10/10 and emerged 10/25 the previous season.

[3] Effective planting date for established alfalfa is date growth begins in spring or harvest of preceding crop dates for these cuttings are indicated. Final harvest is date crop becomes dormant.

Minor changes from Wright (1982) reflect additional data for some crops (Wright, 1984, personal communication).

TABLE 3.3. **Original Basal ET Crop Coefficients, K_{cb}, for Use with Alfalfa Reference ET_r as computed by the 1982 Kimberly Penman Reference Method** (*Original Crop Coefficients* **by Wright, 1982; Manual 70 Table 6.6; updated by Wright, 1995)**) ***(note: these K_{cb} curves were not used in the IDWR CU study)***

	Basal ET Crop Coefficients, K_{cb}											
	PCT, time from planting to effective cover (%)											
Crop	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	
Spring grain[1]	0.15	0.15	0.16	0.2	0.25	0.4	0.52	0.65	0.81	0.96	1	
Peas	0.15	0.15	0.16	0.18	0.2	0.29	0.38	0.47	0.65	0.8	0.9	
Sugar Beets	0.15	0.15	0.15	0.15	0.15	0.15	0.16	0.21	0.35	0.69	1	
Potatoes	0.15	0.15	0.15	0.15	0.15	0.2	0.32	0.47	0.62	0.7	0.75	
Corn	0.15	0.15	0.15	0.16	0.17	0.18	0.25	0.38	0.55	0.74	0.93	
Beans	0.15	0.15	0.16	0.18	0.22	0.34	0.45	0.6	0.75	0.88	0.92	
Winter Wheat	0.15	0.15	0.15	0.3	0.55	0.8	0.95	1	1	1	1	
	DT, days after effective cover											
	0	10	20	30	40	50	60	70	80	90	100	
Spring grain[1]	1	1	1	1	0.9	0.4	0.15	0.07	0.05			
Peas	0.9	0.9	0.72	0.5	0.32	0.15	0.07	0.05				
Sugar Beets	1	1	1	0.98	0.94	0.89	0.84	0.79	0.74	0.69	0.64	
Potatoes	0.75	0.75	0.73	0.7	0.66	0.63	0.59	0.52	0.2	0.1	0.1	
Field Corn	0.93	0.93	0.93	0.9	0.87	0.83	0.77	0.7	0.3	0.2	0.15	
Sweet Corn	0.93	0.91	0.9	0.88	0.8	0.7	0.5	0.25	0.15			
Beans	0.92	0.92	0.86	0.65	0.3	0.1	0.05					
Winter Wheat	1	1	1	1	0.95	0.5	0.2	0.1	0.05			
	Time from new growth or harvest to harvest (%)											
Crop	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	
Alfalfa (1st cycle)[2]	0.4	0.5	0.62	0.8	0.9	0.95	1	1	0.98	0.96	0.94	
(Intermediate cycles)	0.25	0.3	0.4	0.7	0.9	0.95	1	1	0.98	0.96	0.94	
(Last cycle)	0.25	0.3	0.4	0.5	0.55	0.5	0.4	0.35	0.3	0.27	0.25	
	Total Season (days from beginning of spring growth) (These are Kcmeans)											
	0	**20**	**40**	**60**	**80**	**100**	**120**	**140**	**160**	**180**	**200**	
Alfalfa	0.45	69	0.87	0.88	0.7	0.75	0.88	0.81	0.88	0.71	0.65	
(seasonal)	0.5	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.75	0.6	
(overall seasonal mean)						0.85						
perennial rye grass	0.6	0.7	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.76	0.75	(8-15 cm)

[1] Spring grain includes wheat and barley.

[2] 1st denotes first harvest, intermediate harvests may be 1 or more depending on length of season. The last harvest is when crop becomes dormant in cool weather. See text for further discussion. Cultivar used was Ranger.

Minor changes from Wright (1982) reflect additional data for some crops (Wright, 1984, personal communication).

TABLE 3.4. Basal ET Crop Coefficients, K_{cb}, for Use with Alfalfa Reference ET_r as computed by the *ASCE Standardized Penman-Monteith Reference Method* (Converted from Original Crop Coefficients by Wright, 1982; Manual 70 Table 6.6; updated by Wright, 1995)) and for use on a normalized time basis. (note: these K_{cb} curves were not used in the IDWR CU study, but were converted to a normalized cumulative degree day basis (see Table 3.5 following) for use in the IDWR CU study).

	Basal ET Crop Coefficients, K_{cb}											
	PCT, time from planting to effective cover (%)											
Crop	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	
Spring grain[1]	0.15	0.15	0.15	0.19	0.24	0.36	0.48	0.62	0.92	0.98	1.03	
Peas	0.12	0.13	0.14	0.15	0.18	0.27	0.36	0.5	0.65	0.78	0.92	
Sugar Beets	0.15	0.15	0.15	0.15	0.15	0.16	0.17	0.21	0.4	0.66	1.03	
Potatoes	0.15	0.15	0.15	0.15	0.15	0.2	0.34	0.49	0.64	0.72	0.77	
Corn	0.15	0.15	0.15	0.16	0.17	0.2	0.27	0.41	0.55	0.8	0.96	
Beans	0.15	0.15	0.17	0.19	0.23	0.35	0.46	0.6	0.78	0.93	0.95	
Winter Wheat	0.12	0.12	0.14	0.22	0.45	0.7	0.84	0.96	1	1.03	1.03	
	DT, days after effective cover											
	0	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	
Spring grain[1]	1.03	1.03	1.03	1.03	0.94	0.4	0.15	0.07	0.05			
Peas	0.92	0.92	0.72	0.52	0.32	0.16	0.07	0.05				
Sugar Beets	1.03	1.03	1.02	0.98	0.93	0.86	0.78	0.72	0.66	0.6	0.54	
Potatoes	0.77	0.77	0.73	0.68	0.64	0.59	0.54	0.47	0.2	0.08	0.08	
Field Corn	0.96	0.96	0.96	0.92	0.85	0.79	0.72	0.62	0.28	0.16	0.12	
Sweet Corn	0.96	0.95	0.93	0.88	0.8	0.65	0.47	0.23	0.12			
Beans	0.95	0.95	0.88	0.64	0.3	0.09	0.05					
Winter Wheat	1.03	1.03	1.03	1.03	1	0.5	0.2	0.1	0.05			
	Time from new growth or harvest to harvest (%)											
Crop	0	10	20	30	40	50	60	70	80	90	100	
Alfalfa (1st cycle)[2]	0.35	0.45	0.56	0.72	0.82	0.9	1	1	1	0.98	0.96	
(Intermediate cycles)	0.25	0.3	0.42	0.72	0.9	0.95	1	1	0.98	0.96	0.94	
(Last cycle)	0.25	0.27	0.36	0.42	0.5	0.45	0.35	0.3	0.25	0.22	0.22	
	Total Season (days from beginning of spring growth) (These are K_{cmeans})											
	0	20	40	60	80	100	120	140	160	180	200	
Alfalfa	0.45	69	0.87	0.88	0.7	0.75	0.88	0.81	0.88	0.71	0.65	
(seasonal)	0.5	0.74	0.82	0.86	0.88	0.88	0.86	0.84	0.78	0.7	0.5	
(overall seasonal mean)						0.85						
perennial rye grass	0.6	0.68	0.76	0.78	0.8	0.8	0.79	0.76	0.73	0.68	0.6	(8-15 cm)

[1] Spring grain includes wheat and barley.

[2] 1st denotes first harvest, intermediate harvests may be 1 or more depending on length of season. The last harvest is when crop becomes dormant in cool weather. Cultivar used was Ranger.

Growing Degree-Day Basis for Crop Coefficients

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) as a means for automatic adjusting lengths of development and growth periods to account for variation in temperature among years and as a means to facilitate transfer of crop coefficients among regions. Plant functions of evapotranspiration, photosynthesis, water and nutrient absorption and transport, enzyme activity, and other biological and chemical activities are regulated by temperature. For this reason, the development of the crop is generally 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:

$$GDD_{corn} = \frac{max(min(T_{max},30),10)\ + max(min(T_{min},30),10)}{2} - 10 \qquad (3.1)$$

where T_{max} is daily maximum air temperture, ^{O}C and T_{min} is daily minimum air temperature, ^{O}C. 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^{O}C and minimum threshold of 10^{O}C, which are 86 and 50 ^{O}F. The GDD equation for corn assumes no growth at air temperatures above 30^{O}C and no negative 'penalty' for growth if the minimum temperature goes below 10^{O}C.

A common, basic formula[14] 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:

$$GDD = max\left(\frac{T_{max} + T_{min}}{2} - T_{base},\ 0\right) \qquad (3.2)$$

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. 3.2 to have lower growth rates than by Eq. 3.1, where T_{min} is 'boosted.' Wright (2001) suggested that Eq. 3.2 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. 3.1 was applied to corn for consistency with standardized usage within the U.S. and Eq. 3.2 was applied to all other crops. Values for T_{base} in (3.2) ranged from 0^{O}C for early spring crops such as spring grain to 5^{O}C for crops such as potatoes and dry beans as shown in Table 3.5.

The conversion of the K_c time base to a normalized GDD base was recomputed during this study and follows that originally developed by Wright (2001). The conversion was recomputed here to create tables of crop coefficients for use with the standardized ASCE-PM ET_r method and as a check for the 1982 Kimberly Penman method. Tables 3.3 and 3.4 were used for the conversion and weather data for the specific year of curve development was used to compute CGDD. Tbases used for different crops based on selection by

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

Wright (2001). All crops used Eq. 3.2 for GDD with the exception of corn, where the standard corn GDD method was used (Tbase = 10 and Tupper threshold = 30 ^oC).

Following Wright (2001), the CGDD basis was normalized in terms of the quantity of CGDD required to advance from planting or green-up to effective full cover. This normalized CGDD (termed NCGDD) ranged from 0 to 1.0 over the period from planting or green-up until effective full cover. NCGDD ranged from 1.0 to typically more than 2.0 for the period from effective full cover to harvest or die-down. Effective full cover dates were taken from Table 3.2, column 5, based on Wright (1982). Dates specified by Wright (1982) and repeated in Jensen et al. (1990) for effective full cover are listed in Table 3.2.

Curves were developed similar to the time-based translation for the ASCE-PM ET_r, where cumulative ET was computed vs. time using the 1982 Kimberly Penman ET_r applied using the weather data for the specific year of lysimeter measurement and multiplied by the crop coefficient curve of Wright (1982). The crop coefficient curve of Wright (1982) was constructed using the dates for planting, effective full cover and harvest given in that paper as well as the crop coefficients reported there or updated by Wright (1995) and listed in Table 3.2. The result was a 'reconstructed' lysimeter ET data set that reflected the smoothing by the K_c curves and filtering and decision-making by Wright (1981, 1982, 1996).

The cumulative ET vs. time curves were then paired against equivalent normalized CGDD calculated for the same year and weather data set, and the value for CGDD at the time of reported effective full cover was determined. NCGDD was computed each day by dividing by the CGDD for that day by the CGDD at effective full cover. Finally, percentile values for K_{cb} were selected from the plots, numerically in increments of 10% for NCGDD.

The K_c v. NCGDD curve for winter wheat was begun Oct. 1 and run through the winter, which deviates from Wright (2001) where his NCGDD curve began at a 'pseudo' greenup date during late winter or early spring. The Oct. 1 date was selected as a typical planting date in many parts of Idaho and agrees relatively closely with the Oct. 10 date reported by Wright (1982) for the winter wheat crop of 1977-78. The 'new' CGDD based K_{cb} curve for winter wheat that extends back to Oct. 1 has a shape following heading that agrees closely with the Wright (1982) K_{cb} curve.

For the winter wheat crop during winter, some adjustments were made periodically to the CGDD 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^{o}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^{o}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^{o}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^{o}C is based on observations by (Wright, 2002, pers. comm.).

In the case of snap beans (also representing dry, edible beans), crops were grown at Kimberly during 1973 and 1974. The NCGDD curves were developed using data from 1973. 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. The month of January in Idaho usually represents a period of no significant CGDD accumulation, and where the alfalfa crop is dormant, and thus is a good starting point to begin the CGDD accumulation for alfalfa. 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.

To apply the K_c vs. NCGDD curves, one needs to determine the planting or green up date to begin the season. No other information other than daily calculated CGDD is required. To construct the curve, CGDD from the estimated day of planting or greenup is accumulated using the Base temperature noted and using Eq. (2) for all crops except corn, where Eq. (1) is used. NCGDD is calculated as the ratio of CGDD to the CGDD entered in Table 3.5 for the "CGDD Planting to FC" entry in the table. For example, for spring wheat, the $CGDD_{Planting\ to\ FC}$ value is 935 ^oC-days. The ratio NCGDD is used as the entry point in column 1 of Table 3.5 and the value for K_{cm} or K_{cb} is selected by interpolation. The ratio NCGDD is calculated by dividing CGDD accumulated since planting (or greenup of alfalfa) by the $CGDD_{Planting\ to\ FC}$. This 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.

In applications to Idaho NWS stations, T_{max} and T_{min} data were reduced for some stations according to any perceived station aridity effects, as described in Appendix 8, using aridity ratings listed in Tables 5.2 and 5.3 and maximum temperature adjustments listed in Table 8.2. This adjustment was done prior to calculation of CGDD since the CGDD thresholds 'expect' to have input from weather stations having relatively well-watered surroundings. The adjustments to T_{max} and T_{min} were done after computation of ET_r.

Adjustments to K_{cb} Computation Procedures

The following adjustments were made to computation procedures during application to the 123 weather station data sets in Idaho. The adjustments were made to account for differences between Kimberly data derived from lysimeter measurements in the 1970's and 1980's and current conditions and observations.

Cumulative growing degree day values at the time of effective full cover ($CGDD_{EFC}$) were reduced for potatoes by 5% relative to values for $CGDD_{EFC}$ that occurred during the specific year of lysimeter mesurements (Appendix 3) to produce seasonal curves that terminated naturally before killing frosts during more years at major potato growing locations. To compensate, the CGDD from EFC to termination was lengthened for late potatoes by 25% in SW Idaho where growing seasons are longer (see Table 7). Cumulative growing degree day values at the time of effective full cover ($CGDD_{EFC}$) were increased for corn by 5% and CGDD at harvest ($CGDD_{term}$) was increased by about 20% relative to values for $CGDD_{EFC}$ that occurred during the specific year of lysimeter mesurements (Appendix 3). This was done to produce seasonal curves that reflected behavior of current corn cultivars.

$CGDD_{EFC}$ was reduced for spring grain by 10% and for winter grain by approximately 25% to shorten estimated season lengths observed across southern Idaho. The $CGDD_{EFC}$ for winter grain was shortened to insure estimated harvest before spring grain for most years and locations.

The $CGDD_{EFC}$ for sugar beets was increased from 710 to 970 to better reflect observations for south-central Idaho. The $CGDD_{term}$ was increased from 1843 to 2600 to lengthen growing seasons, on average.

Table 3.5. K_{cb} for use with the Standardized ASCE-EWRI Penman-Monteith based on Normalized Cumulative Growing Degree-Day from Planting to Effective Full Cover, traceable to Wright (1982) and the USDA-ARS Kimberly lysimeter systems.

Curve no.:	1	2	3	4	5	6	7	8	9	10
Percent cumulative GDD from Plant (or Greenup) to Effective Full Cover	**Spring wheat**	**Winter Wheat**	**Peas, seed**	**Peas, fresh**	**Sugar Beets**	**Potato baking**	**Potato processing**	**Field Corn**	**Silage Corn**	**Sweet Corn**
0	0.15	0.12	0.12	0.12	0.15	0.15	0.15	0.15	0.15	0.15
10	0.15	0.12	0.14	0.14	0.15	0.15	0.15	0.15	0.15	0.15
20	0.20	0.15	0.15	0.15	0.16	0.15	0.15	0.15	0.15	0.15
30	0.28	0.20	0.16	0.16	0.17	0.17	0.17	0.17	0.17	0.17
40	0.40	0.27	0.20	0.20	0.18	0.23	0.23	0.19	0.19	0.19
50	0.50	0.40	0.32	0.32	0.21	0.35	0.35	0.28	0.28	0.28
60	0.59	0.72	0.46	0.46	0.40	0.48	0.48	0.42	0.42	0.42
70	0.82	0.93	0.63	0.63	0.57	0.62	0.62	0.54	0.54	0.54
80	0.95	0.99	0.77	0.77	0.73	0.69	0.69	0.73	0.73	0.73
90	0.99	1.03	0.85	0.85	0.88	0.74	0.74	0.86	0.86	0.86
(Eff. Full Cov.)100	1.03	1.03	0.92	0.92	1.03	0.77	0.77	0.96	0.96	0.96
110	1.03	1.03	0.92	0.92	1.03	0.77	0.77	0.96	0.96	0.96
120	1.03	1.03	0.92	0.92	1.03	0.77	0.76	0.96	0.96	0.95
130	1.03	1.03	0.91	0.91	1.03	0.75	0.72	0.96	0.96	0.94
140	1.03	1.02	0.84	0.84	1.02	0.72	0.70	0.96	0.96	0.93
150	1.03	1.00	0.78	0.78	1.01	0.70	0.68	0.94	0.94	0.90
160	1.03	0.72	0.71	0.71	0.99	0.68	0.65	0.90	0.90	0.86
170	1.01	0.43	0.65	0.65	0.97	0.66	0.63	0.86	0.86	0.82
180	0.97	0.25	0.58		0.95	0.64	0.59	0.82	0.82	
190	0.88	0.15	0.52		0.91	0.61	0.54	0.78	0.78	
200	0.64	0.10	0.45		0.87	0.58	0.40	0.73	0.73	
210	0.41	0.05	0.38		0.82	0.54	0.10	0.65	0.65	
220	0.28		0.31		0.77	0.48		0.44	0.20	
230	0.16		0.27		0.73	0.16		0.22	0.10	
240	0.10		0.22		0.69	0.10		0.13	0.10	
250	0.05		0.18		0.63					
260			0.14		0.57					
270			0.10		0.10					
280										
290										
300										
GDD Base, °C[a]	0	0	0	0	5	5	5	10-corn	10-corn	10-corn
CGDD Planting to EFC[b]	935[e]	1350[e]	635	635	710[e]	780[e]	780	510[e]	510	510
CGDD Planting to Terminate[c]	2160	2608	1616	1000	1843[f]	1850[f]	1600[f]	1200[f]	1000	800[f]

[a] The GDD Base, °C is base or minimum threshold used when computing the growing degree day.

[b] The CGDD Planting to FC is the cumulative growing degree days from planting (or greenup) until effective full cover. Effective full cover is set differently for each crop Wright (1982).

[c] The CGDD Planting to Terminate is the total cumulative growing degree days from planting (or greenup) until termination (harvest) of the crop. This parameter signals the end of the K_{cb} curve construction.

[e] The 935 value for spring wheat was changed to 840 during processing, the 1350 value for winter grain was changed to 1080 during processing, the 780 for baking potatoes was reduced to 700, the 710 for sugar beets was increased to 970 and the 510 value for corn was changed to 540 during processing for this report to fit recent observations of crop development.

[f] The 1843 value for sugar beets was changed to 2600, the 1850 and 1600 for potatoes were changed to 1780 and 1550, and the 1200 value for field corn was changed to 1400 and the 800 value for sweet corn was changed to 1000 to fit recent observations.

Table 3.5 continued. Kcb for use with the Standardized ASCE-EWRI Penman-Monteith based on Normalized Cumulative Growing Degree-Day from Planting to Effective Full Cover, traceable to Wright (1982) and the USDA-ARS Kimberly lysimeter systems, plus lentils, mint and grass hay.

Curve no.:	11	12	13	14	15	16	17	18	19
Percent PL-EC or PL-TM (type 1-2-4)	**Snap Beans-dry**	**Snap Beans-fresh**	**Alfalfa 1st cycle**	**Alfalfa Int cycle**	**Alfalfa Last cycle**	**Alfalfa, peak**	**Lentils**	**Mint**	**Grass Hay**
0	0.15	0.15	0.25	0.25	0.25	0.35	0.15	0.35	0.20
10	0.16	0.16	0.51	0.33	0.29	0.51	0.15	0.51	0.46
20	0.19	0.19	0.73	0.45	0.38	0.73	0.18	0.73	0.68
30	0.23	0.23	0.84	0.80	0.56	0.84	0.25	0.84	0.79
40	0.38	0.38	0.90	0.93	0.79	0.90	0.36	0.90	0.85
50	0.49	0.49	0.98	0.99	0.91	0.98	0.45	0.98	0.93
60	0.60	0.60	1.00	1.00	0.96	1.00	0.53	1.00	0.95
70	0.74	0.74	1.00	0.99	1.00	1.00	0.74	1.00	0.95
80	0.86	0.86	0.99	0.97	0.99	1.00	0.86	0.99	0.94
90	0.94	0.94	0.97	0.96	0.96	1.00	0.89	0.97	0.92
(Eff. Full Cov.) 100	0.95	0.95	0.96	0.94	0.94	1.00	0.93	0.96	0.91
110	0.95	0.95				1.00	0.93	0.25	0.50
120	0.95	0.95				1.00	0.93	0.33	0.55
130	0.93	0.93				1.00	0.93	0.45	0.70
140	0.90	0.90				1.00	0.93	0.75	0.75
150	0.85	0.85				1.00	0.93	0.75	0.75
160	0.75	0.75				1.00	0.93	0.75	0.75
170	0.64					1.00	0.91	0.75	0.75
180	0.49					1.00	0.87	0.75	0.75
190	0.34					1.00	0.79	0.75	0.70
200	0.19					1.00	0.58	0.75	0.70
210	0.08					1.00	0.37	0.75	0.70
220						1.00	0.25	0.75	0.65
230						1.00	0.16	0.75	0.65
240						1.00	0.10	0.75	0.65
250								0.75	0.60
260								0.75	0.55
270								0.75	0.50
280									0.45
290									0.45
300									0.45
GDD Base, °C[a]	5	5	0	0	0	0	0	0	0
CGDD Planting to FC[b]	670	670	—	—	—	700	935	1400	1300
CGDD Planting to Terminate[c]	1350	950	850	1050[e]	1050[e]	—	2160	4000	4000
CGDD Planting to Terminate-alt[d]			700	850[e]	850[e]				

[a] The GDD Base, °C is base or minimum threshold used when computing the growing degree day.

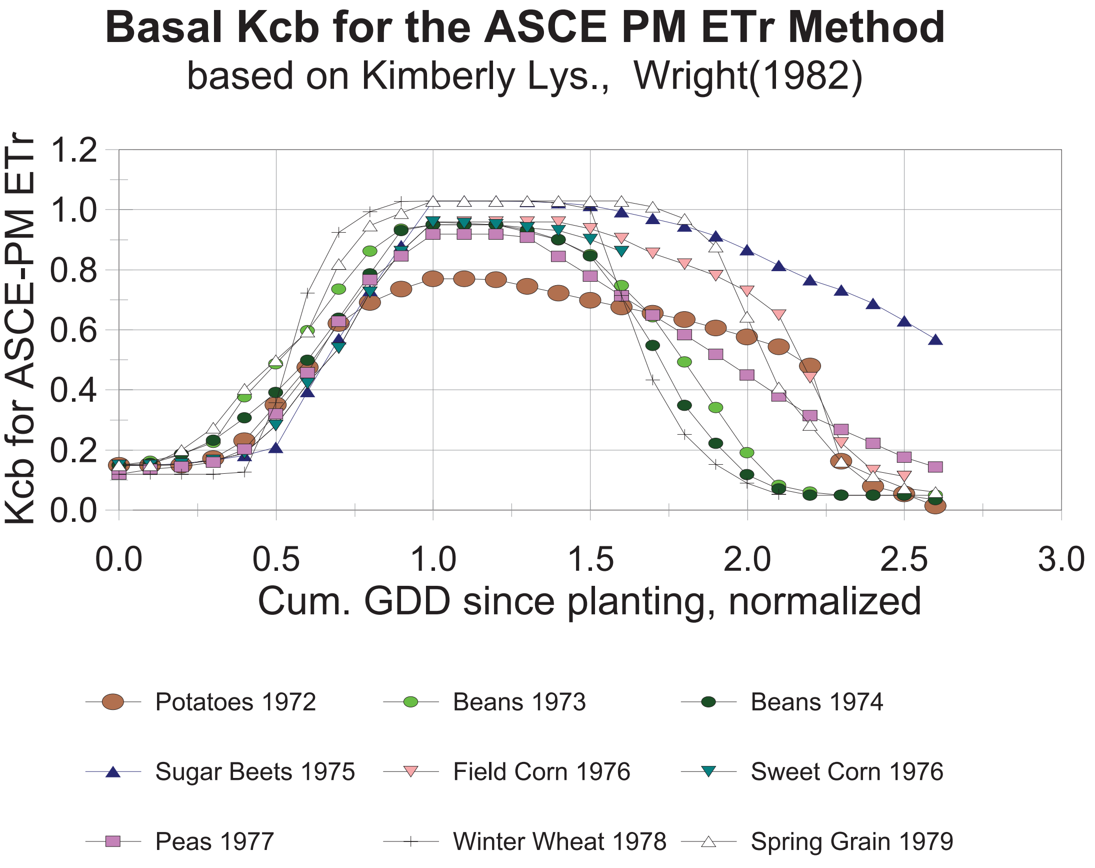
[b] The CGDD Planting to FC is the cumulative growing degree days from planting (or greenup) until effective full cover. Effective full cover is set differently for each crop Wright (1982).

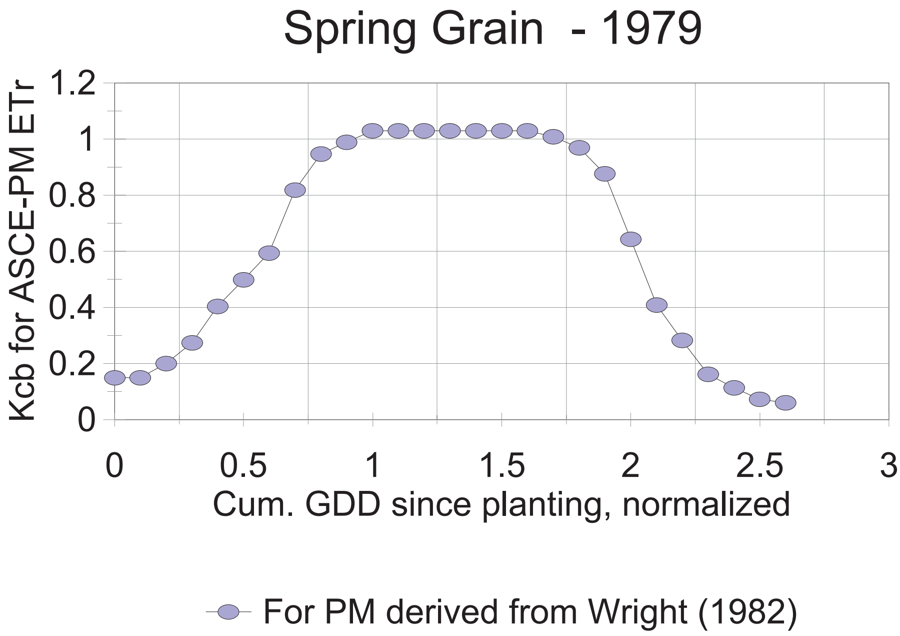
[c] The CGDD Planting to Terminate is the total cumulative growing degree days from planting (or greenup) until termination (harvest) of the crop. This parameter signals the end of the K_{cb} curve construction.

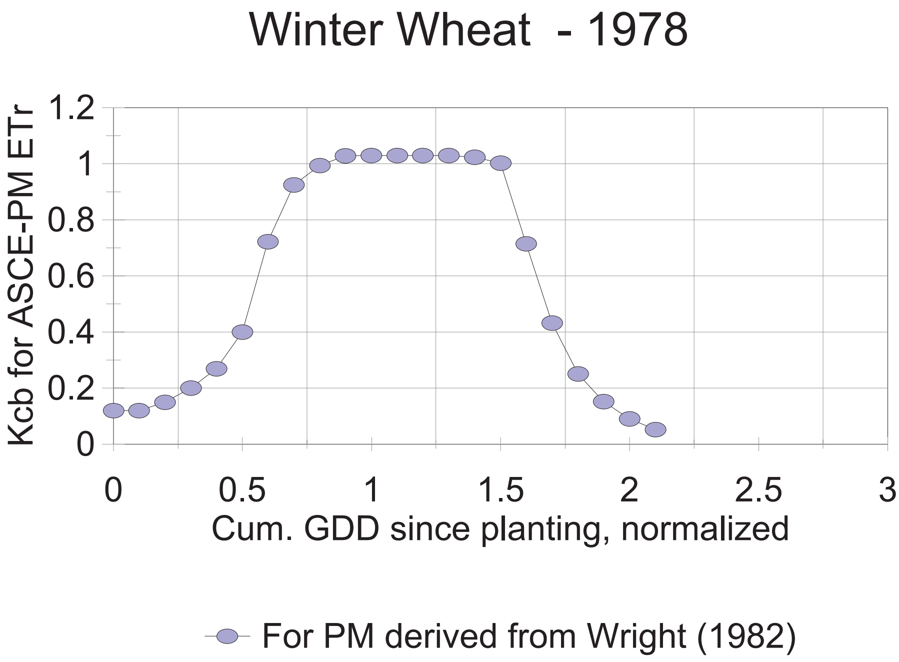
[d] For hay, the value of CGDD Planting to Terminate for 'dairy hay' having relatively frequent cuttings.

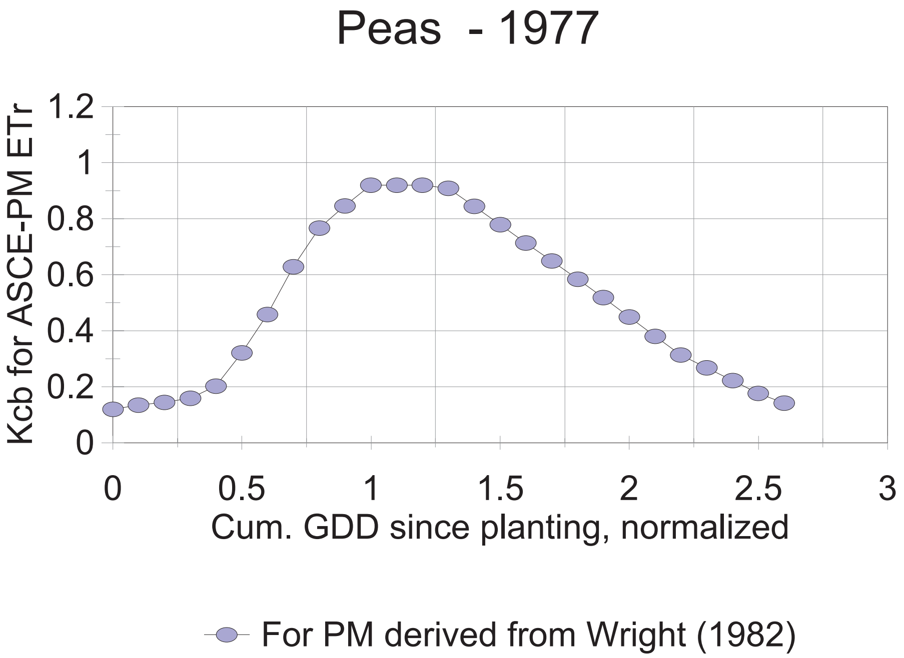
[e] The value of 1050 (for 'beef style' hay) was reduced to 900 during ET processing for this report and the 850 value (for 'dairy style' hay) was set to 650 to better match recent, local observations

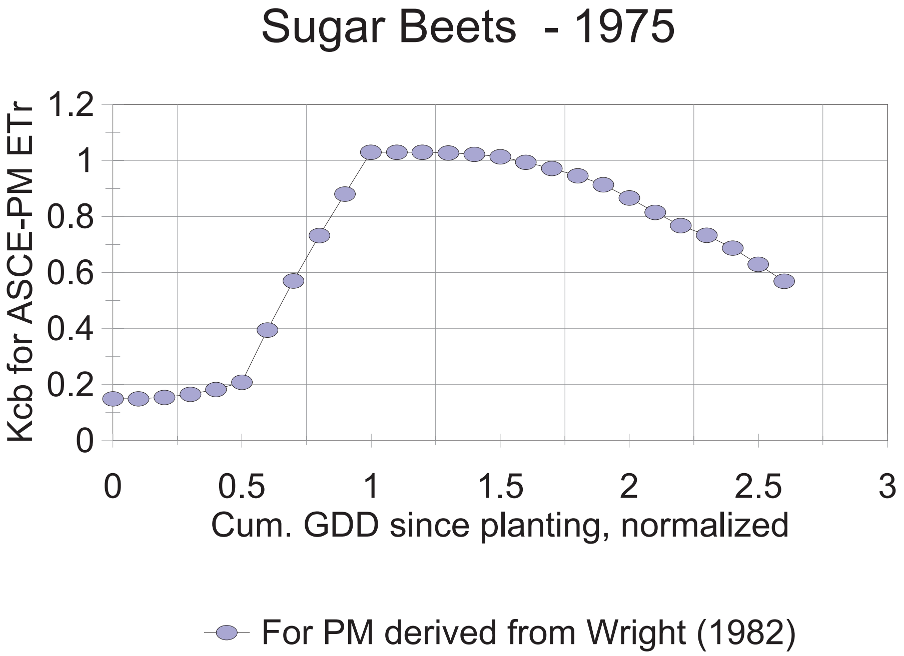
The following figures show K_{cb} vs. NGCDD curves for use with the ASCE standardized Penman-Monteith ET_r method that are based on Kimberly lysimeter data.

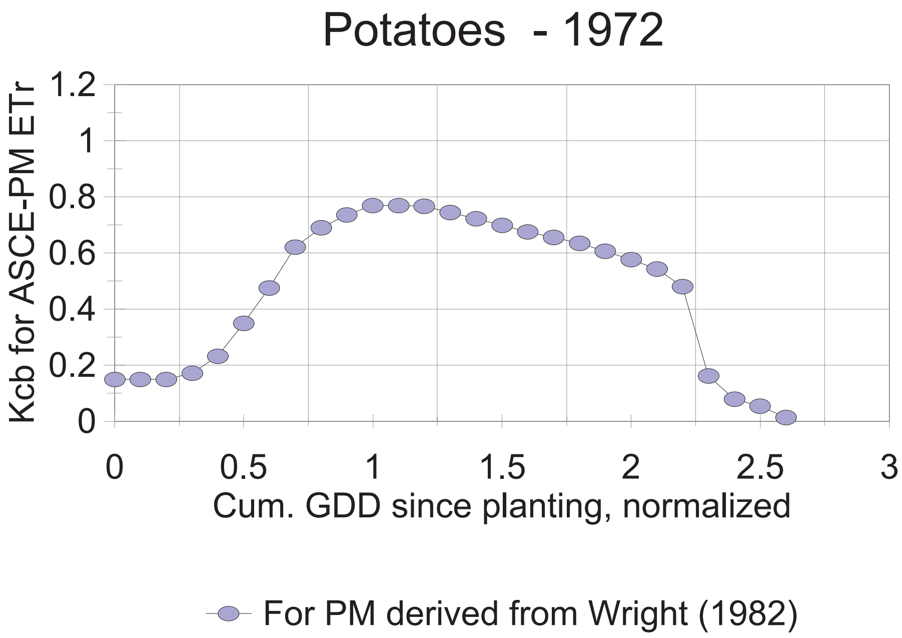



Spring Grain - 1979
Kcb for ASCE-PM ETr
1.2
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
2.5
3
Cum. GDD since planting, normalized
For PM derived from Wright (1982)

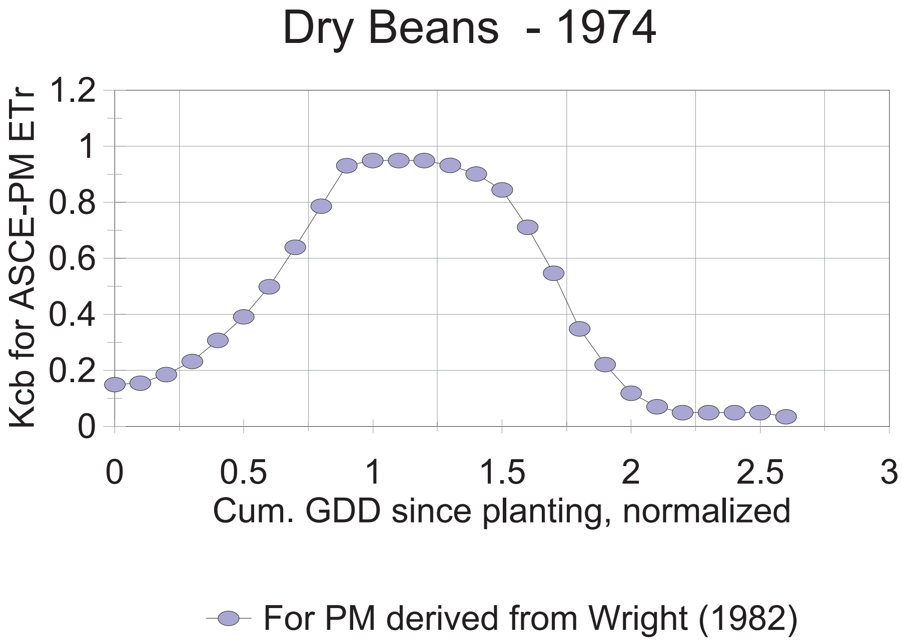

Winter Wheat - 1978
Kcb for ASCE-PM ETr
1.2
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
2.5
3
Cum. GDD since planting, normalized
For PM derived from Wright (1982)


Peas - 1977
Kcb for ASCE-PM ETr
1.2
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
2.5
3
Cum. GDD since planting, normalized
For PM derived from Wright (1982)

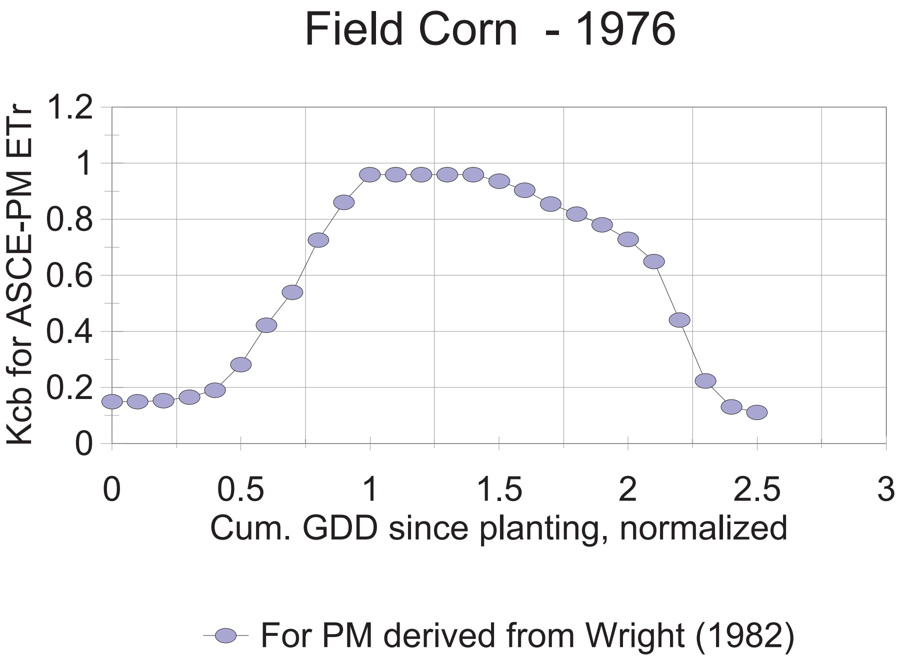

Sugar Beets - 1975
Kcb for ASCE-PM ETr
1.2
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
2.5
3
Cum. GDD since planting, normalized
For PM derived from Wright (1982)

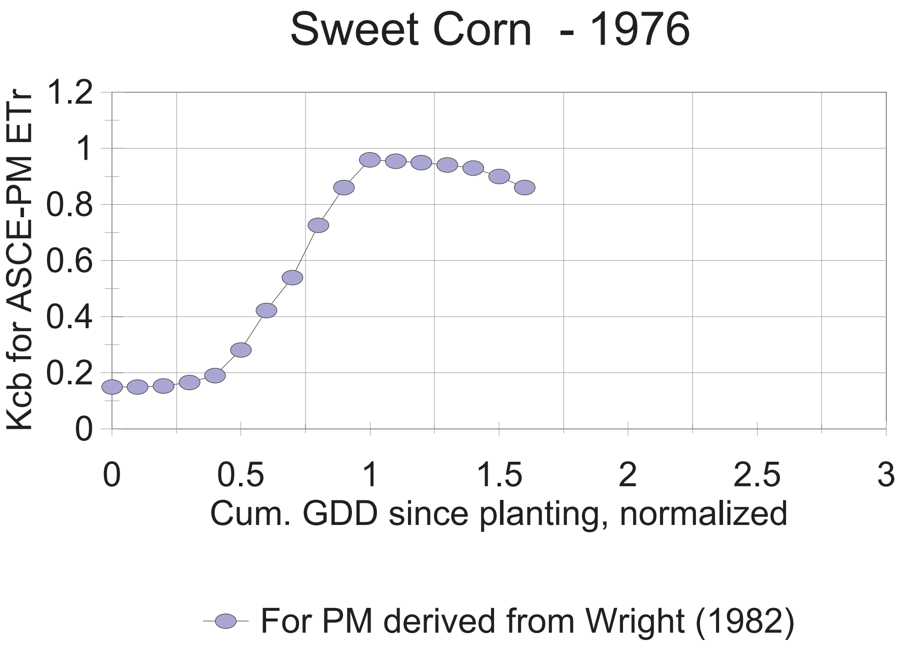


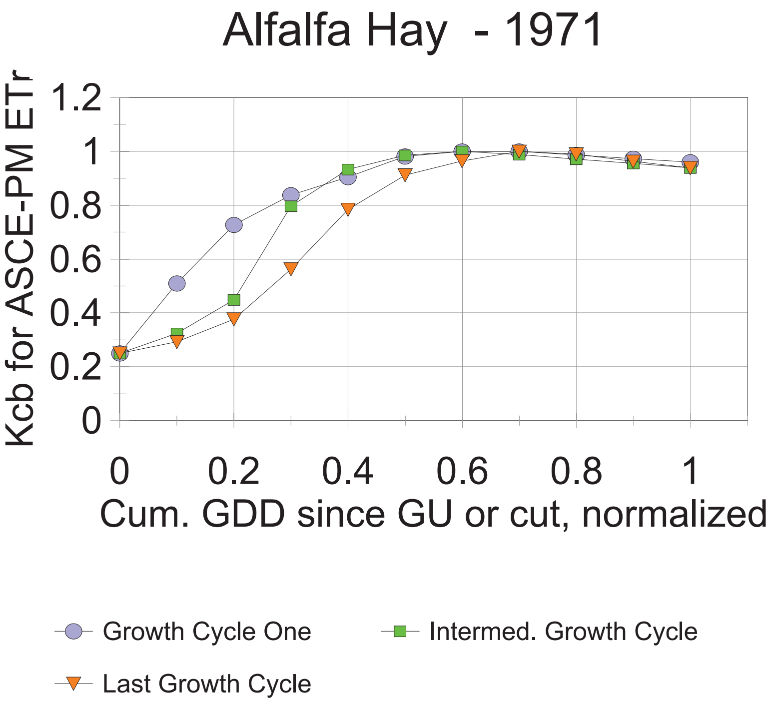
Potatoes - 1972



Dry Beans - 1974


Field Corn - 1976
Kcb for ASCE-PM ETr
0
0.2
0.4
0.6
0.8
1
1.2
0
0.5
1
1.5
2
2.5
3
Cum. GDD since planting, normalized
For PM derived from Wright (1982)


Sweet Corn - 1976
Kcb for ASCE-PM ETr
0
0.2
0.4
0.6
0.8
1
1.2
0
0.5
1
1.5
2
2.5
3
Cum. GDD since planting, normalized
For PM derived from Wright (1982)


Alfalfa Hay - 1971
Kcb for ASCE-PM ETr
1.2
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
Cum. GDD since GU or cut, normalized
Growth Cycle One
Intermed. Growth Cycle
Last Growth Cycle

K_{cb} vs. NGCDD for additional crops

Basal crop coefficients for additional crops were developed using the Kimberly K_{cb} curves and other sources.

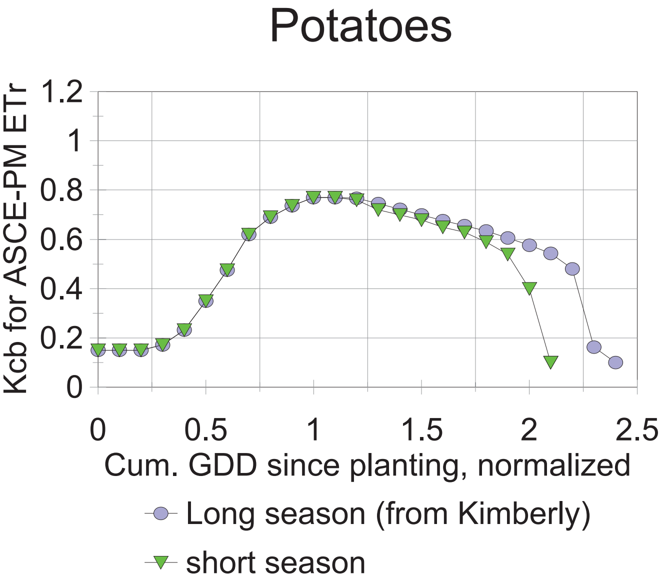
Peas Fresh. The K_{cb} vs. NCGDD curve for peas harvested fresh (curve no. 4) was derived from the Dry Peas (for seed) curve (no. 3) by terminating the curve at NCGDD = 1.6.

Silage Corn. The K_{cb} vs. NCGDD curve for corn silage (curve no. 9) was derived from the field corn curve (no. 8) by reducing the field corn K_{cb} beginning at NCGDD = 2.2 and terminating at 0.1 at NCGDD = 2.3.

Snap Beans Fresh. The K_{cb} vs. NCGDD curve for snap beans harvested fresh (curve no. 12) was derived from the Dry Beans curve (no. 11) by terminating the curve at NCGDD = 1.6.

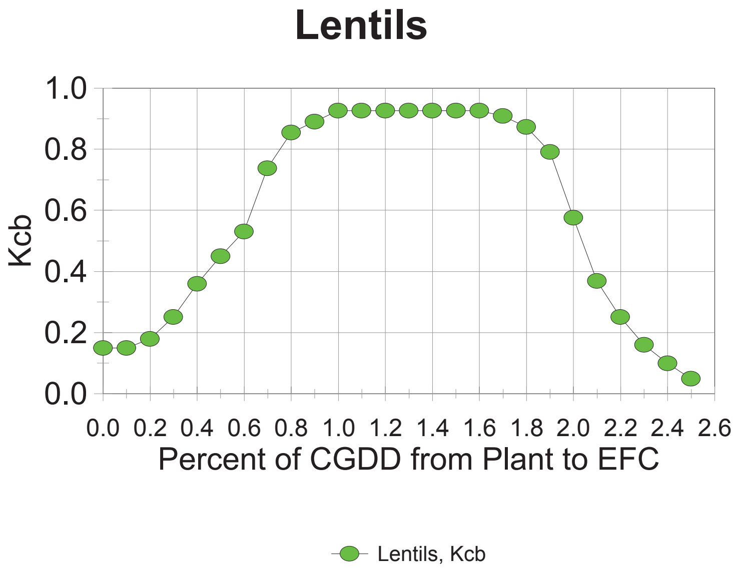
Peak Alfalfa. A 'peak' alfalfa curve was developed (curve 16) to represent the peak K_{cb} for alfalfa when at peak development in the absence of cuttings. This curve is a hypothetical curve since the K_{cb} for alfalfa will in practice begin to decline if the crop is not cut due to leaf aging and seed set. The peak alfalfa curve is patterned after the usage by AgriMet and is useful for irrigation system capacity design. The beginning of the curve was synthesized by following the curve for the first growth cycle, but beginning at K_{cb} = 0.35, following Wright (1982).

K_{cb} curve for early harvested Potatoes. Potato crops are expressed in the ET_c calculations in the form of two classes: a) long season varieties representing baking potatoes and other varieties that are harvested in September and October and b) short season varieties representing processing potatoes that begin to be harvested as early as August. Planting and development dates for both varieties are generally similar and therefore a single curve is used for the period between planting and effective full cover. Separate curves are used for the period from effective full cover to harvest, both based on a normalized cumulative growing degree-day scale. The K_{cb} vs. NCGDD relationship for the long season class is that developed from Wright (1982) and listed in Table 3.5 as curve no. 6. The K_{cb} vs. NCGDD relationship for the short season class (curve 7) was developed from that for the long season variety by shortening the relative time required for maturity and reducing values for K_{cb} geinning at about 1.75 times $NCGDD_{planting\ to\ cover}$, as shown in the

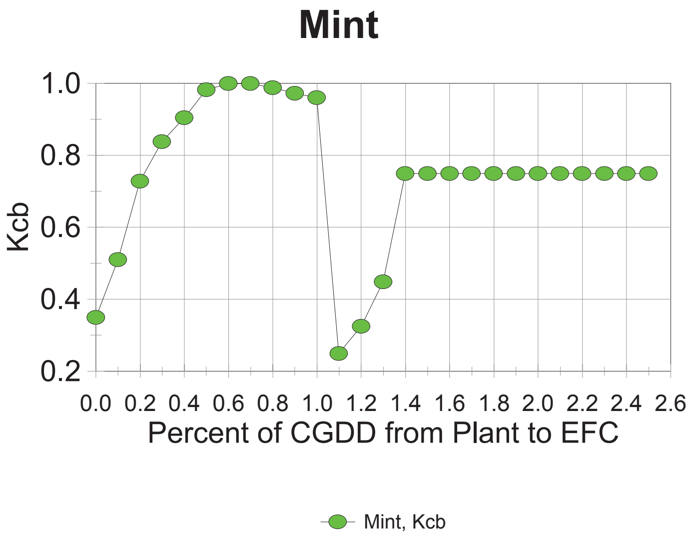


following figure. The recommended CGDD at harvest for the long season variety is about 1800 GDD and that for the short season variety is about 1600 GDD. The second curve is entered in Table 3.5 as curve number 7.

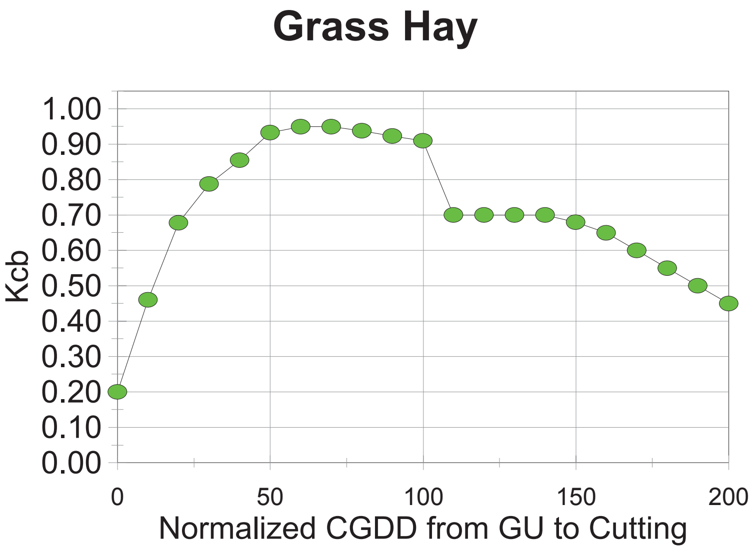
Lentils. Lentils have similar seeding dates and K_{cb} pattern as spring grain in northern Idaho. Therefore, the the spring grain K_{cb} v. NCGDD curve was used, but with values for K_{cb} multiplied by 0.9 to account for shorter, thinner stand density for lentils as compared to spring grain. Harvest dates are typically similar to spring grain or a few days earlier. (Typically 120 days planting to harvest, 65 days to bloom, with mid August swathing). The crop is typically swathed when fields are 2/3 brown, so that the actual K_{cb} curve will follow that for spring grain. No irrigation is assumed for lentils.



Mint. The Mint K_{cb} curve was developed using the K_{cb} curve shape for the first growing cycle of alfalfa (using a CGDD base 0) for the period from greenup until harvest (cutting) (at NCGDD = 1.0). Following cutting the K_{cb} during the regrowth follows that for the second growing cycle of alfalfa, with upper limit of K_{cb} = 0.75 to reflect less care for the crop following harvest. Only one cutting is assumed. The latter portion of the K_{cb} curve is run until mint is frozen (-4^{o}C).



Grass Hay. The grass hay K_{cb} curve was constructed to follow the shape of the K_{cb} curve for first cycle alfalfa, similar to mint, but with peak K_{cb} of 0.95 rather than 1.0 and with 50% longer CGDD required until cutting (1300 ^{o}C-days at base 0^{o}C). Following a first cutting (at NCGDD = 1.0), the K_{cb} is presumed to stay near 0.70 and then decline towards fall, when grazing may occur. The curve is terminated at killing frost. The shape is similar to the AgriMet grass hay curve.



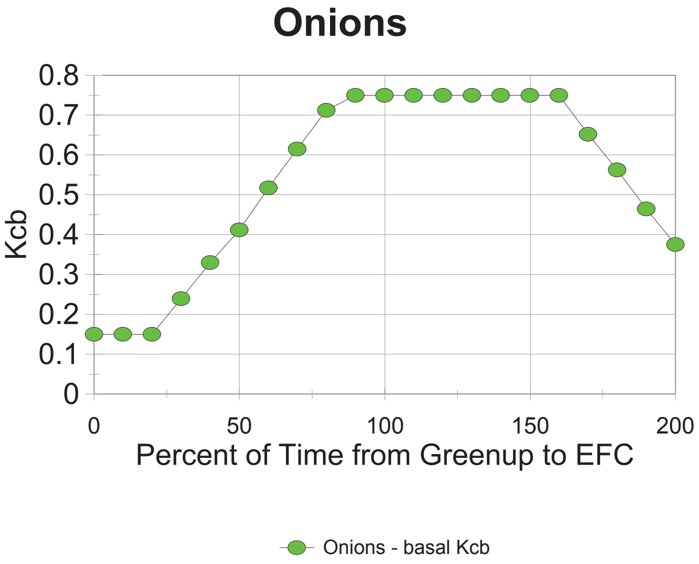
K_{cb} based on Percent Time from Planting (or Greenup) until Effective Full Cover Applied all Growing Season

Basal crop coefficients for additional crops were developed using a variety of normalized bases. Tables 3.6 and 3.7 list K_{cb} curves for use with the Standardized ASCE-EWRI Penman-Monteith that are based on Normalized Time from Planting to Effective Full Cover (curves 20 – 36). This normalized ratio is applied for the whole growing season. Primary data or literature sources for developed curves are listed in Table 2 of the main text. The following section describes how these curves were developed.

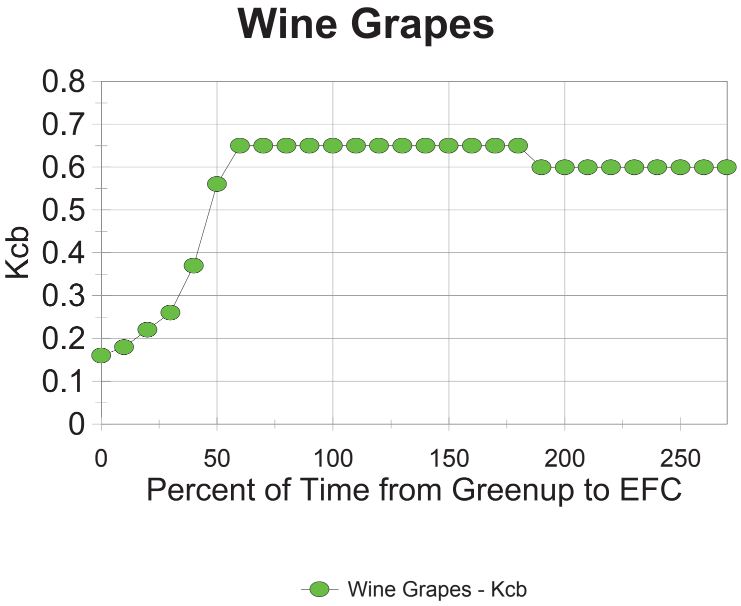
Table 3.6. K_{cb} for use with the Standardized ASCE-EWRI Penman-Monteith based on Normalized Time from Planting to Effective Full Cover.

Curve no.:	20	21	22	23	24	25	26	27	28	29	41	42
Percent Time from Plant (or Greenup) to Effective Full Cover	Onions	Wine grapes	Melons	Hops	Apples w/GC	Apples no GC	Asparagus	Canola	Sunflower/Safflower	Lawn	Cotton wood	Willow
0	0.15	0.16	0.15	0.10	0.15	0.15	0.10	0.15	0.15	0.15	0.15	0.15
10	0.15	0.18	0.15	0.10	0.20	0.15	0.13	0.15	0.15	0.25	0.20	0.15
20	0.15	0.22	0.17	0.10	0.24	0.18	0.17	0.15	0.15	0.38	0.24	0.18
30	0.24	0.26	0.20	0.12	0.33	0.25	0.20	0.19	0.19	0.48	0.33	0.25
40	0.33	0.37	0.24	0.13	0.44	0.35	0.23	0.29	0.29	0.59	0.44	0.35
50	0.41	0.56	0.31	0.32	0.55	0.44	0.27	0.66	0.56	0.65	0.55	0.44
60	0.52	0.65	0.44	0.55	0.66	0.57	0.30	0.85	0.75	0.70	0.66	0.57
70	0.62	0.65	0.56	0.69	0.77	0.66	0.40	0.95	0.85	0.70	0.77	0.66
80	0.71	0.65	0.65	0.79	0.84	0.72	0.50	0.97	0.87	0.70	0.80	0.72
90	0.75	0.65	0.65	0.87	0.87	0.75	0.60	0.97	0.87	0.70	0.83	0.75
(Eff. Full Cov.)100	0.75	0.65	0.65	0.96	0.90	0.75	0.70	0.97	0.87	0.70	0.85	0.75
110	0.75	0.65	0.65	1.00	0.90	0.75	0.70	0.97	0.87	0.70	0.85	0.75
120	0.75	0.65	0.65	1.00	0.90	0.75	0.70	0.97	0.87	0.70	0.85	0.75
130	0.75	0.65	0.65	1.00	0.90	0.75	0.70	0.97	0.87	0.70	0.85	0.75
140	0.75	0.65	0.65	0.97	0.90	0.75	0.70	0.96	0.86	0.70	0.85	0.75
150	0.75	0.65	0.65	0.89	0.90	0.75	0.70	0.81	0.71	0.70	0.85	0.75
160	0.75	0.65	0.65	0.71	0.90	0.75	0.70	0.58	0.48	0.70	0.85	0.75
170	0.65	0.65	0.65	0.52	0.90	0.75	0.70	0.36	0.31	0.70	0.85	0.75
180	0.56	0.65	0.65	0.30	0.90	0.75	0.70	0.25	0.20	0.70	0.85	0.75
190	0.47	0.60	0.65	0.26	0.90	0.75	0.70	0.10	0.10	0.70	0.85	0.75
200	0.38	0.60	0.65	0.22	0.90	0.75	0.70			0.70	0.85	0.75
210		0.60	0.65		0.90	0.75	0.70			0.70	0.85	0.75
220		0.60	0.65		0.73	0.70	0.70			0.70	0.73	0.70
230		0.60	0.65		0.55	0.55	0.70			0.70	0.70	0.65
240		0.60	0.65		0.55	0.55				0.70	0.70	0.65
250		0.60	0.65		0.55	0.55				0.70	0.70	0.65
260		0.60	0.65		0.55	0.55				0.70	0.70	0.65
270		0.60	0.65		0.55	0.55				0.70		
280												
290												
300												

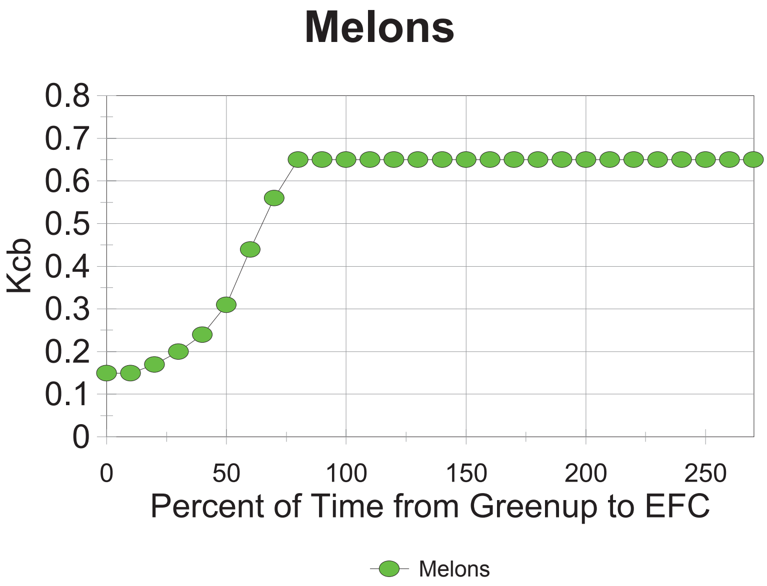
Onions. The onion K_{cb} curve was developed from the K_{cm} curve of AgriMet curve by multiplying by 0.75 and adding values of 0.15 during the planting or transplanting to emergence period (AgriMet K_{cm} curves characteristically begin only at emergence). Full cover date was approximated by AgriMet as when half of the onion stand has 12 leaves. For applications in this report, 80 days from planting to effective full cover was generally assumed, with generally an early April planting and mid Sept. harvest.



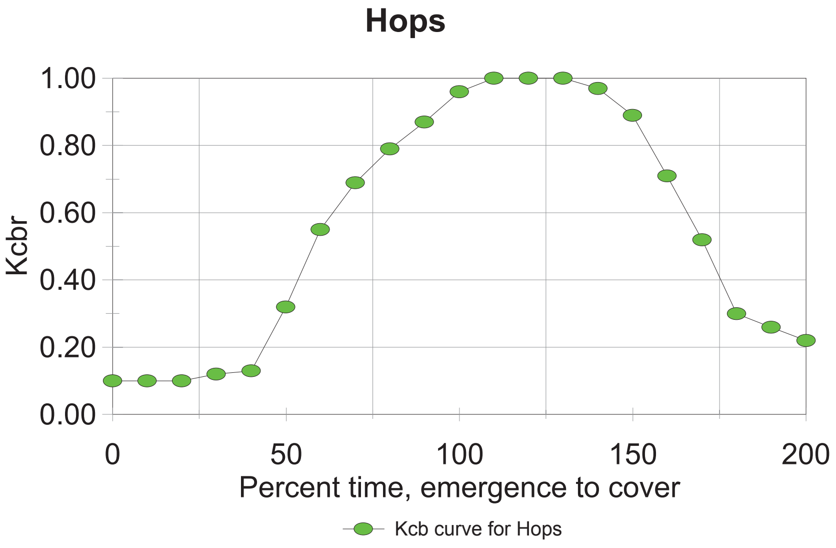
Wine grapes. The K_{cb} curve for wine grapes is essentially the same as used by AgriMet, with slight variation in values for the 30 and 40% entries. The AgriMet curve was extended past 200% of time from greenup to effective full cover (EFC) to 270 by the addition of $K_{cb} = 0.60$. The peak value for K_c (0.65) was not reduced for use as basal K_{cb}, based on values reported in FAO-56.



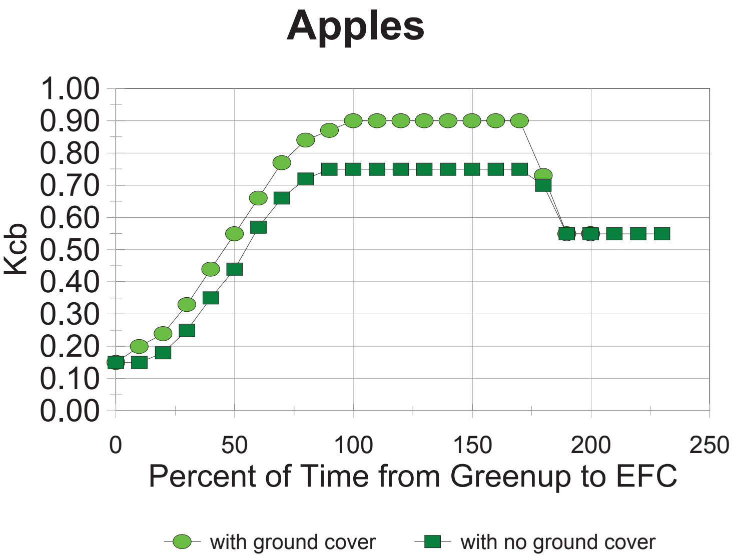
Melons. The melon curve was derived from that of AgriMet by shifting the curve in time by the equivalent of 10 days to account for the period between planting and emergence. The peak value for K_c (0.65) was not reduced for use as basal K_{cb}, based on values reported in FAO-56.



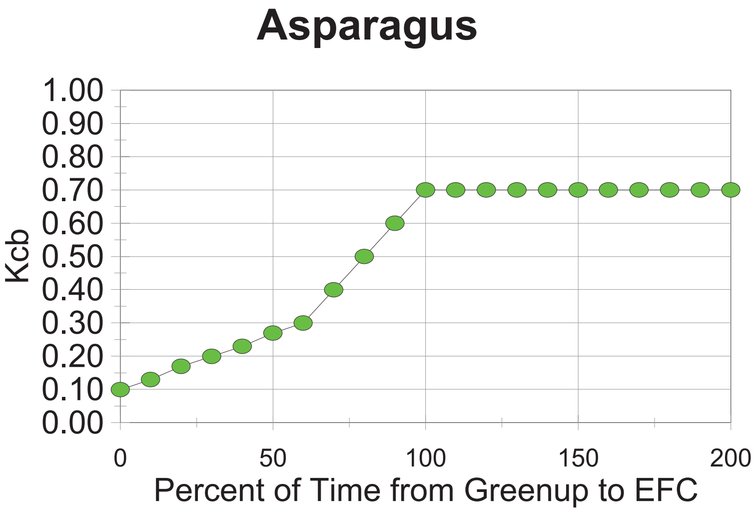
Hops. The K_{cb} curve for hops was derived from a K_{cm} curve developed by Wright (pers. comm.. 2003) for use with AgriMet. The K_{cb} values were derived by subtracting about 0.05 from K_{cm} values to convert to a basal curve. The Wright K_{cm} curve is similar to that used by AgriMet.



Apples. K_{cb} curves were developed for apples having ground cover (grass or other vegetation) and no ground cover, based on FAO-56 K_{cb} data. The general curve shape was made similar to the AgriMet apple K_{cm} curve. To apply the apple K_{cb} curve, one needs to estimate the effective full cover to occur approximately 55 days after bloom (greenup) to fit the shape of the AgriMet curve. The curves are run until frost. K_{cb} is reduced after about 175% of the time from greenup to EFC to account for leaf aging.

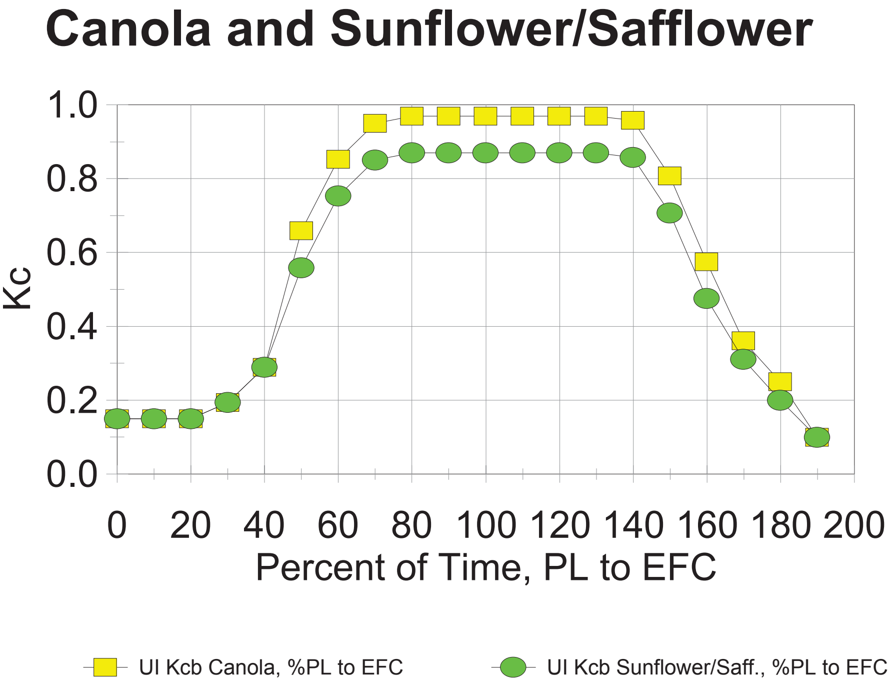


Asparagus. The asparagus K_{cb} curve shape was patterned after AgriMet. The K_{cm} values of the AgriMet K_{cm} curve were reduced by 0.3 to reflect basal K_{cb} conditions and lower values for K_c as recommended by FAO-56. The curve is run at the end value until frost.



Canola. The K_{cb} curve for canola was patterned after the AgriMet Rapeseed curve, but with 7 days added to the beginning of the curve to account for the planting to emergence period and 0.03 subtracted during the midseason. In addition, the develop before effective full cover was delayed to better fit conditions of northern Idaho. The developed K_{cb} curve was also shortened from the AgriMet curve. In northern Idaho, canola is typically planted around April 25, flowers in July and is harvested around August 1, with effective full ground cover about June 5 (Dr. Stephen Guy, UI, pers. comm.. 2006).

Sunflower/Safflower. The Sunflower/Safflower curve was developed during this study from the Canola K_{cb} curve by subtracting 0.10 during the peak period to account for generally less dense planting and ground cover for sunflower and safflower as compared to canola and for the tendency of these plants to exhibit some stomatal control under high VPD[15]. In northern Idaho, sunflower typically has a mid May to early June plant with a 120 day growing season (late September harvest after drydown) and with about 70 days from planting until EFC (Dr. Stephen Guy, UI, pers. comm.. 2006). Safflower in northern Idaho typically has a late April to mid May plant with a 110-140 day growing season (late September harvest after drydown) and with about 70 days from planting until EFC.



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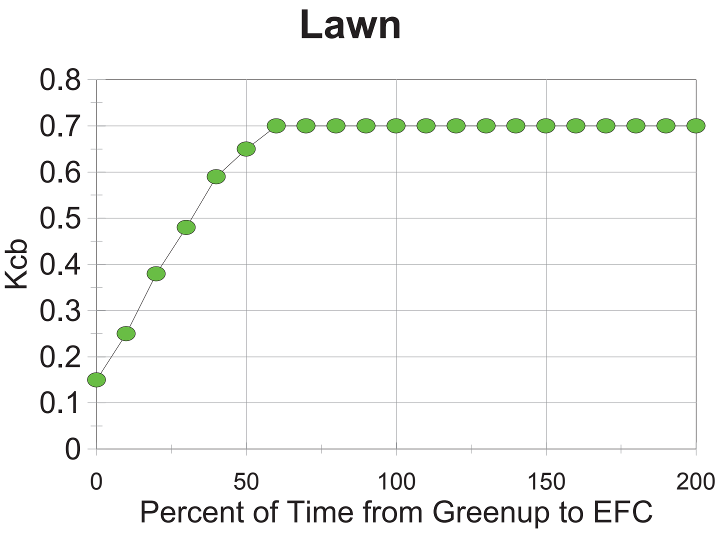
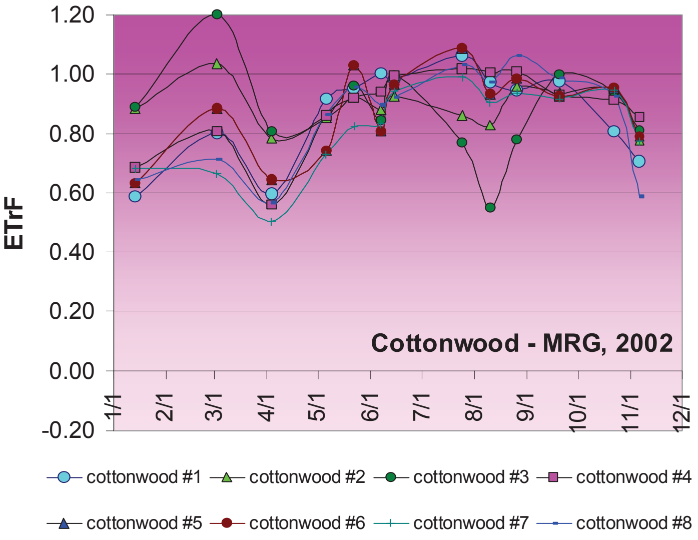
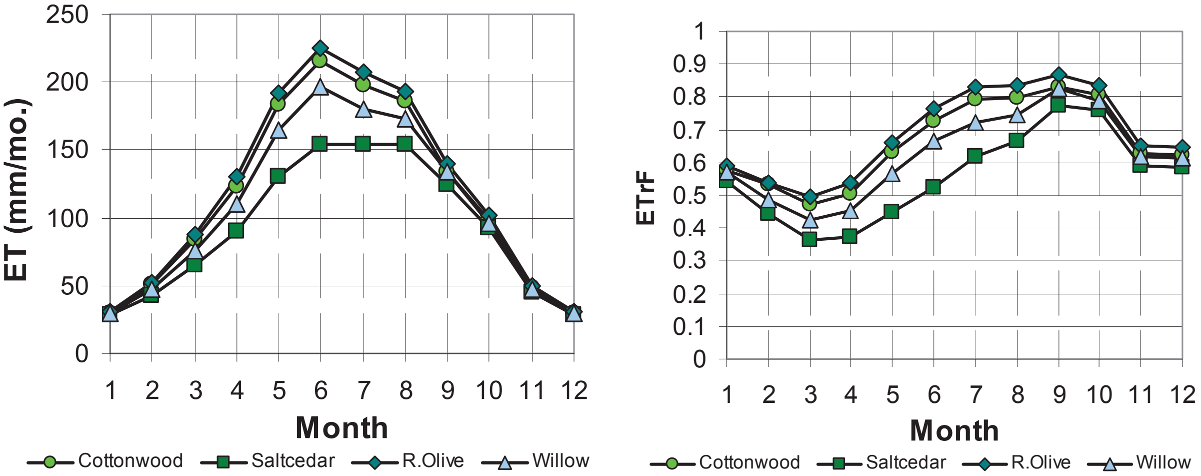
[15] Stomatal control by fed or endogenous xylem ABA in sunflower: interpretation of correlations between leaf water potential and stomatal conductance in anisohydric species. F. TARDIEU, T. LAFARGE & Th. SIMONNEAU. 1996. Plant, Cell and Environment, Volume 19 Page 75 - January 1996

Lawn. The K_{cb} curve for lawn was developed from the AgriMet turf K_{cm} curve by subtracting 0.10 during the peak period. This curve requires about 60 days time specification for the period from greenup (GU) to EFF. The curve is run until a killing frost.



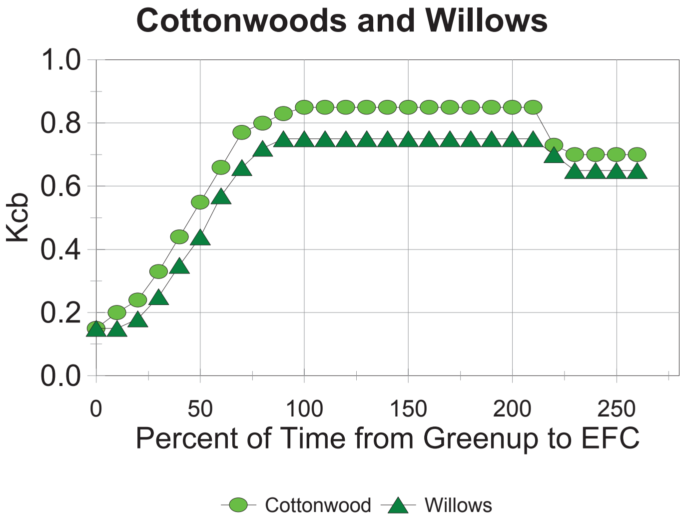
Cottonwoods. The K_{cb} curve for cottonwoods represents ET from riparian systems of cottonwood trees that generally have ready access to a shallow water table. The K_{cb} curve is based on work by Allen and Tasumi (2004) where the METRIC satellite-based ET mapping system was applied to riparian systems along the Middle Rio Grande (MRG) of central-north New Mexico. The riparian system was classified into various vegetation classifications that included cottonwoods and willows. Computed ET from these two systems were sampled by Allen and Tasumi (2004) and the results have been used to develop basic K_{cb} curves for use in Idaho. The figure to the right shows K_c (denoted as ETrF, which is an acronym for Reference ET fraction) for eight sample areas of cottonwoods along the MRG. The high ETrF (i.e., mean K_c) in late winter was caused by wet soil. Following greenup in April, the K_{cm} curves approached 1.0 for some locations during the summer and averaged about 0.95.





Figures above: Monthly ET and ET_rF (fraction of reference ET = K_{cm}) for four riparian classes integrated over a large area along the Middle Rio Grande of New Mexico (from Allen and Tasumi, 2004).

When averaged over the 10,000 acres of cottonwoods classified along the MRG, the ETrF (i.e., K_{cm}) averaged about 0.8 during midsummer. The cottonwood curve from the Allen and Tasumi (2004) work represents the average K_{cb} from a population of cottonwood that naturally includes some areas of poor or sparse stands that were included in the cottonwood classification. Therefore, the K_{cb} and ET_c for tall, dense, healthy stands of cottonwoods may exceed that shown in the above figure and for the cottonwood K_{cb} curve derived here. In that case, the user may consider using the ET_c estimates made for the poplar land-use class, which has a higher peak K_{cb}. The following K_{cb} was determined from the trends in ETrF data of Allen and Tasumi and setting peak K_{cb} to 0.85 during summer. The K_{cb} curve is run until a killing frost.



The following figure gives an indication of the amount of within-population variation that was found by Allen and Tasumi (2004) for ET determined for cottonwoods along the MRG. While a majority of the cottonwood community had substantial ET, some of the classified population had relatively low ET caused by low plant density, large depth to groundwater, etc. This caused the K_c representing the population as a whole to be lower.

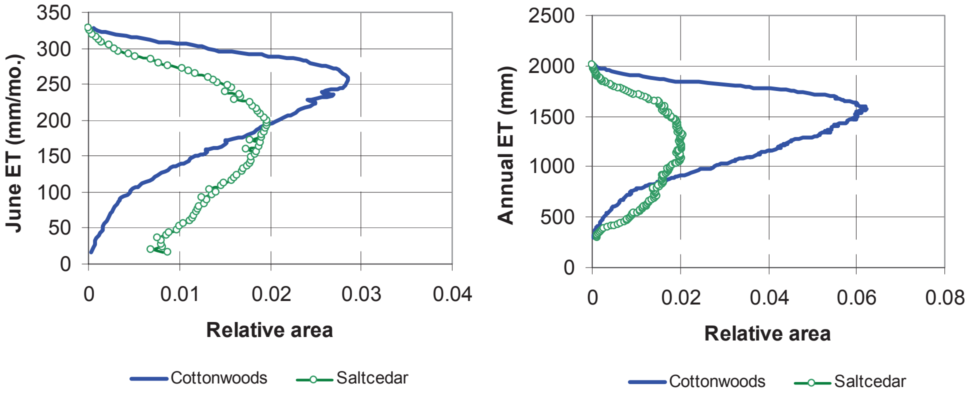


Figure: Statistical distribution of monthly ET (June, 2002) and annual ET for 2002 by relative area of cottonwood and salt cedar along the Middle Rio Grande (from Allen and Tasumi, 2004).

Willows. The development of the K_{cb} curve for willows was similar to that for cottonwoods, with the K_c data taken from the Allen and Tasumi (2004) study. The K_{cb} curve is shown above. The willows K_{cb} curve is run until a killing frost.

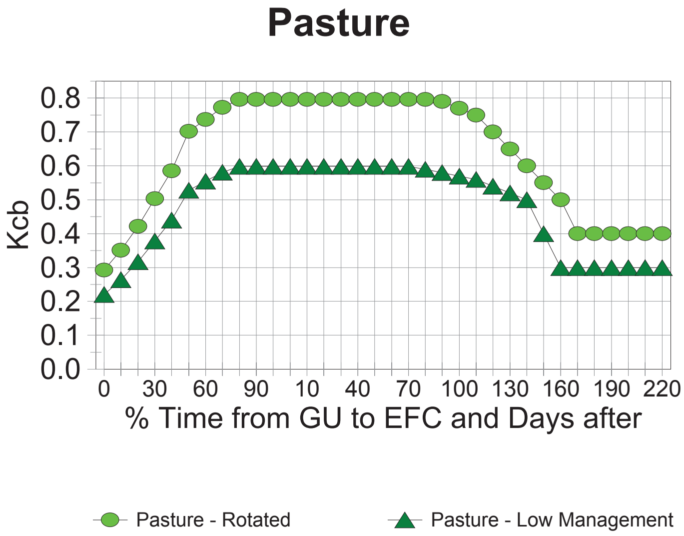
K_{cb} vs. Percent Time from Planting (or Greenup) until Effective Full Cover and days after Effective Full Cover

Table 3.7 lists K_{cb} curves for use with the Standardized ASCE-EWRI Penman-Monteith that are based on Normalized Time from Planting to Effective Full Cover until effective full cover and then as days after effective cover. This is the procedure introduced by Wright (1981, 1982). Primary data or literature sources for developed curves are listed in Table 2 of the main text. The following section describes how these curves were developed.

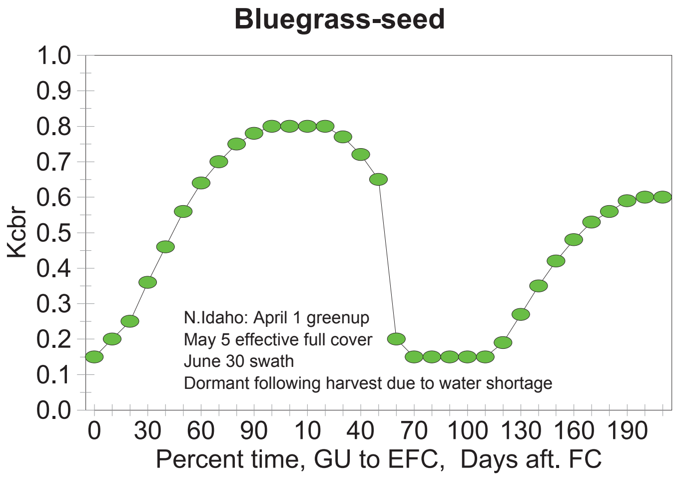
Table 3.7. Kcb for use with the Standardized ASCE-EWRI Penman-Monteith based on Normalized Time from Planting to Effective Full Cover and then days after.

Curve no.:	30	31	32	33	34	35	36
Percent Time from Plant (or Greenup) to Effective Full Cover and then Days after EFC	**Pasture Rotated**	**Pasture Low Manag.**	**Blue Grass Seed**	**Alfalfa Seed**	**Poplar**	**Wetlands-Large stand**	**Wetlands-Small Stand**
0	0.29	0.22	0.15	0.35	0.10	0.20	0.20
10	0.35	0.26	0.20	0.50	0.19	0.27	0.33
20	0.42	0.32	0.25	0.60	0.27	0.36	0.45
30	0.50	0.38	0.36	0.67	0.36	0.45	0.60
40	0.59	0.44	0.46	0.73	0.44	0.55	0.74
50	0.70	0.53	0.56	0.79	0.53	0.64	0.87
60	0.74	0.55	0.64	0.82	0.61	0.73	1.00
70	0.77	0.58	0.70	0.83	0.70	0.82	1.17
80	0.80	0.60	0.75	0.84	0.78	0.92	1.31
90	0.80	0.60	0.78	0.84	0.87	0.99	1.41
(Eff. Full Cov.)100	0.80	0.60	0.80	0.85	0.95	1.05	1.50
0	0.80	0.60	0.80	0.85	0.95	1.05	1.50
10	0.80	0.60	0.80	0.85	1.00	1.05	1.50
20	0.80	0.60	0.80	0.85	1.00	1.05	1.50
30	0.80	0.60	0.77	0.85	1.00	1.05	1.50
40	0.80	0.60	0.72	0.83	1.00	1.05	1.50
50	0.80	0.60	0.65	0.81	1.00	1.05	1.50
60	0.80	0.60	0.20	0.79	1.00	1.05	1.50
70	0.80	0.60	0.15	0.70	1.00	1.05	1.50
80	0.80	0.59	0.15	0.57	1.00	1.05	1.50
90	0.79	0.58	0.15	0.45	0.96	1.05	1.50
100	0.77	0.57	0.15	0.40	0.92	1.05	1.50
110	0.75	0.56	0.15		0.88	1.05	1.50
120	0.70	0.54	0.19		0.84	1.05	1.50
130	0.65	0.52	0.27		0.81	1.05	1.50
140	0.60	0.50	0.35		0.77	1.05	1.50
150	0.55	0.40	0.42		0.73	1.05	1.50
160	0.50	0.30	0.48		0.68	1.05	1.50
170	0.40	0.30	0.53		0.60	1.05	1.50
180	0.40	0.30	0.56		0.55	1.05	1.50
190	0.40	0.30	0.59		0.50	1.05	1.50
200	0.40	0.30	0.60		0.50	1.05	1.50
210	0.40	0.30	0.60		0.50		
220	0.40	0.30			0.50		
230	0.40	0.30					

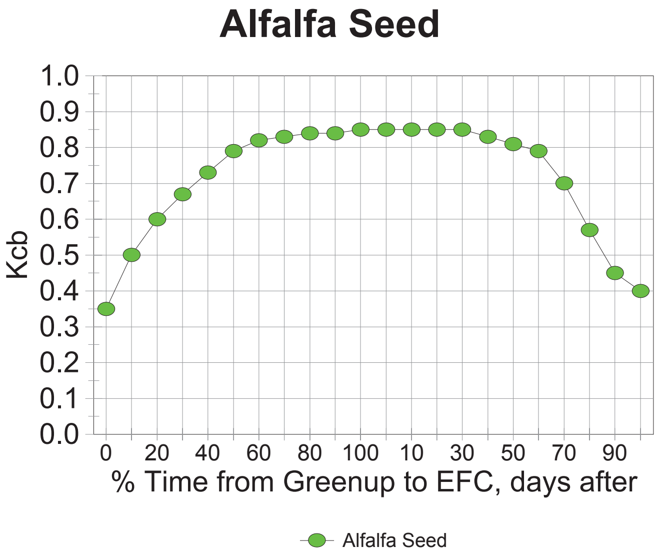
Pasture. ET has been calculated for two classes of pasture: a) pasture having high management and rotated grazing and b) pasture having relatively low management and with less vigorous growth and with sustained lower grazing height. The two curves were developed from the AgriMet K_{cm} curve for pasture by multiplying by 1.17 for the high management K_{cb} curve so that peak K_{cb} = 0.8 and by multiplying by 0.88 for the low management K_{cb} curve so that peak K_{cb} = 0.6. In addition, the AgriMet curve was converted to a percent time from GU to EFC and days after EFC so that the K_{cb} curves could be run at values of 0.4 and 0.3 respectively during fall until terminated by a killing frost.



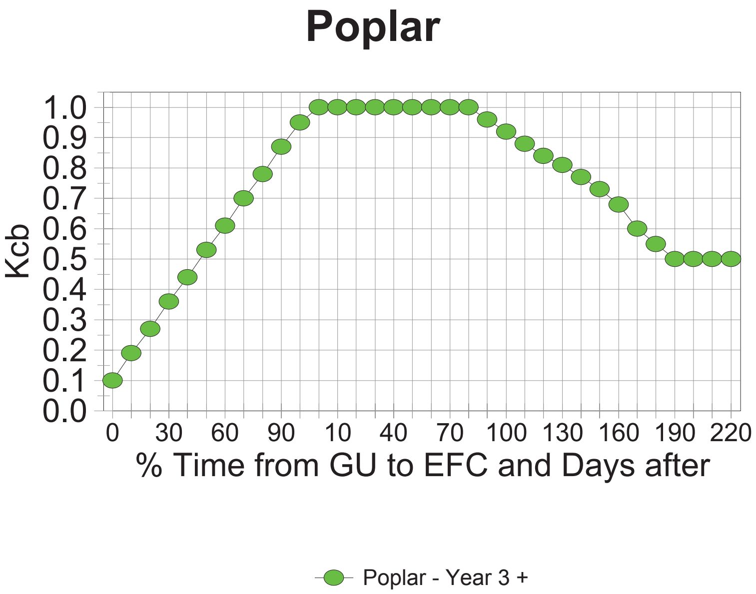
Bluegrass seed. Bluegrass grown for seed in northern Idaho has a typical greenup of April 1 and effective full cover date of around May 5, with swathing for harvest around June 30 (55 days following attainment of full cover) (Dr. Stephen Guy, UI, pers. commun., 2006). The crop is not irrigated and generally remains dormant for the rest of the growing season until rains occur during September. Burning may be applied during August and September. The K_{cb} curve was developed during this study assuming that the bluegrass will attain about 0.2-0.3 m height and will behave similar to cool season, clipped grass reference until stressed. Therefore, the maximum K_{cb} for the ET_r basis will be about 0.8.



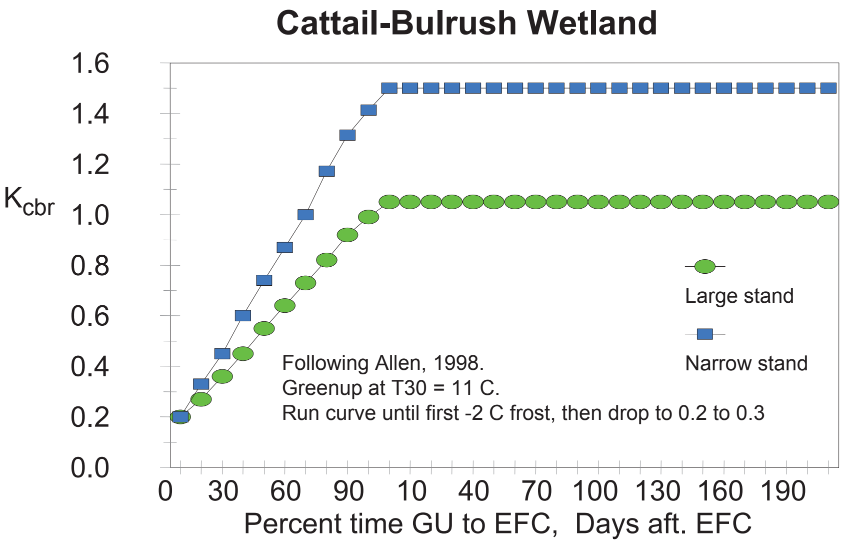
Alfalfa Seed. The alfalfa seed K_{cb} curve is the K_{cm} curve used by Allen and Brockway (1983), but with 0.05 subtracted to convert to K_{cb}.



Poplar. Poplar trees are estimated to bud out at 8°C and to reach full leafout (EFC) at 21 days. The curve was taken from the AgriMet K_{cm} curve for third year poplar, but was converted to days after EFC basis to allow it to be continued at the final value until killing frost. In addition, initial values for K_{cb} before EFC were reduced from the AgriMet K_{cm} by 0.05 to reflect ET from a dry soil surface. The curve represents stands of trees that are 5 to 10 m tall or taller.



Wetlands. The K_{cb} curve developed for wetlands is based on Allen (1998) and represents ET from cattail and bulrush systems having mostly vegetation cover (as opposed to open water). Two curves are presented representing a) large expanses of wetlands and b) narrow stands. The K_{cb} curve for narrow stands reaches a peak value of 1.5 that represents the extreme clothesline behavior of narrow stands of cattails and bulrushes that can be found along canals or in road ditches. Because of the near infinite water supply generally associated with wetlands, no stress factor is applied. Greenup is estimated to occur when $T_{30} = 11^oC$. This coincides with a May 20 date, on average, at Kimberly. The development period is assumed to last 45 days. The full cover period is run until a killing frost, which in the case of cattails is set at -2^oC, as cattails are highly susceptible to freezing. The use of -2^oC rather than 0^oC is intended to compensate for air temperature differences between the weather station and wetlands, where surrounding water tends to contribute warmth to the air. Upon freezing in fall, the K_{cb} reverts to 0.2, with fraction of cover (f_c) set to 0.4 to characterize effectiveness of dead mulch in reducing evaporation during the nongrowing season..



K_{cb} vs. Percent Time from Planting (or Greenup) until End of Season

Table 3.8 lists K_{cb} curves for use with the Standardized ASCE-EWRI Penman-Monteith that are based on Normalized Time from Planting to End of Season. Primary data or literature sources for developed curves are listed in Table 2 of the main text. The following section describes how these curves were developed.

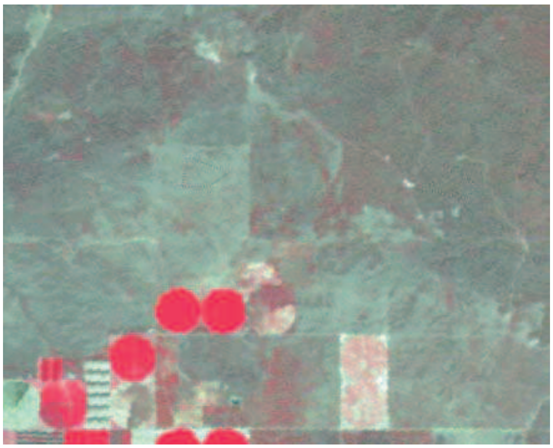
Table 3.8. Kcb curves for Desert Vegetation Expressed as a Percent time from Greenup until End of Season[1] for use with the Standardized ASCE-EWRI Penman-Monteith ET_r method.

Curve no:	37	38	39	30
Percent time from Greenup until End of Season	Sage	cheatgrass	bunch grass	bromegrass
0	0.15	0.05	0.05	0.05
10	0.03	0.30	0.20	0.40
20	0.35	0.60	0.45	0.70
30	0.35	0.60	0.55	0.80
40	0.35	0.50	0.55	0.80
50	0.33	0.15	0.55	0.77
60	0.31	0.10	0.45	0.70
70	0.30	0.08	0.30	0.55
80	0.30	0.05	0.15	0.35
90	0.28	0.05	0.05	0.20
100	0.15	0.05	0.05	0.05

[1] To apply, assume that end of season is equal to July 15 + (July 15 - Greenup) (i.e., symmetry in time around July 15). Estimate greenup from 30 day Tmean = 5 C (at end of 30 day period), less 10 days (10). Note that these K_{cbr} curves are potential Kc's and must be used with a soil water balance and stress reduction coefficient to derive actual ET. Brome is assumed to have a good water supply early for relatively dense stand development.

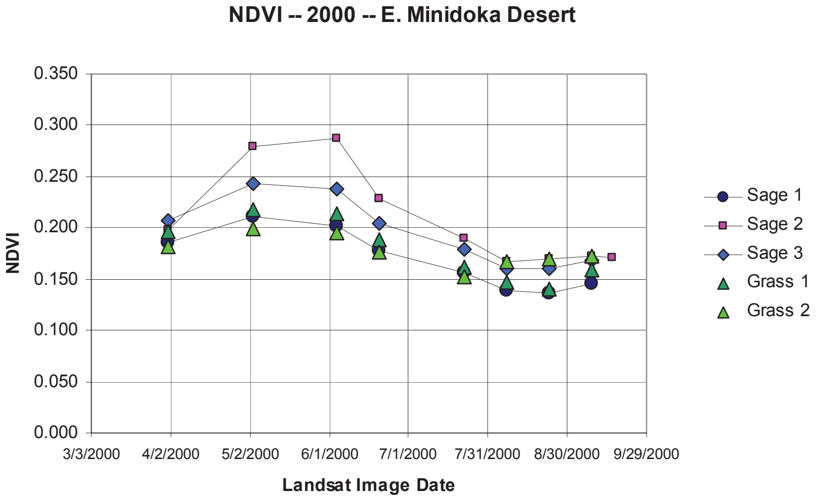
Desert Vegetation

Sagebrush. The sagebrush K_{cb} curve was developed based on K_c vs. NDVI relationships developed by Allen et al. (2006) and NDVI trends in sagebrush communities as measured by Landsat satellite system where NDVI is the normalized difference vegetation index used to indicate the presence of vegetation. NDVI typically ranges from about 0.1 to 0.15 for bare soil to about 0.85 for full ground cover by vegetation.

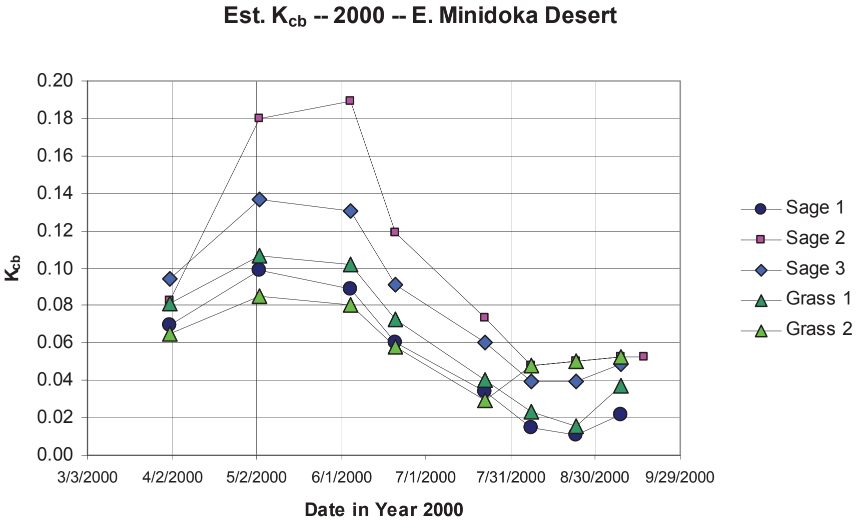


The figure to the right shows a typical Landsat image for a desert area north of Twin Falls Idaho where high NDVI areas, such as in the center pivot fields, show as bright red. Traces of sage brush systems show as light red in the desert areas.

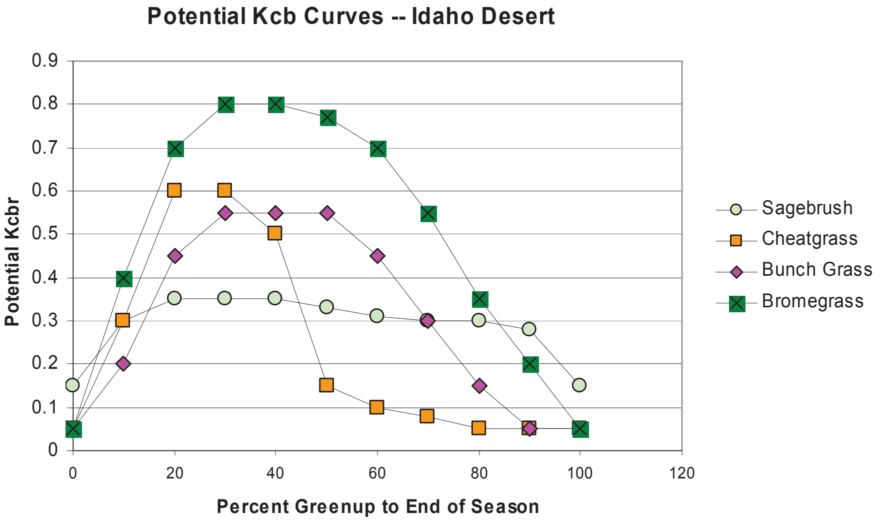
The following figure shows trends in NDVI during growing seasons in the Minidoka area of southcentral Idaho for areas of predominately sagebrush and predominately grasses. The NDVI for both systems increases during April and May when precipitation and stored soil water from winter support leaf growth. Beginning in June, lack of soil water causes a reduction in the vegetation index, reaching a low during August and into September. The sagebrush systems are still alive during late summer, but vitality of green leaves is suppressed by dryness. The grass systems are senesced or dormant by late summer.



The NDVI trends were converted into an equivalent K_{cb} trends using the relationship K_{cb} = 1.18 NDVI – 0.15. This relationship is similar to the relationship developed by Allen et al. (2006) for K_{cm} = 1.18 NDVI + 0.04 that was derived for application to agricultural vegetation, but with a lower offset to calculate K_{cb} and to adjust for desert vegetation. The K_{cb} curves for the sampled desert areas show maximum K_{cb} during May and near zero values during late summer.



Based on the above results, the ‘potential’ K_{cb} curves in Table 3.8 were created to serve as upper limits to K_{cb} for desert under greater than normal precipitation conditions. These K_{cb} values were reduced during computations in this report when soil water was too low to support the potential ET. The K_{cb} curves of Table 3.8 are reproduced in the following figure. The two desert grass curves tend toward 0.05 during late summer to reflect senescence of these grasses. Bromegrass is expected to sustain higher K_{cb} into late summer unless limited by soil water availability. None of these grasses are assumed to receive any irrigation.



In application of the K_{cb} curves for the four desert vegetation classes, the green-up in spring was estimated to occur when the 30 day average air temperature has reached 5°C, less 10 days. The 30 day Tmean = 5 C is posted on the date at end of the 30 day period. Total season length was estimated by assuming that end of season was equal to July 15 + (July 15 - Greenup) (i.e., symmetry around July 15). The seasons progressed until a killing frost or end of the K_{cb} curve. Once desert vegetation was stressed (when $K_s < 0.2$), it was assumed to become permanently dormant for the balance of the growing season. Only turf and bluegrass for seed are presumed to wake up from dormancy.

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APPENDIX 4.

QUALITY ASSESSMENT OF AGRIMET WEATHER DATA

A quality assessment analysis was conducted on the daily AgriMet weather data for the periods of record. The assessment was made to 24-hour data only. The primary assessment procedure was based on that recommended and described by ASCE-EWRI (2005).

Based on the analyses, some adjustments to solar radiation data were made. Generally the adjustments were to multiply AgriMet R_s data over an identified period by a factor determined during visual comparisons of measured R_s with a theoretical clear sky R_s curve (termed R_{so}) that was based on the ASCE-EWRI (2005) standardization work (in their Appendix D). An example of the procedure is shown in Figures 1.1 and 2.3 of Appendices 1 and 2 of this report. These adjustments tended to adequately correct for what were identified as periods of low or high measurements caused by calibration error or drift in the R_s sensors. Adjustments were mostly required during the first half of the 1990's as noted in the following Table 4.1. R_s measurements since about 1996 were typically very good.

Quality analysis of humidity data was comprised of plotting daily minimum air temperature and mean daily dewpoint temperature on the same graph vs. time and noting the correspondence between the two measurements. Reasons for close correspondence are given in Appendix 2 and an example of the plot of T_{min} and T_{dew} is given in Figure 2.2 of that appendix.

AgriMet wind, temperature and humidity data were generally found to be of very good quality, measurement wise, and few 'corrections' were required to these data. Some of the AgriMet locations exhibited some 'aridity' effects in the humidity and temperature parameter data sets, where dewpoint sometimes ran significantly below daily minimum air temperature. These sites were Glenns Ferry, Kettle Butte (expected because of the desert location), and Picabo. The Glenns Ferry site is at the upwind (west) interface of irrigated fields and desert. Therefore, ET_r and ET_c estimated from the Glenns Ferry and Kettle Butte AgriMet sites may run higher than expected for irrigated settings. The other AgriMet locations evaluated exhibited relatively good behavior between T_{dew} and T_{min} that is characteristic of well-watered (irrigated) settings.

Daily wind speed averages were plotted against time and visually screened for unexpected data patterns. Wind speeds were found to be relatively calm at Parma, Picabo, Rexburg, Fallon and Grandview. Wind speeds at Grandview were on average substantially more calm than at Glenns Ferry. Differences may be due to site exposure.

In summary, the AgriMet daily data sets represent exceptional and relatively complete records of high quality agricultural weather data, especially following adjustments to some solar radiation data as noted in the following Table 4.1. No adjustments to humidity or wind data were recommended nor made.

A plot of daily R_s is shown in Figure 4.1 for the AgriMet station near Aberdeen for the period 1992-1993 to demonstrate the impact of data adjustment. The top figure shows data prior to the adjustment, where R_s during some periods ranges from 14 to 20% below the theoretical R_{so} curve for large numbers of days at a time, when some clear sky days are expected. The bottom figure shows the data following multiplication by the simple multiplier listed in Table 4.1. Following adjustment, R_s bumps against the R_{so} curve for a number of days.

Reference to Appendix 4

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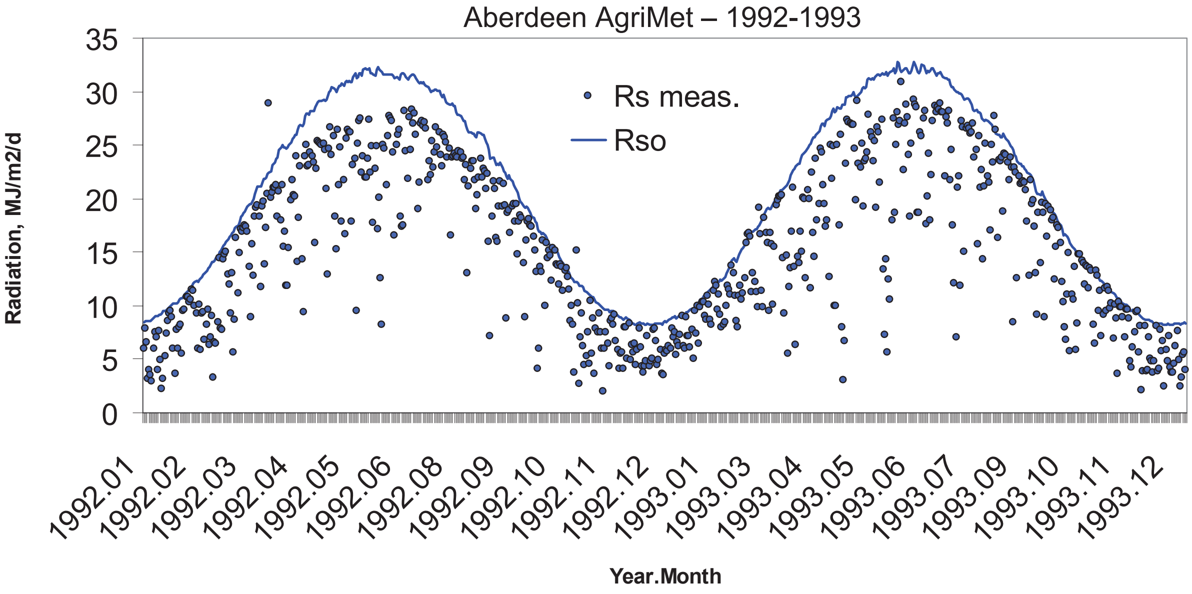


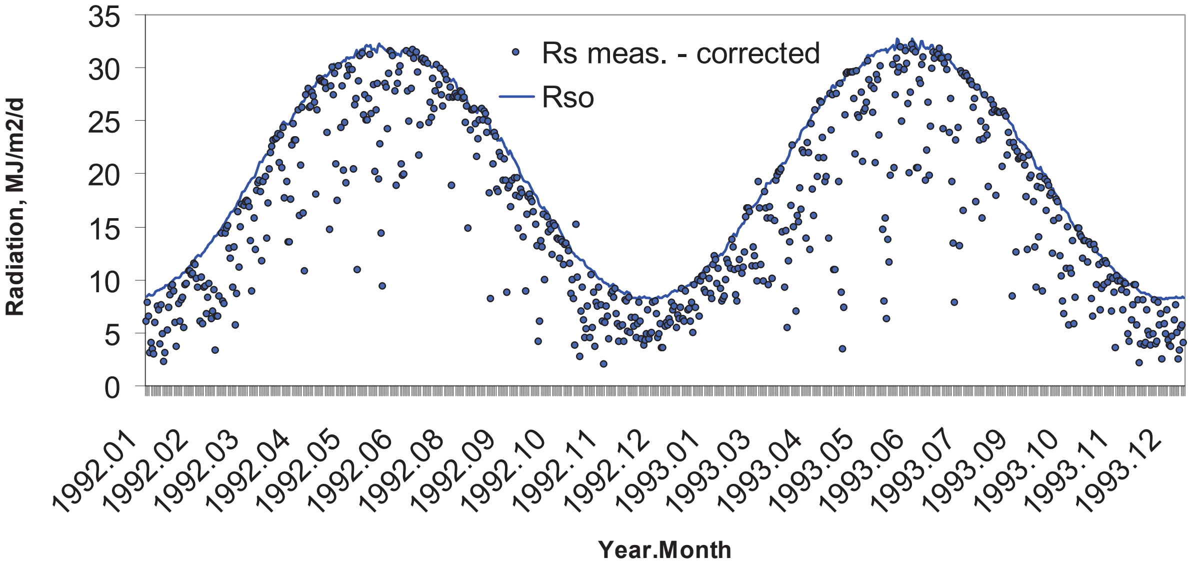


Figure 4.1. Daily measured solar radiation reported for the Aberdeen AgriMet station during 1992-1993 before adjustment (following Table 4.1) and after adjustment.

Table 4.1. Quality control assessment summary for daily AgriMet weather data in Idaho ('day' and 'DoY' represent the day of year (1-366), Rs denotes solar radiation).

Station	Correction	Comments
Aberdeen	1991: day 122 to 260, mult R_s by 1.20	R_s is 14 to 20% low during specific periods
	1992: day 90 to 250, mult R_s by 1.14	
	1993: day 90 to 240, mult R_s by 1.16	
Ashton	1990: 6/1 to 10/1, mult R_s by 1.07	R_s is 5 to 20% low during specific periods
	1991: day 100 to 290, mult R_s by 1.11	
	1992: day 1 to 300, mult R_s by 1.12	
	1993: day 100 to 250, mult R_s by 1.10	
	1994: day 100 to 250, mult R_s by 1.05	
	1997: day 215 to 365, mult R_s by 1.25	R_s is 20% low
	1998: day 1 to 180, mult R_s by 1.25	R_s is 20% low
Fairfield	1992: day 100 to 250, mult R_s by 1.08	
	1993: day 150 to 365, mult R_s by 1.08	
	1994: day 1 to 365, mult R_s by 1.15	
	1995: day 1 to 160, mult R_s by 1.15	
Fallon		During 2005 at Fallon, either the DoY is off or the R_s is low for DoY < 180 and too high for DoY > 180
Fort Hall	1993: day 1 to 365, mult R_s by 1.09	
	1994: day 1 to 365, mult R_s by 1.08	
Glenns Ferry	1993: day 1 to 365, mult R_s by 1.15	
	1994: day 1 to 365, mult R_s by 1.15	
	1995: day 1 to 365, mult R_s by 1.25	
	1996: day 1 to 365, mult R_s by 1.25	Glenns-Ferry exhibits strong aridity in the T and T_{dew} data in 1996, 1999-2005. T_{min}-T_{dew} is often > 10 deg. C.
	1997: day 1 to 120, mult R_s by 1.25	R_s is 20% low
Grandview	1993: day 1 to 365, mult R_s by 1.23	R_s is 20% low
	1994: day 1 to 365, mult R_s by 1.12	
	1995: day 1 to 365, mult R_s by 1.12	Wind is on the calm side at GV, especially relative to Glenns Ferry
	1996: day 1 to 365, mult R_s by 1.12	
	1997: day 1 to 365, mult R_s by 1.03	
Kettle Butte		R_s is OK. Some aridity in T and Tdew data during 1999-2005. Wind speeds are moderate to high.
Malta	1990: day 100 to 220, mult R_s by 1.05	
	1991: day 100 to 300, mult R_s by 1.12	
	1992: day 1 to 365, mult R_s by 1.08	Some really high wind days in all years
	1993: day 150 to 300, mult R_s by 1.08	
	1994: day 90 to 270, mult R_s by 1.08	
	1995: day 100 to 365, mult R_s by 1.08	
	1996: day 1 to 150, mult R_s by 1.08	
Monteview	2000: day 1 to 365, mult R_s by 0.94	R_s is high during this period
	2001: day 1 to 190, mult R_s by 0.94	R_s is high during this period

Nampa	1996: day 1 to 210, mult R_s by 1.45	R_s is 40% low!!!
Parma	1989: day 1 to 250, mult R_s by 1.07	
	1993: day 150 to 365, mult R_s by 1.05	
	1995: day 100 to 240, mult R_s by 1.07	
	2000: day 40 to 365, mult R_s by 0.95	R_s is high during this period
	2001: day 1 to 320, mult R_s by 0.95	R_s is high during this period
Picabo	1993: day 1 to 365, mult R_s by 1.08	
	1994: day 1 to 365, mult R_s by 1.08	
	1995: day 1 to 365, mult R_s by 1.08	Some aridity behavior during 1999-2003. Wind is quite calm, especially during winter.
	1996: day 1 to 150, mult R_s by 1.08	
Rexburg	1992: day 1 to 365, mult R_s by 1.07	
	1993: day 1 to 365, mult R_s by 1.03	Quite a few low wind days, which is somewhat surprising for Rexburg.
	2000: high outliers. Limited to R_{so}*1.03 (all years)	
Rupert	1989: day 1 to 365, mult R_s by 1.07	
	1990: day 1 to 365, mult R_s by 1.07	
	1991: day 1 to 365, mult R_s by 1.07	
	1992: day 1 to 365, mult R_s by 1.07	
	1993: day 1 to 365, mult R_s by 1.07	
	1994: day 1 to 365, mult R_s by 1.07	
	1995: day 1 to 240, mult R_s by 1.10	
	1995: day 240 to 365, mult R_s by 1.08	
	1996: day 1 to 150, mult R_s by 1.08	
	1998: day 180 to 365, mult R_s by 0.94	
	1999: day 1 to 195, mult R_s by 0.94	
Twin Falls	1990: day 1 to 240, mult R_s by 1.08	
	1991: day 50 to 250, mult R_s by 1.08	
	1992: day 50 to 270, mult R_s by 1.07	
	1993: day 140 to 250, mult R_s by 1.05	

During processing of the QC analysis, R_s ws limited to <= R_{so} *1.02 for all years at nearly all stations

R_s correction was based on visual comparisons between daily measured R_s and the theoretical clear sky R_{so} curve computed using procedures from ASCE-EWRI (2005) that varies with elevation and humidity, as described in Appendix 2 and as computed using the UI REF-ET software and as summarized in individual spreadsheets per station.

APPENDIX 5

GENERAL INFILTRATION CHARACTERISTICS AND WATER HOLDING PROPERTIES FOR WEATHER STATIONS

Soil infiltration characteristics were used during ET_c modeling to estimate surface runoff from precipitation. Soil water holding properties were used to estimate expected irrigation schedules by which to estimate evaporation losses form soil, to estimate deep perclation from root zones, and to estimate total depth of evapoation per wetting event.

The cooperative NOAA station locations were entered into a GIS system based on their reported latitude and longitude. The GIS system was used to partition the domain of the State of Idaho into areas represented by each of the climatic stations by constructing Thiessen polygons using ArcGIS 9.1. The polygons associated with each station are shown in Figure 5.2. These polygons were overlaid with soils information from the USDA STATS-GO state-wide soils coverage to determine average surface permeability characteristics and water holding capacity of the upper 36 inch for each Thiessen polygon area.

The STATS-GO (State Soil Geographic Database) is a digital soil association map, developed by the National Cooperative Soil Survey, depicting information about soil features on or near the surface for regional, multicounty, river basin, state and multistate resource planning activities. The geographic unit in the database is referred to as a mapping unit. Each mapping unit is described with one or more soil components that may have one or more layers. The various soil map units (507) from the STATS-GO database for Idaho are comprised of 2 to 20 soil components, with the various components having between 1 and 6 soil layers. Each component is attributed with its proportional extent within the mapping unit. The soil component descriptive data utilized in the land surface quantification are:

- comppct – Percentage of map unit described by soil component.
- slopel – The minimum value for the range of slopes for the component within the mapping unit (percent).
- slopeh – The maximum value for the range of slopes for the component within the mapping unit (percent).
- perml – The minimum value for the range in permeability rate for the soil layer (inches per hour).
- permh – The maximum value for the range in permeability rate for the soil layer (inches per hour).
- laydepl – Depth to the upper boundary of the soil layer (inches)
- laydeph – Depth to the lower boundary of the soil layer (inches)
- awcl – The minimum value for the range in available water capacity for the soil layer (inches/inch).
- awch – The maximum value for the range in available water capacity for the soil layer (inches/inch).

The root zone available water capacity (AWC) for the upper 36 inches of each soil component was determined by weighted averaging (by layer thickness) of minimum and maximum AWC of each layer (reported as ranges) over the first 36 inches (root zone) of the profile based on the individual layer thickness and AWC range estimates. If a layer extended below 36 inches only that portion within the 36 inch range was used. For components having soil depths less than 36 inches, only soil depth was used and a "root zone" was set to the depth available. These two estimates in inches of water were then averaged to obtain a midpoint AWC for the soil component.

Aggregation of soil characteristics for a mapping unit and climatic station area was made using 5 classes based on slope and water as shown in Table 5.1.

Table 5.1. Slope/Water Classifications

Slope Classifications – Based on midpoint of slope range in soil component.	
A	0 to 2%
B	2% to 4%
C	4% to 6%
D	Greater than 6%
W	Water

The midpoint permeability, availble water capacity, and "root zone" were weighted, based on the component's areal extent with in the soil mapping unit and climatic area. Estimated values for the weather station polygon were determined from the weighted midpoints for each of the slope classifications. Minimum and maximum values for the characterization parameters were also obtained.

Permeability estimates for the soil components within a mapping unit were based on the first layer of the soil component to represent surface characteristics that govern infiltration of water. The low and high values for the range of permeabilities were averaged together to obtain a midpoint permeability estimate in inches per hour. State wide, the average minimum thickness of surface soil layers ranged between 2 and 8 inches with an average maximum thickness between 11 and 53 inches. The overall first layer average thickness for the climatic station areas ranged between 6 and 21 inches.

During post-processing, these values were multiplied by 0.85 to account for the logarithmic nature of the NRCS style of permeability ranges, which are:

USDA-NRCS Permeability ranges in inches/hour
0.00 - 0.06
0.06 - 0.20
0.20 - 0.60
0.60 – 2.00
2.00 - 6.00
6.00 - 20.0
> 20.0

The NRCS permeabilities are intended to represent long-term hydraulic conductivity under a unit hydraulic gradient. The majority (67%) of the more than 4000 soil groupings had permabilities in the 0.60 to 2.00 inch/hour range, which is a common, but broad range.

The permeability values were used to assign a 'Hydrologic Group' class to the weather station for use in estimating precipitation runoff with the USDA-NRCS curve number method. The three primary hydrologic groups, A (coarse soils), B (medium textured soils) and C (fine-textured soils), were assigned to the permeability ranges as follows:

Hydrologic Group A - 0 to 1 inch per hour

Hydrologic Group B – 1 to 4 inch per hour

Hydrologic Group C - > 4 inch per hour

This assignment was made based on familiarity with southern Idaho soils, since the averages of the permeability ranges are only approximate numbers and the relative values may not have direct physical meaning.

During aggregation over the four slope classes, most weighted averages were based on slopes < 6% to represent those areas most likely to be associated with irrigated agriculture. For a few stations in mountain valleys, the vast majority of soils were classed in the > 6% slope category, so that this category was included in the averaging.

Results of average water holding capacities and permeabilities are shown in Figure 5.4 for the NWS and AgriMet weather locations. Hydrologic Group assignments are summarized in Table 5.2 for NWS weather locations and in Table 5.3 for AgriMet stations as are general irrigated condition and aridity ratings.

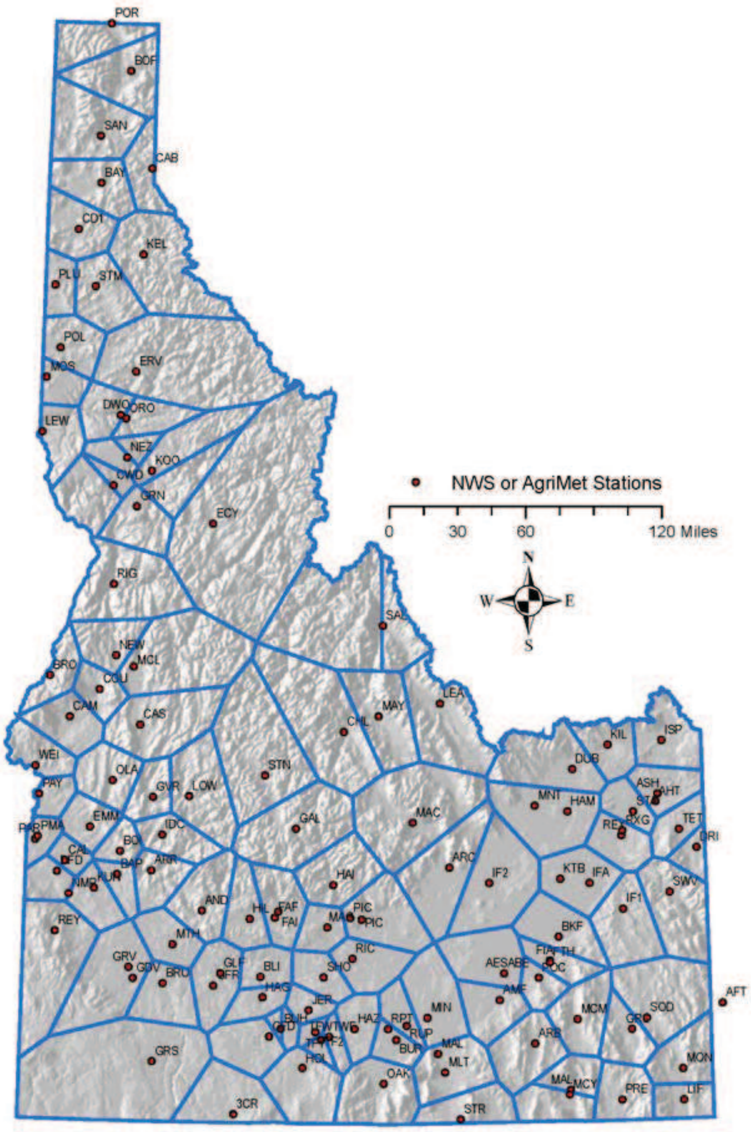


Figure 5.1. Thiessen-type polygons drawn around each NWS weather station used for developing mean characteristics for soil permeability and available water holding capacity. AgriMet stations utilized the polygon for the nearest NWS station.

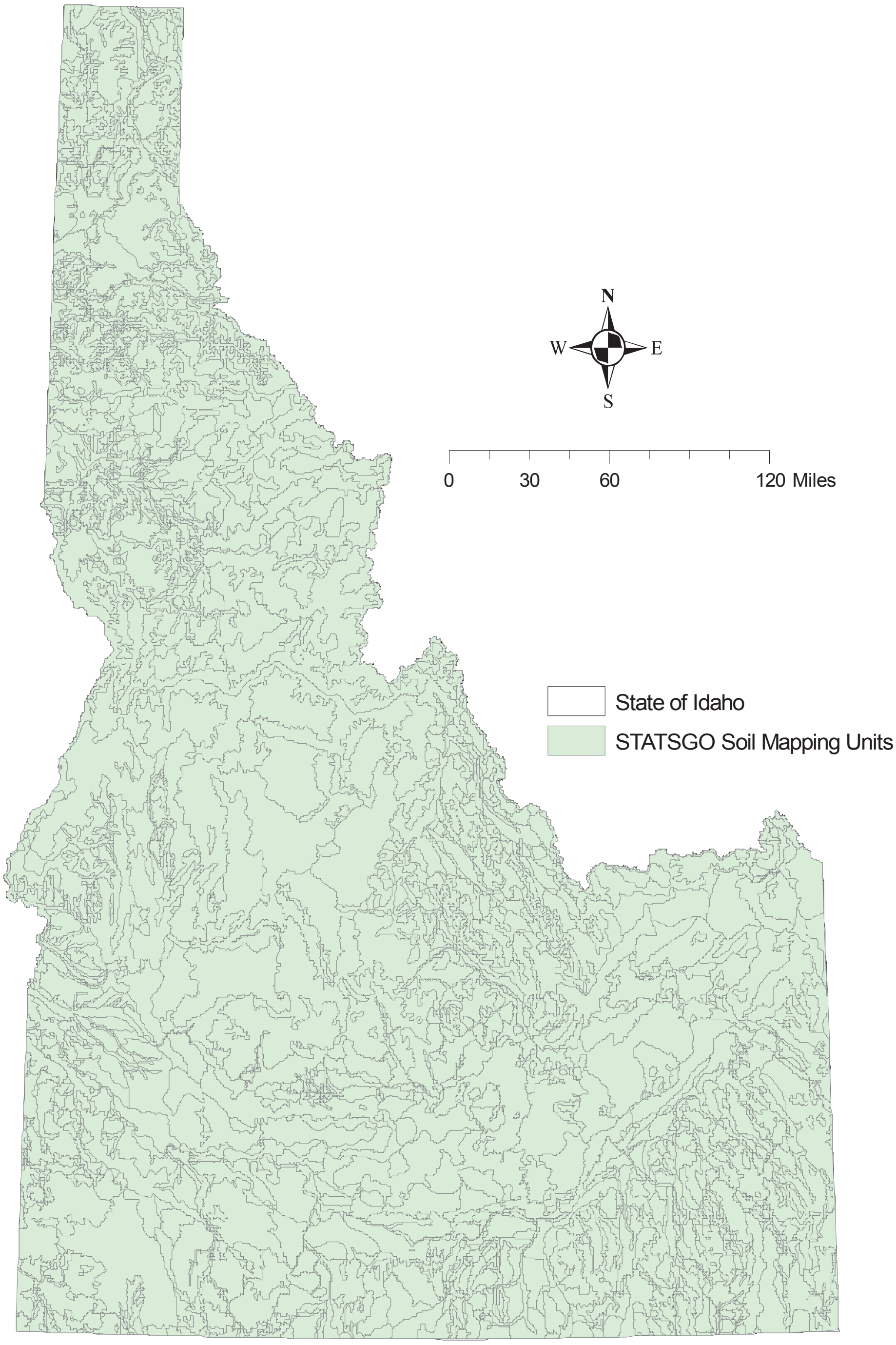


Figure 5.2. Original StatsGo soil mapping unit distributions across Idaho.

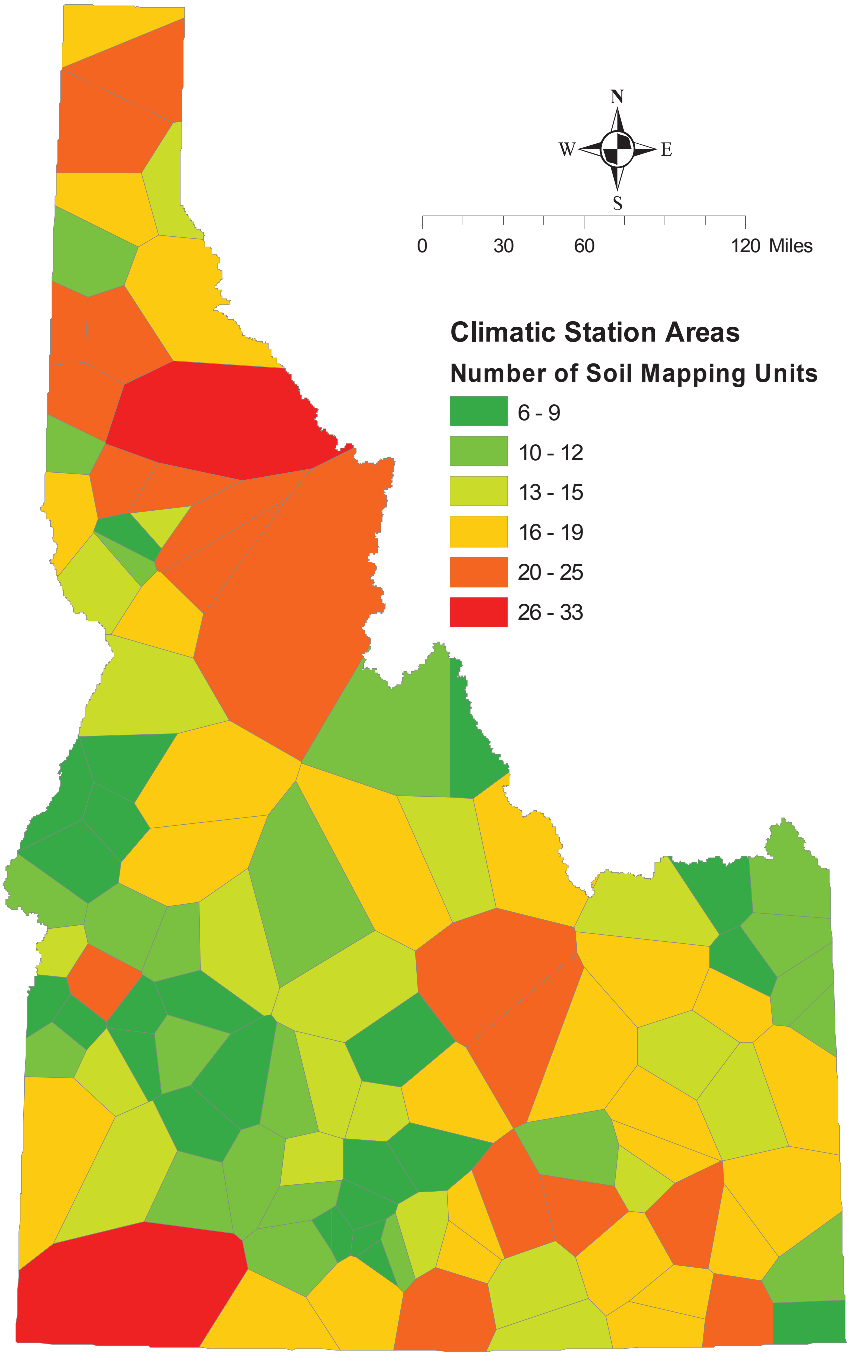


Figure 5.3. Thiessen-type polygons drawn around each NWS weather station showing the number of StatsGo soil mapping units contained within the polygon.

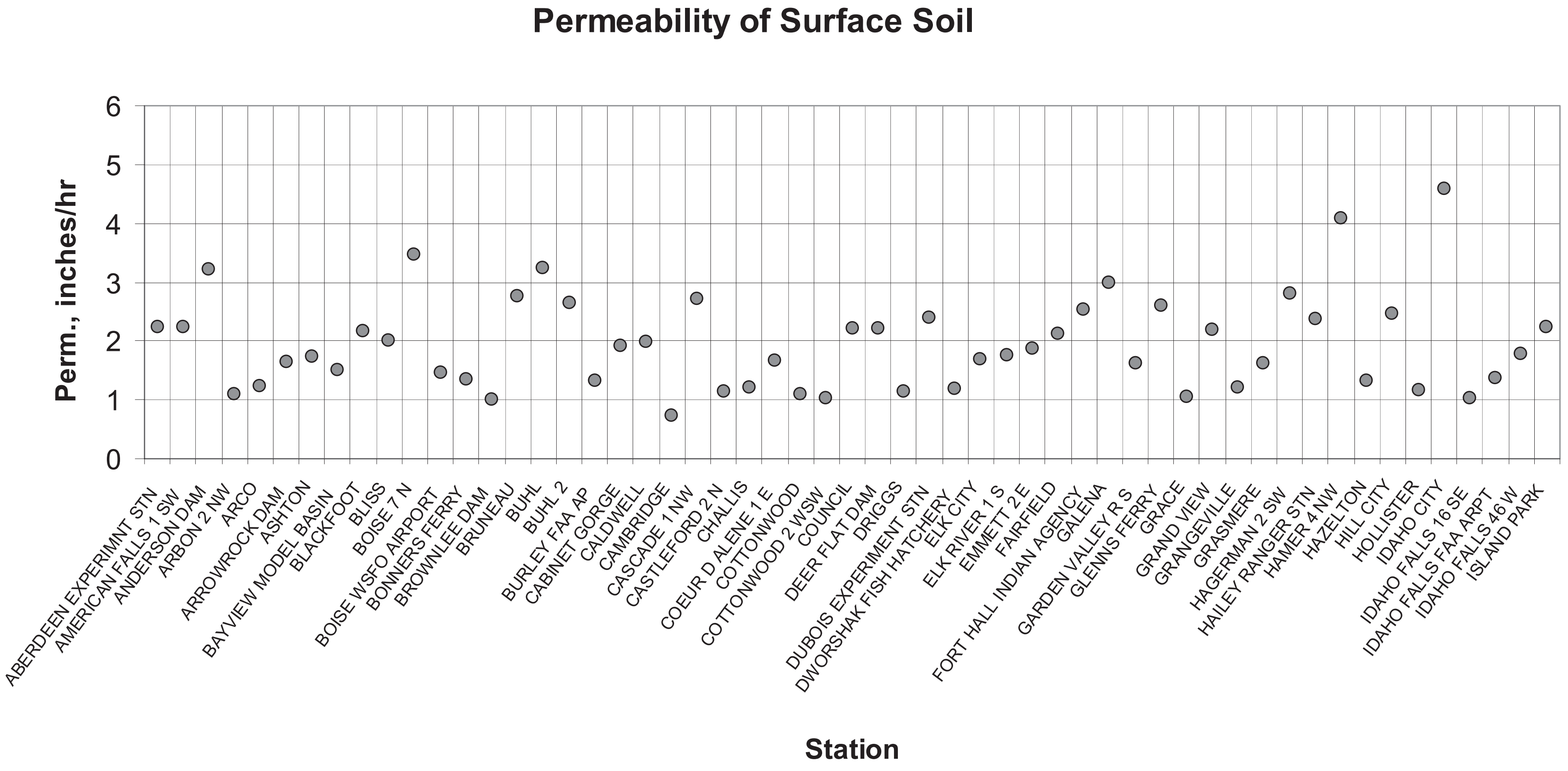


Figure 5.4a. Mean weighted permeabilities of surface soil layers for agricultural areas surrounding weather stations for land slopes less than 6%.

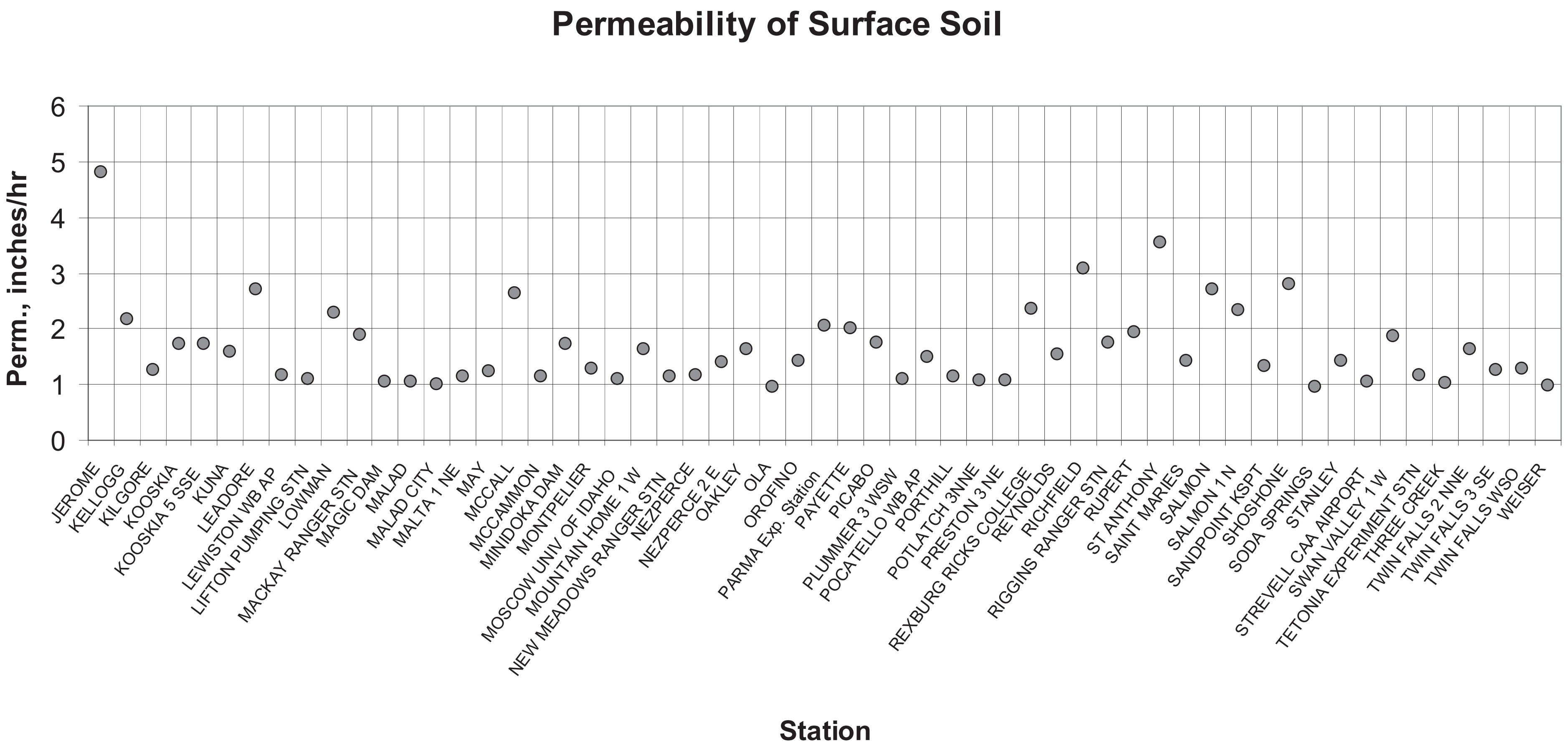


Figure 5.4b. Mean weighted permeabilities of surface soil layers for agricultural areas surrounding weather stations for land slopes less than 6%.

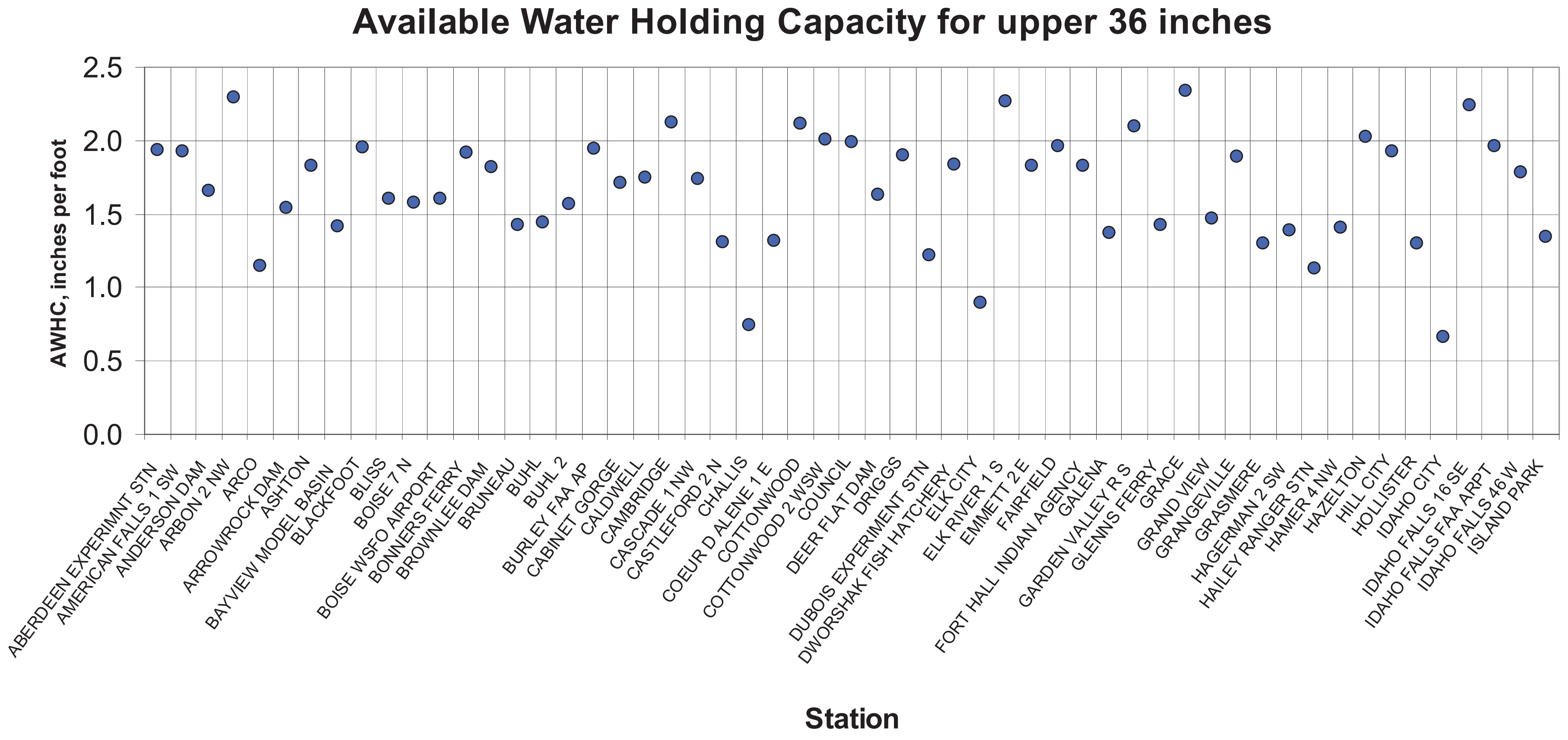


Figure 5.5a. Mean weighted available water holding capacities for soil profiles for agricultural areas surrounding weather stations for land slopes less than 6%.

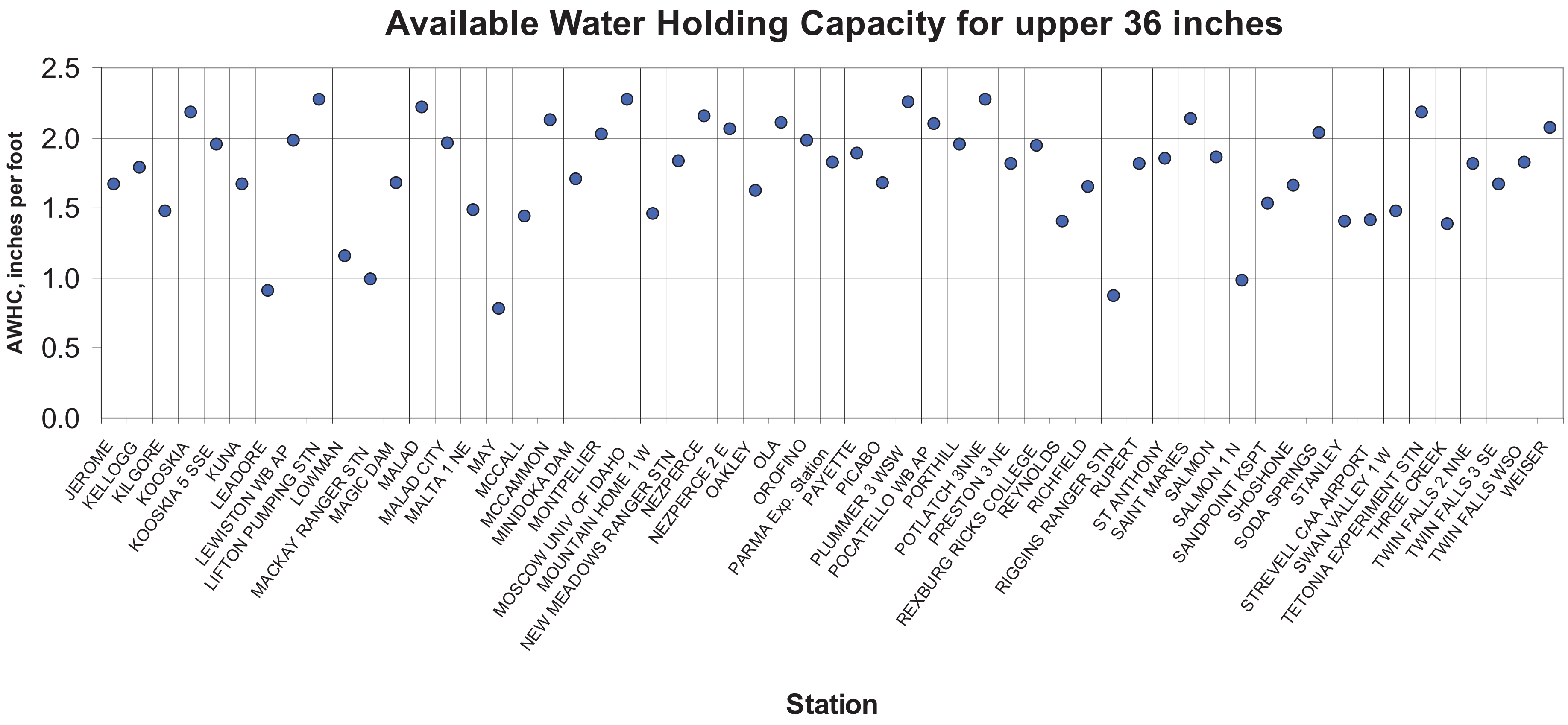


Figure 5.5a. Mean weighted available water holding capacities for soil profiles for agricultural areas surrounding weather stations for land slopes less than 6%.

In the application of the daily water balance model that includes simulation of evaporation from the upper 0.10 to 0.15 m surface layer of the soil, the REW (readily evaporable water) and TEW (total evaporable water) terms, described in Annex I are estimated from the Available Water Holding Capacity (AW) values as:

$$REW = 0.8 + 54.4\frac{AW}{1000} \tag{5.1}$$

where REW is in mm and AW is in mm/m and

$$TEW = -3.7 + 166\frac{AW}{1000} \tag{5.2}$$

where TEW is in mm and AW is in mm/m. The estimate for REW is limited to less than or equal to 0.8 TEW during the growing season and 0.7 TEW during winter periods having low ET. These equations were based on trends in values of REW and TEW vs. values for AW presented in Table 1 of the ASCE-EWRI (2005) paper listed in Annex 1.

Reference to Appendix 5

State Soil Geographic (STATSG0) Data Base Data use information. United States Department of Agriculture Natural Resources Conservation Service, National Soil Survey Center. Miscellaneous Publication Number 1492. Issued August 1991, Slightly revised May 1993, Revised December 1994. Converted to .PDF September 1995

Table 5.2. Permeability, water holding capacity, irrigation and aridity rating characteristics for Idaho NWS Temperature/Precipitation Stations.

Internal ET Sta. no.	Heritage Flag*	NOAA Station Name	NCDC Coop no.	Irrig. Flag 1= yes	Aridity Rating (0-100)	Area wtd. ave. Perm. – in/hr	Area wtd. ave. WHC – in/ft	Hydrologic Soil Group (1-3)	Aridity Rating (0-100)
1	1	ABERDEEN EXP. STN	100010	1	45	2.63	1.93	2	45
2	1	AMERICAN FALLS 1 SW	100227	1	60	2.62	1.93	2	60
3	1	ANDERSON DAM	100282	1	65	3.78	1.66	2	65
4	1	ARBON 2 NW	100347	1	45	1.30	2.29	2	45
5	1	ARCO	100375	1	55	1.46	1.15	2	55
6	2	ARROWROCK DAM	100448	1	100	1.94	1.54	2	100
7	1	ASHTON	100470	1	30	2.05	1.83	2	30
8	1	BAYVIEW MODEL BASIN	100667		20	1.77	1.42	2	20
9	1	BLACKFOOT	100915	1	40	2.55	1.96	2	40
10	1	BLISS	101002	1	35	2.36	1.61	2	35
11	2	BOISE 7 N	101017	1	70	4.09	1.57	1	70
12	1	BOISE WSFO AIRPORT	101022	1	75	1.72	1.60	2	75
13	1	BONNERS FERRY	101079	1	25	1.58	1.92	2	25
14	2	BROWNLEE DAM	101180	1	100	1.17	1.82	2	100
15	1	BRUNEAU	101195	1	40	3.24	1.43	2	40
16	2	BUHL	101217	1	60	3.80	1.44	2	60
17	1	BURLEY FAA AP	101303	1	40	1.55	1.94	2	40
18	1	CABINET GORGE	101363		35	2.26	1.71	2	35
19	1	CALDWELL	101380	1	35	2.33	1.75	2	35
20	1	CAMBRIDGE	101408	1	30	0.86	2.12	3	30
21	1	CASCADE 1 NW	101514	1	35	3.20	1.74	2	35
22	1	CASTLEFORD 2 N	101551	1	20	1.35	1.31	2	20
23	1	CHALLIS	101663	1	60	1.43	0.74	2	60
24	1	COEUR D ALENE 1 E	101956	1	45	1.96	1.32	2	45
25	1	COTTONWOOD	102154		20	1.28	2.11	2	20
26	1	COUNCIL	102187	1	45	2.61	1.99	2	45
27	1	DEER FLAT DAM	102444	1	5	2.61	1.63	2	5
28	1	DRIGGS	102676	1	25	1.33	1.90	2	25
29	1	DUBOIS EXPERIMENT STN	102707	1	90	2.81	1.21	2	90
30	2	DWORSHAK FISH HATCHERY	102845		10	1.39	1.84	2	10
31	2	ELK CITY	102875		20	1.98	0.89	2	20
32	2	ELK RIVER 1 S	102892		10	2.06	2.27	2	10
33	1	EMMETT 2 E	102942	1	20	2.19	1.82	2	20
34	1	FAIRFIELD	103108	1	15	2.49	1.96	2	15

*Heritage Flag = 1 if station was included in Allen and Brockway (1983); Flag = 2 indicates a "new" station
Irrigation Flag = 1 indicates that managed agricultural crops are typically irrigated.
Aridity Rating (0 – 100%) is from Allen and Brockway (1983), and is used to adjust air temperature prior to calculating cumulative growing degree days and 30-day running average air temperature (0% indicates well-watered condition in vicinity and area of weather station and 100% indicates dry, arid (natural) condition in vicinity and area of weather station). (Air temperature was not adjusted during calculation of reference ET_r).
Hydrologic Soil Group: 1 = course soil, 2 = medium textured soil, 3 = fine textured soil.

Table 5.2, continued. Permeability, water holding capacity, irrigation and aridity rating characteristics for Idaho NWS Temperature/Precipitation Stations.

Internal ET Sta. no.	Heritage Flag*	NOAA Station Name	NCDC Coop no.	Irrig. Flag 1= yes	Aridity Rating (0-100)	Area wtd. ave. Perm. – in/hr	Area wtd. ave. WHC – in/ft	Hydrologic Soil Group (1-3)	Aridity Rating (0-100)
35	1	FORT HALL INDIAN AGENCY	103297	1	30	2.97	1.83	2	30
36	2	GALENA	103417		20	3.52	1.37	2	20
37	1	GARDEN VALLEY R S	103448	1	65	1.90	2.10	2	65
38	1	GLENNS FERRY	103631	1	60	3.05	1.42	2	60
39	1	GRACE	103732	1	25	1.24	2.34	2	25
40	1	GRAND VIEW	103760	1	35	2.57	1.47	2	35
41	1	GRANGEVILLE	103771		45	1.43	1.89	2	45
42	2	GRASMERE	103809	1	40	1.92	1.30	2	40
43	2	HAGERMAN 2 SW	103932	1	50	3.31	1.38	2	50
44	1	HAILEY RANGER STN	103942	1	70	2.80	1.13	2	70
45	1	HAMER 4 NW	103964	1	60	4.81	1.40	1	60
46	1	HAZELTON	104140	1	65	1.56	2.02	2	65
47	1	HILL CITY	104268	1	30	2.89	1.92	2	30
48	1	HOLLISTER	104295	1	70	1.38	1.30	2	70
49	1	IDAHO CITY	104442		25	5.40	0.67	1	25
50	1	IDAHO FALLS 16 SE	104456	1	35	1.20	2.24	2	35
51	1	IDAHO FALLS FAA ARPT	104457	1	75	1.62	1.96	2	75
52	1	IDAHO FALLS 46 W	104460	1	100	2.09	1.78	2	100
53	1	ISLAND PARK	104598		30	2.62	1.34	2	30
54	1	JEROME	104670	1	65	5.66	1.66	1	65
55	1	KELLOGG	104831		45	2.55	1.79	2	45
56	1	KILGORE	104908	1	20	1.48	1.48	2	20
57	2	KOOSKIA	105011		30	2.02	2.18	2	30
58	1	KUNA	105038	1	0	1.86	1.66	2	0
59	2	LEADORE 2	105177	1	50	3.18	0.90	2	50
60	1	LEWISTON WB AP	105241	1	55	1.38	1.98	2	55
61	1	LIFTON PUMPING STN	105275	1	25	1.28	2.27	2	25
62	2	LOWMAN	105414		40	2.68	1.15	2	40
63	1	MACKAY RANGER STN	105462	1	40	2.22	0.99	2	40
64	2	MAGIC DAM	105510	1	100	1.22	1.68	2	100
65	1	MALAD	105544	1	40	1.24	2.21	2	40
66	2	MALAD CITY	105559	1	45	1.18	1.96	2	45
67	1	MALTA 1 NE	105563	1	15	1.35	1.48	2	15
68	1	MAY	105685	1	45	1.46	0.78	2	45

*Heritage Flag = 1 if station was included in Allen and Brockway (1983); Flag = 2 indicates a "new" station
Irrigation Flag = 1 indicates that managed agricultural crops are typically irrigated.
Aridity Rating (0 – 100%) is from Allen and Brockway (1983), and is used to adjust air temperature prior to calculating cumulative growing degree days and 30-day running average air temperature (0% indicates well-watered condition in vicinity and area of weather station and 100% indicates dry, arid (natural) condition in vicinity and area of weather station). (Air temperature was not adjusted during calculation of reference ET_r).
Hydrologic Soil Group: 1 = course soil, 2 = medium textured soil, 3 = fine textured soil.

Table 5.2, continued. Permeability, water holding capacity, irrigation and aridity rating characteristics for Idaho NWS Temperature/Precipitation Stations.

Internal ET Sta. no.	Heritage Flag*	NOAA Station Name	NCDC Coop no.	Irrig. Flag 1= yes	Aridity Rating (0-100)	Area wtd. ave. Perm. – in/hr	Area wtd. ave. WHC – in/ft	Hydrologic Soil Group (1-3)	Aridity Rating (0-100)
69	1	MCCALL	105708	1	45	3.09	1.44	2	45
70	2	MCCAMMON	105716	1	35	1.35	2.12	2	35
71	1	MINIDOKA DAM	105980	1	60	2.03	1.71	2	60
72	1	MONTPELIER	106053	1	45	1.52	2.02	2	45
73	1	MOSCOW UNIV OF IDAHO	106152		15	1.29	2.27	2	15
74	1	MOUNTAIN HOME 1 W	106174	1	75	1.93	1.46	2	75
75	1	NEW MEADOWS RNG. STN	106388	1	20	1.35	1.83	2	20
76	1	NEZPERCE	106421		15	1.38	2.15	2	15
77	1	OAKLEY	106542	1	35	1.93	1.62	2	35
78	1	OLA	106586	1	35	1.12	2.11	2	35
79	1	OROFINO	106681		30	1.66	1.98	2	30
80	1	PARMA Exp. Station	106844	1	10	2.41	1.83	2	10
81	1	PAYETTE	106891	1	15	2.37	1.89	2	15
82	1	PICABO	107040	1	20	2.05	1.68	2	20
83	2	PLUMMER 3 WSW	107188		30	1.29	2.26	2	30
84	1	POCATELLO WB AP	107211	1	90	1.75	2.10	2	90
85	1	PORTHILL	107264		45	1.33	1.95	2	45
86	1	POTLATCH 3NNE	107301		10	1.27	2.27	2	10
87	1	PRESTON 3 NE	107346	1	40	1.26	1.81	2	40
88	2	REXBURG RICKS COLLEGE	107644	1	30	2.78	1.95	2	30
89	1	REYNOLDS	107648	1	90	1.82	1.40	2	90
90	1	RICHFIELD	107673	1	35	3.62	1.65	2	35
91	1	RIGGINS RANGER STN	107706	1	70	2.06	0.87	2	70
92	1	RUPERT	107968	1	50	2.29	1.82	2	50
93	1	ST ANTHONY	108022	1	55	4.18	1.85	1	55
94	1	SAINT MARIES	108062		40	1.68	2.13	2	40
95	1	SALMON	108076	1	80	3.20	1.86	2	80
96	1	SANDPOINT KSPT	108137		30	1.58	1.53	2	30
97	1	SHOSHONE	108380	1	75	3.30	1.66	2	75
98	2	SODA SPRINGS	108535	1	20	1.12	2.03	2	20
99	1	STANLEY	108676	1	60	1.68	1.40	2	60
100	1	STREVELL CAA AIRPORT	108786	1	45	1.24	1.41	2	45
101	1	SWAN VALLEY 1 W	108937	1	30	2.19	1.47	2	30
102	1	TETONIA EXPERIMENT STN	109065	1	10	1.38	2.18	2	10
103	1	THREE CREEK	109119	1	80	1.20	1.38	2	80
104	1	TWIN FALLS 2 NNE	109294	1	55	1.92	1.81	2	55
105	2	TWIN FALLS 3 SE	109299	1	35	1.50	1.67	2	35
106	1	TWIN FALLS WSO	109303	1	0	1.50	1.83	2	0
107	1	WEISER	109638	1	20	1.17	2.07	2	20

*Heritage Flag = 1 if station was included in Allen and Brockway (1983); Flag = 2 indicates a "new" station
Irrigation Flag = 1 indicates that managed agricultural crops are typically irrigated.

Table 5.3. Permeability, water holding capacity, irrigation and aridity rating characteristics for AgriMet agricultural weather stations in Idaho or nearby.

Internal ET Sta. no.	Internal AgriMet Sta. no.	AgriMet Station Location	Irrig. Flag 1= yes	Area wtd. ave. Perm. – in/hr	Area wtd. ave. WHC – in/ft	Hydrologic Soil Group (1-3)	Aridity Rating (0-100)
108	1	Aberdeen	1	2.63	1.93	2	40
109	2	Ashton	1	2.05	1.83	2	20
110	3	Fairfield	1	2.05	1.68	2	20
111	4	Glenns Ferry	1	3.05	1.42	2	50
112	5	Grand View	1	2.57	1.47	2	50
113	6	Malta	1	1.35	1.48	2	20
114	7	Monteview	1	2.78	1.95	2	10
115	8	Nampa	1	1.72	1.60	2	0
116	9	Parma	1	2.41	1.83	2	10
117	10	Picabo	1	2.05	1.68	2	30
118	11	Rexburg	1	2.78	1.95	2	5
119	12	Rupert	1	2.29	1.82	2	0
120	13	Twin Falls	1	1.50	1.83	2	0
121	14	Afton, WY	1	1.28	2.27	2	5
122	15	Fort Hall	1	2.97	1.83	2	0
123	16	Kettle Butte	1	2.09	1.78	2	50

Irrigation Flag = 1 indicates that managed agricultural crops are typically irrigated.
Aridity Rating (0 – 100%) is from Allen and Brockway (1983), and is used to adjust air temperature prior to calculating cumulative growing degree days and 30-day running average air temperature (0% indicates well-watered condition in vicinity and area of weather station and 100% indicates dry, arid (natural) condition in vicinity and area of weather station). (Air temperature was not adjusted during calculation of reference ET_r).
Hydrologic Soil Group: 1 = course soil, 2 = medium textured soil, 3 = fine textured soil.

APPENDIX 6.

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 can be estimated using the USDA-NRCS Curve Number approach. The NRCS curve number is simple to apply and is widely used within the hydrologic, soils and water resources communities. Required data are daily precipitation depth and computation of a daily soil water balance by which to select the antecedent soil water condition.

The NRCS Curve Number

The curve number (CN) represents the relative imperviousness of a soil-vegetation complex and ranges from 0 for infinite perviousness and infiltration to 100 for complete imperviousness and total runoff (beyond abstraction). Generally the value for CN is selected from standard tables based on general crop and soil type and is adjusted for the soil water content prior to the wetting event. Values for CN for various crop and soil combinations are given in Table 6.1. Parameter S in the CN procedure is the maximum depth of water that can be retained as infiltration and canopy interception during a single precipitation event [mm]. S is calculated as:

$$S = 250\left(\frac{100}{CN} - 1\right) \tag{6.1}$$

and surface runoff is then calculated for P > 0.2 S as:

$$RO = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{6.2}$$

where RO is the depth of surface runoff during the event [mm], and P is the depth of rainfall during the event [mm]. The 0.2S term is abstracted precipitation, i.e., that intercepted by canopy and soil surface before any runoff occurs. If $P \le 0.2$ S, then RO = 0.0. In addition, $RO \le P$ applies.

The curve number is affected by the soil water content prior to the rainfall event, since soil water content affects the soil infiltration rate. Therefore, the CN is adjusted according to estimated soil water content prior to the rainfall event. This soil water content is termed the "antecedent soil water condition" or AWC. Adjustment ranges for CN were defined by USDA-SCS (1972) for dry (AWC I) and wet (AWC III) conditions. USDA-SCS defined AWC I as occurring when "watershed soils are dry enough for satisfactory plowing or cultivation to take place." and AWC III as when the "watershed is practically saturated from antecedent rains." (National Engineering Handbook, Section 4 Hydrology, 1972, p. 4.10). AWC II is defined as the "average condition" and represents values in Table 6.1.

Table 6.1. Typical curve numbers for general crops for antecedent soil water condition (AWC) II from SCS (1972) and Allen (1988).

	Soil Texture		
Crop	Coarse	Medium	Fine
Spring Wheat	63	75	85
Winter Wheat	65	75	85
Field Corn	67	75	85
Potatoes	70	76	88
Sugar Beets	67	74	86
Peas	63	70	82
Dry Edible Beans	67	75	85
Sorghum	67	73	82
Cotton	67	75	83
Paddy Rice	50	60	70
Sugar Cane-Virgin	60	69	75
Sugar Cane-Ratoon	60	68	76
Fruit Trees-Bare Soil	65	72	82
Fruit Trees-Grnd. Cov.	60	68	70
Small Garden Veg.	72	80	88
Tomatoes	65	72	82
Alfalfa Hay	60	68	77
Suggested defaults:	65	72	82

Curve number values in Table 6.1 were used in calculations made for this report. For crop and land-use types not listed, the following values in Table 6.2 were used based on judgement.

Table 6.2. Curve numbers estimated for specific crop or land-use types for antecedent soil water condition (AWC) II.

Crop/Land-use	Coarse Texture Soil	Medium Texture Soil	Fine Texture Soil
Pasture	40	70	82
Lentils, canola, safflower, sunflower, mustard	58	72	83
Bare soil	77	86	92
Desert grasses	49	69	81
Wetlands	30	40	50

Hawkins, et al., (1985) expressed tablular relationships in SCS (1972) in the form of equations relating CN for AWC I and AWC III to CN for AWC II:

$$\mathrm{CN_I} = \frac{\mathrm{CN_{II}}}{2.281 - 0.01281\ \mathrm{CN_{II}}} \tag{6.3}$$

$$CN_{III} = \frac{CN_{II}}{0.427 + 0.00573\,CN_{II}} \tag{6.4}$$

where CN_I is the curve number associated with AWC I (dry) [0 - 100], CN_{II} is the curve number associated with AWC II (average condition) [0 - 100], and CN_{III} is the curve number associated with AWC III (wet) [0 - 100].

The soil surface layer water balance associated with the dual K_c procedure can be used to estimate the AWC condition. An approximation for the depletion of the soil surface layer at AWC III (wet) is when D_e = 0.5 REW, i.e., when the evaporation process is half-way through stage 1 drying. This point will normally be when approximately 5 mm or less have evaporated from the top 150 mm of soil since the time it was last completely wetted. Thus, the relationship:

$$D_{\text{e-AWC III}} = 0.5\ \text{REW} \tag{6.5}$$

where $D_{\text{e-AWC III}}$ is the depletion of the evaporative layer at AWC III. AWC I can be estimated to occur when 10 to 20 mm of water have evaporated from the top 100 to 150 mm of soil from the time it was last completely wetted. This is equivalent to when the evaporation layer has dried to the point at which D_e exceeds 30% of the total evaporable water in the surface layer beyond REW. This depletion amount is expressed as D_e = REW + 0.3 (TEW - REW), where TEW is the total evaporable water in the surface layer. Therefore:

$$D_{\text{e-AWC I}} = 0.7\ \text{REW} + 0.3\ \text{TEW} \tag{6.6}$$

where TEW is the cumulative evaporation from the surface soil layer at the end of stage 2 drying. When D_e is in between these two extremes, i.e, 0.5 REW < D_e < 0.7 REW + 0.3 TEW, then the AWC is in the AWC II condition and the CN value is linearly interpolated between CN_I and CN_{III}. In equation form:

$$CN = CN_{III} \quad for\ D_e \le 0.5\ REW \tag{6.7}$$

$$CN = CN_I \quad for\ D_e \ge 0.7\,REW + 0.3\,TEW \tag{6.8}$$

and, for 0.5 REW < D_e < REW + 0.3 (TEW - REW):

$$CN = \frac{(D_e - 0.5\,REW)CN_I + (0.7\,REW + 0.3\,TEW - D_e)CN_{III}}{0.2REW + 0.3TEW} \tag{6.9}$$

Equation 6.9 produces CN_{II} when D_e is half way between the endpoints of CN_I and CN_{III} due to the symmetry of CN_I and CN_{III} relative to CN_{II}.

Infiltrated Precipitation

Once the surface runoff depth is estimated using the curve number procedure, the depth of rainfall infiltrated is calculated as:

$$P_{\inf} = P - RO \tag{6.10}$$

where P_{inf} is the depth of infiltrated precipitation [mm], P is the measured precipitation depth [mm], and RO is the depth of surface runoff [mm]. If the soil will not hold the amount infiltrated, the remainder goes to deep percolation.

References to Appendix 6

Allen, R.G. 1988. *IRRiSKED: Irrigation Scheduling Program for Demand and Rotation Scheduling--User's Manual*. Dept. Biol. and Irrig. Eng., Utah State University, Logan, UT, 84322 U.S.A., 80 pp.

Hawkins, R.H., A.T. Hjelmfelt, and A.W. Zevenbergen. 1985. Runoff probability, storm depth, and curve numbers,. *J. Irrig. and Drain. Eng.* 111(4):330-340.

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

APPENDIX 7

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. The following graphs 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 that represented soil conditions in 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 standardized Penman-Monteith method. Original K_c's by Wright were transformed to the ASCE PM basis during this study. 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.

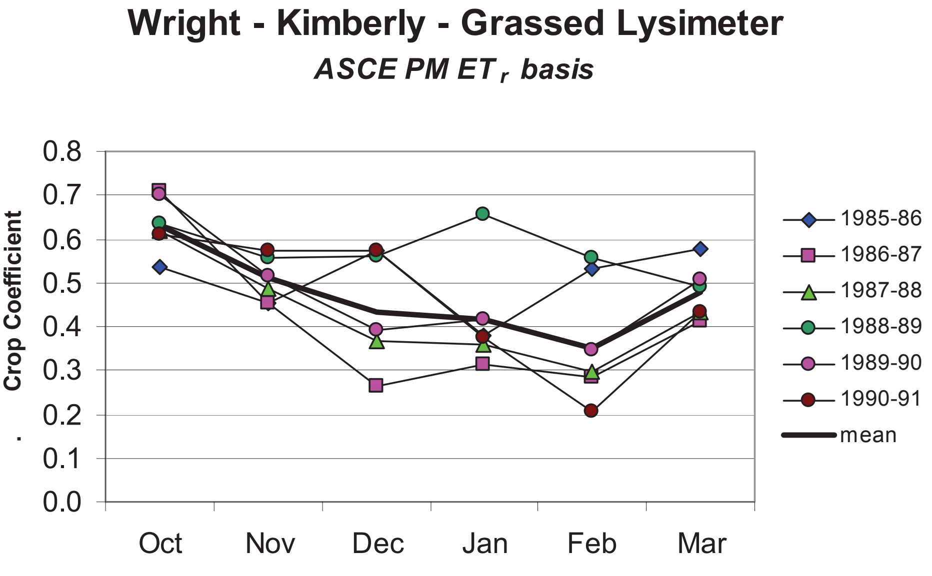


Figure 7.1. Mean monthly K_c measured by Wright (1993) from a grassed (dormant) lysimeter during nongrowing periods at Kimberly, Idaho converted for use with the ASCE Penman-Monteith alfalfa reference ET_r equation.

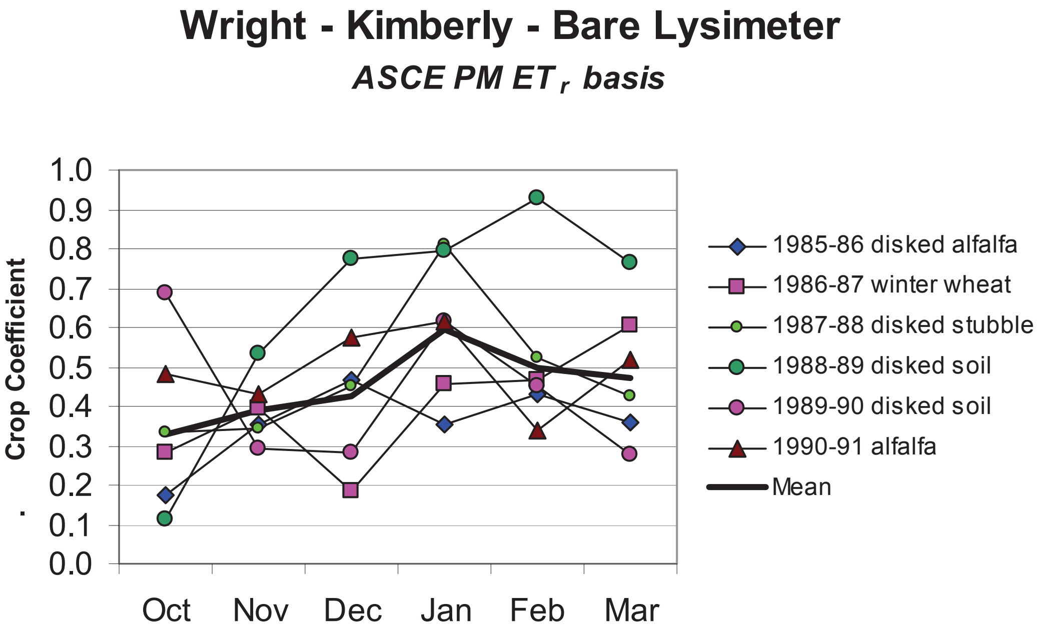


Figure 7.2. Mean monthly K_c measured by Wright (1993) during nongrowing periods at Kimberly, Idaho for various types of surface cover, converted for use with the ASCE Penman-Monteith alfalfa reference ET_r equation.

Calculating Wintertime Evaporation across the State

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 *third surface cover class* of 'mulch', was used to represent surfaces that are part way between bare and grassed conditions. The assumed effective fraction of 'cover' used during estimation of K_e was 0.7 for dormant grass, 0.4 for mulch and 0 for bare soil.

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.

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).

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. The following algorithms were applied:

$$K_{c\_multiplier} = 1 - K_{radiation\_term\_winter} + \frac{(1 - albedo_{snow})}{(1 - albedo_{surface})} K_{radiation\_term\_winter} \tag{7.1}$$

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

$$K_{radiation\_term\_winter} = \frac{\Delta}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)} \tag{7.2}$$

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. (7.1) 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, $K_{RadiationTermWinter}$ 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:

$$K_{RadiationTerm} = 2.2E-08\ J^3 - 2.42E-05\ J^2 + 0.006J + 0.011 \tag{7.3}$$

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.

Occaisionally, some stations reported snow fall (daily), but did not report observations of accumulated snow cover. In these cases, estimated depth of snow on the ground was made by accumulating snow fall and applying a simple melt rate function:

$$Snow\_accumulation_i = Snow\_accumulation_{i-1} + \frac{Snowfall}{2} - Melt_i \tag{7.4}$$

$$Melt = 4\ T_{max} \tag{7.5}$$

where *snow_accumulation* is snow depth accumulation in mm, *Snowfall* is reported snowfall depth for the day in mm, *Melt* is melt rate in mm/day and T_{max} is daily maximum air temperature in ^{o}C. The *snow_accumulation* parameter was calculated for all stations and periods and was used if it exceeded reported snow depth, as a precaution. The reported depth of snowfall was halved to reflect consolidation of the snow cover.

The snow melt rate function was based on about 50 years of snowcover observations for Ashton, Idaho.

Values for total evaporable water (TEW) and readily evaporable water (REW) that are used to estimate the evaporation coefficient, K_e, are described in Appendix 5 and the parameters are described in Annex 1. During wintertime when ET demands are low, the depth of effective drying by evaporation decreases due lower transport of heat into the soil profile and lower vapor pressures in the soil. The recommendation from Allen et al. (2005) (paper included in Annex 1) was followed where if the 30 day average reference ET_r (ending on the day in question) was less than 4 mm/day, then TEW and REW were adjusted as follow:

$$TEW_{applied} = TEW \sqrt{\frac{ET_{r30}}{4}} \tag{7.6}$$

and the value for REW was limited to less than or equal to 0.7 ($TEW_{applied}$).

References to Appendix 7

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.

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

APPENDIX 8

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 follows 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. Year to year variation in 30-day, 21-day, 15-day, 10-day and 5-day running average air temperature was investigated for a 37 year period of record at Kimberly (1969-2005) to determine the necessary averaging length, in days, to produce a generally monotonically increasing average between January and July. Temperature averages that increase during warm periods, but then decrease after that during cold periods can produce unrealistically large swings in planting or greenup estimates. Figures 8.1 and 8.2 show temperature averages at Kimberly for selected years and long-term. The T_{30} exhibits better monotonicism than the 21-day average, as shorter periods had more episodic decreases in average temperature. All averaging periods plot similarly when averaged over the 37 year period. Variation in T_{30} among years was as much as 50 days during April-June at Kimberly for the same mean temperature, representing expected ranges in planting dates from year to year caused by weather.

Table 8.1 shows values for T_{30} at Kimberly that are equivalent to the planting dates noted by Wright (1982) for his lysimeter crops. The values for T_{30} were selected from the year each crop was planted. Similar values for T_{30} were established for pasture, orchard, vegetable and onion crops using long term T_{30} values and planting or greenup dates used by Allen and Brockway (1983). These dates were used as a general basis for T_{30} dates used around the state for estimating startups for growing seasons. Some adjustments were made based on field observations by the authors across southern Idaho. The standard deviation of the T_{30} dates in Table 8.1 was about 14 days for most crops. Therefore, statistically, about 68% of all years will have a start up date within approximately 14 days of the mean startup date. The T_{30} temperatures from SCE TR-21 are also shown in Table 8.1. However, these temperatures are 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. Therefore, the TR-21 values, labeled T_{30m} are higher than T_{30} reported from analyses during this study.

In computing T_{30} for various NWS stations, local aridity of the station can elevate air temperature measurements above that expected within an agricultural field. Therefore, the computed values for T_{30} at NWS stations were adjusted downward in cases where the weather station was considered to be 'arid' using aridity ratings and adjustments used by Allen and Brockway (1983) in a previous consumptive use study. These aridity ratings are listed in Table 5.2 of Appendix 5. The amount of maximum adjustment by month is listed in Table 8.2.

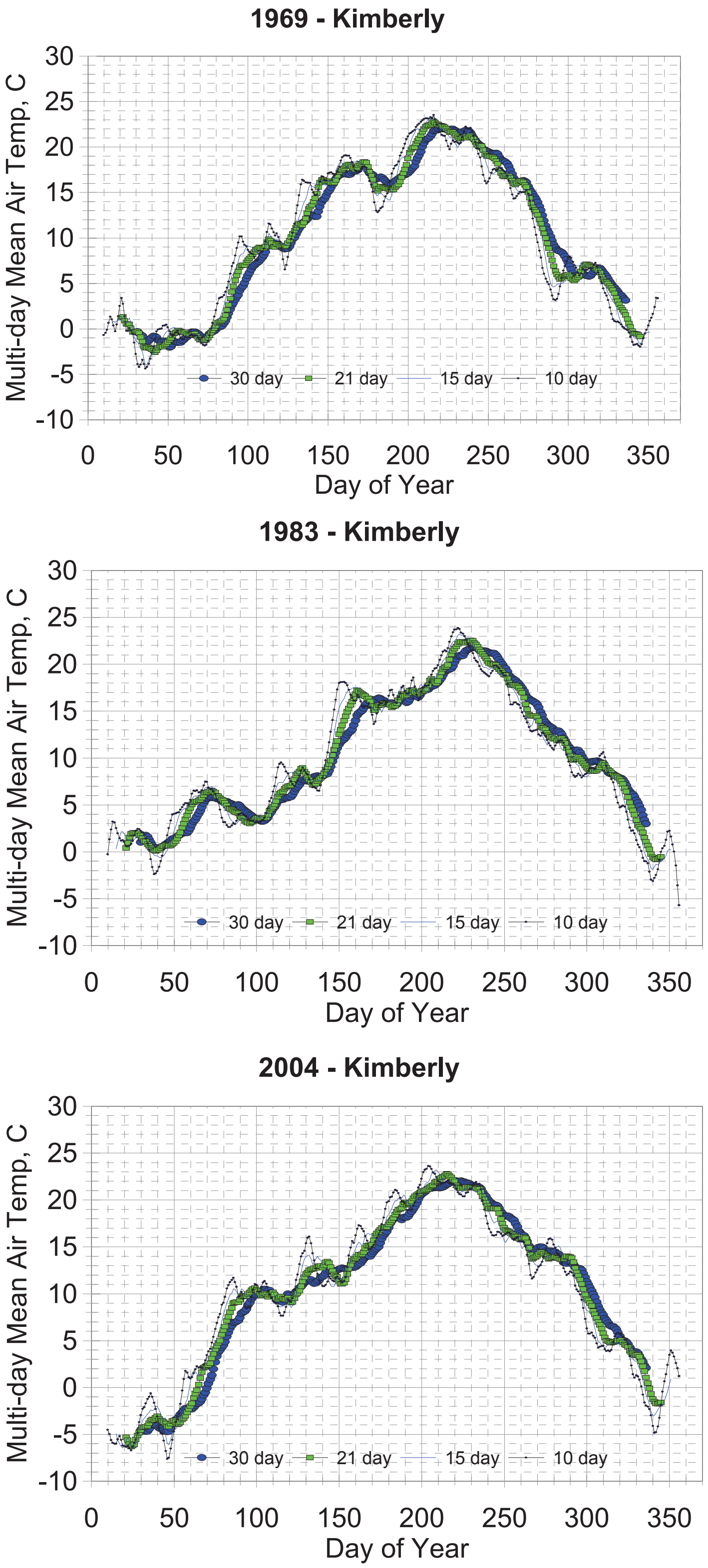
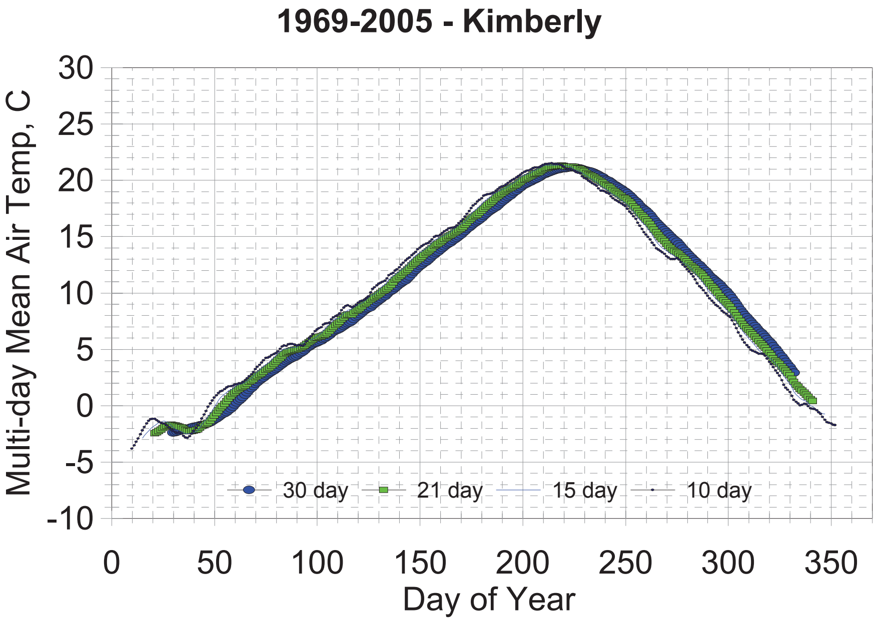


Figure 8.1. 10, 15, 21 and 30 day average mean daily air temperature during three years at Kimberly, Idaho. The values are plotted on the last day within each average.



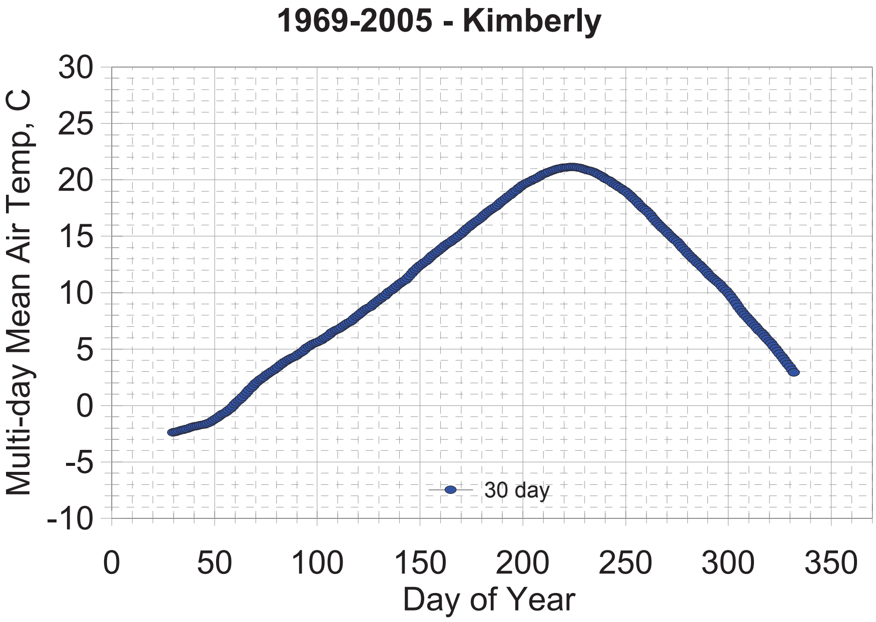


Figure 8.2. 10, 15, 21 and 30 day average mean daily air temperature at Kimberly, Idaho over a 37 year period (top) and the 30 day average only (bottom). The values are plotted on the last day within each average.

Table 8.1. 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 with Allen-Brockway (1983) planting dates and from field notes taken by Allen (pers. comm.) between 1999 and 2005.

Crop	Year	Plant Date	30-day T (C) ending on date	Equiv. 37 yr ave. date	Recomm. T_{30} to use, ^{o}C	Mean date over 37 yr. for Recommended T_{30}	Std. Dev. of dates in 37 yr. period (days)	TR-21 T_{30m}*, ^{o}C
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.

Table 8.2 Aridity Adjustments made to T_{30} from Allen and Brockway (1983) for Stations having Aridity Ratings of 100% (other stations were prorated according to the aridity rating).

Month	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Aridity Adjust. (^{o}C)	0	0	0	1	1.5	2.0	3.5	4.5	3	0	0	0

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.

Final values used for T_{30} for crops during ET_c processing are listed in Table 7 in the main text. Table 8.3 summarizes statistics for estimated planting or greenup dates for seven irrigated crops common to south-central Idaho based on the 37 year temperature record at Kimberly. The second line of the table shows mean dates estimated for each crop type based on the values for T_{30} used for the crop. In the case of alfalfa, greenup was based on cumulative growing degree days since January 1 as described later.

Table 8.3 Statistics describing estimated dates of planting for Kimberly over the 1969-2005 period based on lysimeter records. (Values for T_{30} were revised in the Allen-Robison (2007) calculations for sugar beets, corn and beans (see Table 8.2 and Appendix 13) based on comparisons with METRIC.

	Alfalfa	Spring wheat	Peas and Sugar Beets	Potatoes	Corn	Beans
Mean planting (or greenup) date:	March 30	March 28	March 31	Apr. 16	Apr. 28	May 26
mean Day of Year:	89	87	90	106	118	146
Std dev, days	11	13	14	14	12	10
CGDD:	**240 °C-d**	T_{30}: **4.7 °C**	T_{30}: **5 °C**	T_{30}: **6.5 °C**	T_{30}: **8 °C**	T_{30}: **12 °C**

Year	Date	DoY	Date	DoY	Date	DoY	Date	DoY	Date	DoY	Date	DoY
1969	408	98	406	96	407	97	411	101	419	109	516	136
1970	314	73	409	99	430	120	513	133	517	137	528	148
1971	404	94	406	96	408	98	418	108	502	122	526	146
1972	320	79	312	71	314	73	401	91	511	131	528	148
1973	410	100	411	101	412	102	426	116	506	126	519	139
1974	401	91	407	97	408	98	421	111	502	122	601	152
1975	420	110	501	121	506	126	512	132	516	136	604	155
1976	417	107	409	99	410	100	426	116	506	126	524	144
1977	410	100	411	101	412	102	421	111	425	115	604	155
1978	323	82	322	81	324	83	329	88	410	100	605	156
1979	406	96	331	90	402	92	421	111	501	121	522	142
1980	401	91	311	70	313	72	421	111	425	115	507	127
1981	326	85	324	83	328	87	417	107	426	116	603	154
1982	411	101	422	112	425	115	501	121	507	127	610	161
1983	312	71	307	66	308	67	503	123	514	134	601	152
1984	416	106	404	94	406	96	422	112	511	131	530	150
1985	416	106	410	100	411	101	414	104	417	107	523	143
1986	309	68	307	66	308	67	311	70	415	105	529	149
1987	331	90	330	89	402	92	417	107	423	113	507	127
1988	401	91	323	82	410	100	414	104	417	107	525	145
1989	406	96	401	91	402	92	414	104	418	108	509	129
1990	329	88	322	81	322	81	403	93	411	101	608	159
1991	327	86	404	94	405	95	423	113	515	135	608	159
1992	310	69	301	60	303	62	314	73	404	94	506	126
1993	412	102	401	91	402	92	408	98	510	130	519	139
1994	328	87	316	75	318	77	417	107	420	110	511	131
1995	311	70	314	73	316	75	426	116	510	130	603	154
1996	322	81	327	86	327	86	406	96	425	115	602	153
1997	326	85	326	85	329	88	427	117	505	125	517	137
1998	321	80	402	92	403	93	427	117	501	121	612	163
1999	328	87	324	83	406	96	501	121	520	140	603	154
2000	324	83	401	91	404	94	411	101	417	107	522	142
2001	404	94	324	83	325	84	401	91	506	126	515	135
2002	409	99	405	95	406	96	412	102	416	106	530	150
2003	316	75	326	85	327	86	401	91	503	123	529	149
2004	326	85	320	79	321	80	324	83	331	90	520	140
2005	401	91	319	78	319	78	423	113	503	123	528	148
ave	**---**	**---**	**402**	**92**	**404**	**94**	**417**	**107**	**429**	**119**	**527**	**147**

Alfalfa. 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}. This finding was based on observed greenup during 1969-1971 and field observations by Allen (pers. comm.) between 1998 and 2005. 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. The calculation of GDD is described in Appendix 3. Eq. 3.2 was used to compute GDD. No penalty was applied for cold weather during the winter period. On average, for the 1969-2005 period at Kimberly, CGDD=240 C-days estimates an average greenup date of March 30 with a standard deviation of 11 days (Table 8.3).

Table 8.4 summarizes an assessment of the sensitivity of estimated greenup date to the T_{base} used in the GDD calculation. The last column is the actual greenup date for 1969, 1970 and 1971 at Kimberly. The 0^{o}C base had the best consistency of CGDD among the three years and was selected as the best basis to use.

Table 8.4. Cummulative growing degree days for the date of greenup for alfalfa at Kimberly (Ranger variety)

Year	3^{o} base	2^{o} base	0^{o} base	5^{o} base	Actual Greenup
1969	90	120	200	51	4/3
1970	90	135	240	31	3/15*
1971	95	137	240	36	4/05

*Greenup of 3/15 was noted in logbooks due to warm late February and early March. However, weather cooled substantially following 3/15 and growth following greenup was delayed.

Cutting dates for alfalfa hay were also estimated using cumulative CGDD (base 0^{o}C) based on noted cuttings recorded at Kimberly during 1969-1971. However, the 1969-71 dates in some cases did not follow typical practice due to research needs. In addition the hay crops during that period generally followed what is referred to here as a 'beef hay' cutting practice where three large cuttings of hay are harvested each year for the south-central climate and the alfalfa crop is harvested when the plants have about '1/10 bloom'. Current practice for hay supplied to dairies cuts hay more frequently, often before any bloom on plants occur. This is done to increase protein content of hay and to reduce steminess. Often four cuttings are obtained in south-central Idaho and sometimes five in SW Idaho. To account for both the new and old practices, two alfalfa hay categories were created and termed 'beef cattle style' and 'dairy style'. Values for CGDD for the three years of record at Kimberly are listed in Table 8.5.

Table 8.5. GDD analysis for estimating cutting dates for Ranger Variety Alfalfa at Kimberly (0^{o}C base).

Year	Cutting no.	Date of cutting	Cum.GDD since Jan 1.	Cum GDD since greenup or cut	Cum GDD since first CGDD=240
1969	First	5/28	858	660	620
	Second	7/25	1908	1050	--
	Third	10/14	3259	1350	--
1970	First	6/24	1218	978	978
	Second	8/25	2508	1282	--
1971	First	6/18	1084	844	844
	Second	8/9	2166	1082	--
	Third	9/27	2959	793	--

Based on findings at Kimberly and field observations across southern Idaho, the following values for CGDD were used to approximate cutting dates: for 'beef hay' that is typically cut three times in Magic Valley, calculations used 850 CGDD since greenup until the first cutting and 900 CGDD since first or second cutting until the next cutting. The second and later cycles require more CGDD since these cycles contain a period of nogrowth prior to launch of rapid growth that is not present in the first growth cycle. For 'dairy hay' that is typically cut four times in Magic Valley, calculations used 700 CGDD since greenup until first cutting and 650 CGDD for all subsequent growth cycles. Dairy hay is typically cut earlier than beef hay for higher protein content and may tend to be a less dormant genotype with quicker regrowth, but with less longevity. Semi-dormant alfalfa will tend to grow longer into the fall (lower killing temperature) than older varieties of dormant alfalfa like Ranger. All varieties have similar greenup behavior (Dr. Glen Shewmaker, UI, pers. comm.. July, 2006). The 900 and 650 values for CGDD for second and later cuttings were shortened from the 1050 and 850 values of Table 3.5 in Appendix 3 that were based on Dr. J.L. Wright's data from the 1970's, after review of means and ranges in cutting dates and numbers of cutting cycles estimated at a range of NWS stations across the state.

Adjustment of K_{cb} for Alfalfa During the Fall

For the peak, dairy and beef alfalfa types, 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°C in the fall by 0.005 each day following the -3°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°C.

Estimation of Killing Frosts

Killing frosts can terminate growing seasons prematurely for crops that grow late into fall or for crops that are sensitive to even light frosts. Temperatures for killing frosts were assigned to most crops based on literature and internet searches and personal field notes. The following lines list killing frost temperatures for a variety of crops and land-use types (These values are also listed in Table 7 of the main text):

-7 C for alfalfa (see alfalfa description for reduction of curve)
–4 C for field corn and silage corn and -5 C for early sweet corn. No early frost death was estimated for late sweet corn (assumed to be grow until mechanical harvest). These temperatures are lower than commonly used for some corn varieties, but were required to prevent unreasonably truncated growing seasons in parts of Idaho and to account for differences between temperatures recorded at weather stations and those in a fully vegetated field of corn.
-4 C for mint
-2 C for wetland vegetation (cattails commonly freeze at 0 or -1°C, however -2°C was used to account for differences between weather station environments and wetland environments that benefit from heat transfer from water surfaces.)
-5 C for turf and pasture
-5 C for leaf fall on fruit trees and poplars, -4 C for cottonwoods and -6 C for willows
-4 C for sugar beets
-2 C for potatoes
-2 C for melons
–3 C for grapes
-3 C for asparagus

General Comments regarding the start of growing seasons, etc.

Brome, native grasses, desert grasses, sage brush, use 5°C less 10 days for the start of season. Use 5°C to start season for pasture and turfgrass.

For general trees (poplars, shade trees) use T_{30} = 8°C (May 1 at Kimberly) for bud break. Estimate full leaf-out 21 days later. Carry high K_c into fall and then discount as cold weather, leaf aging occur. Use frost to terminate.

For wine grapes, use T_{30} = 8°C for bud break. Assume effective full cover at 80 days after greenup. Use AgriMet K_{cm} curve – 0.05 for K_{cb}. Use frost to terminate (-3°C).

For sweet corn, estimate for two crops, early and late, with early planted with T_{30} = 8°C and with the late crop lanted with T_{30} = 12°C. These dates correspond to about May 1 and June 1 at Kimberly.

A 'peak' alfalfa curve that represents full-cover alfalfa with no cutting effects is presented for design purposes. This curve uses the first crop cycle curve to simulate greenup. After full cover, the K_{cb} remains at 1.0 until the first T_{min} <= -3 °C, at which time the value is discounted 0.5% per day, to reflect less than optimal growing conditions, until a killing frost.

Summary of Estimated Lengths of Growing Seasons at All Locations

The suite of figures beginning on the next page show a sequence of figures (by crop) summarizing the mean season lengths estimated for the 123 locations studied using the procedures described in this appendix. The mean and mean plus/minus one standard deviation (over the period of record) are plotted vs. the elevation of the location (elevation is in feet above mean sea level). In most cases, season length has strong correlation with elevation due to the impact of elevation on air temperature, which was the primary parameter used to estimate the beginning of growing seasons and the duration.

References to Appendix 8

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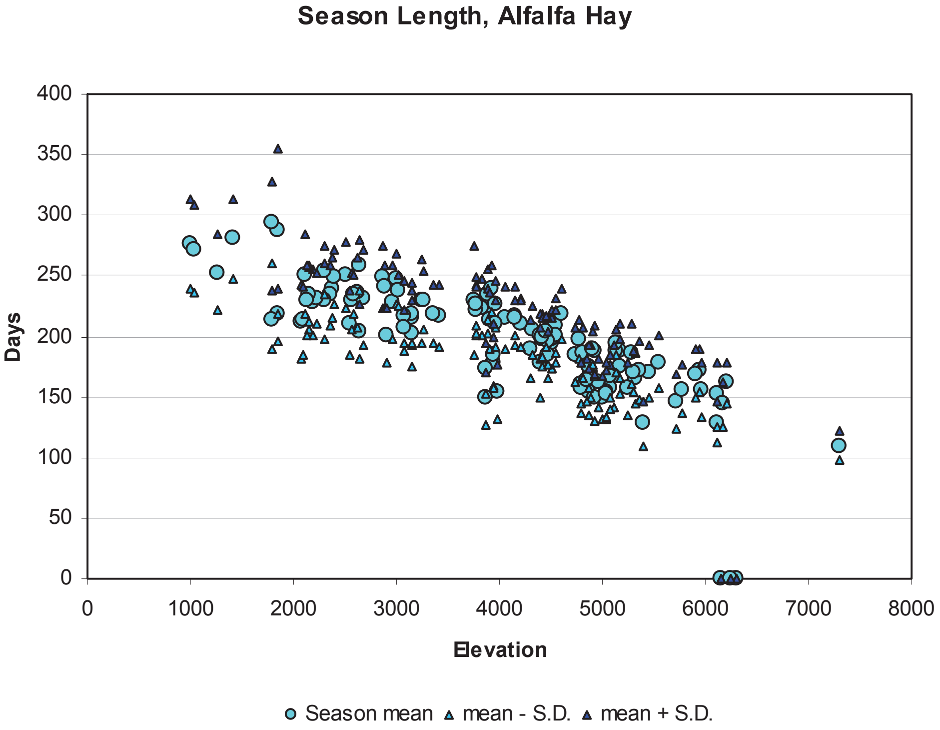
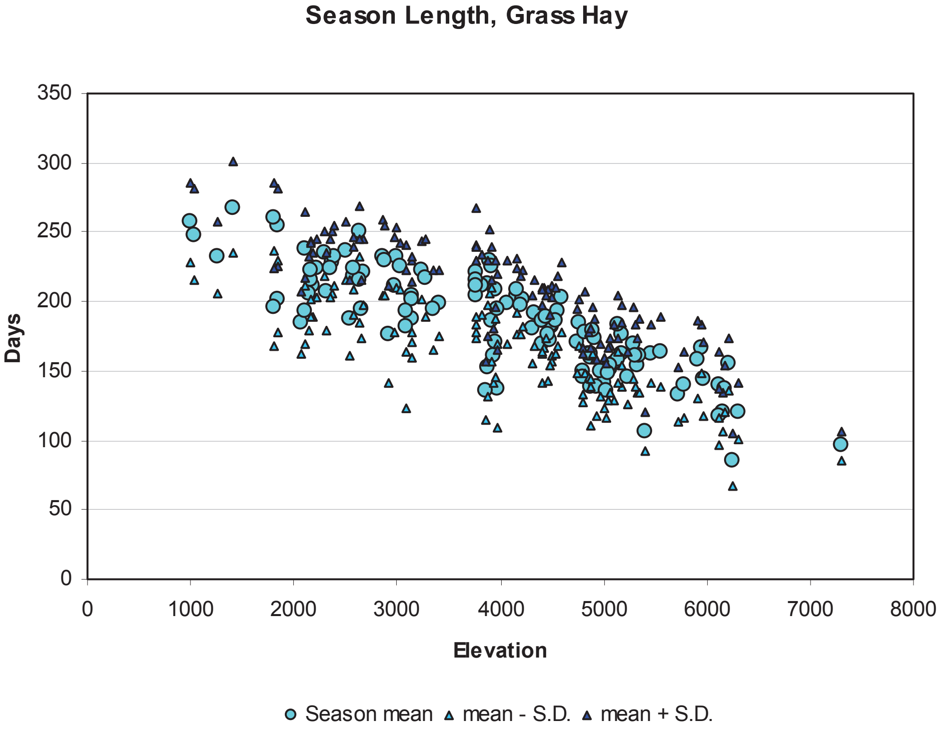

Season Length, Alfalfa Hay
Days
400
350
300
250
200
150
100
50
0
0
1000
2000
3000
4000
5000
6000
7000
8000
Elevation
Season mean
mean - S.D.
mean + S.D.


Season Length, Grass Hay
Days
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300
250
200
150
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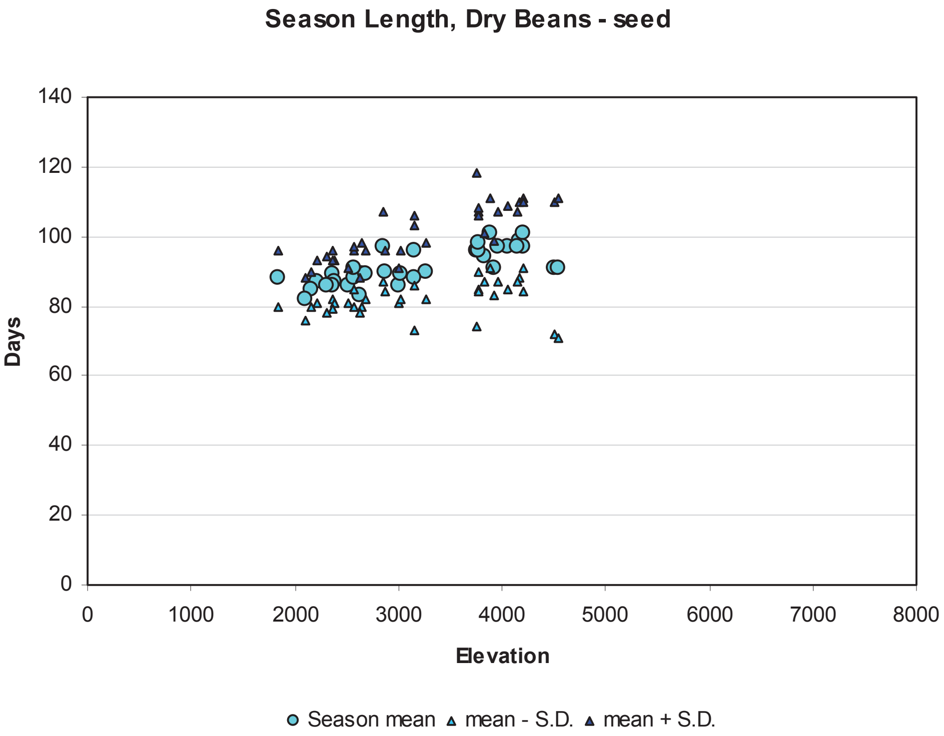
0
1000
2000
3000
4000
5000
6000
7000
8000
Elevation
Season mean
mean - S.D.
mean + S.D.


Season Length, Dry Beans - seed
Days
0
20
40
60
80
100
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2000
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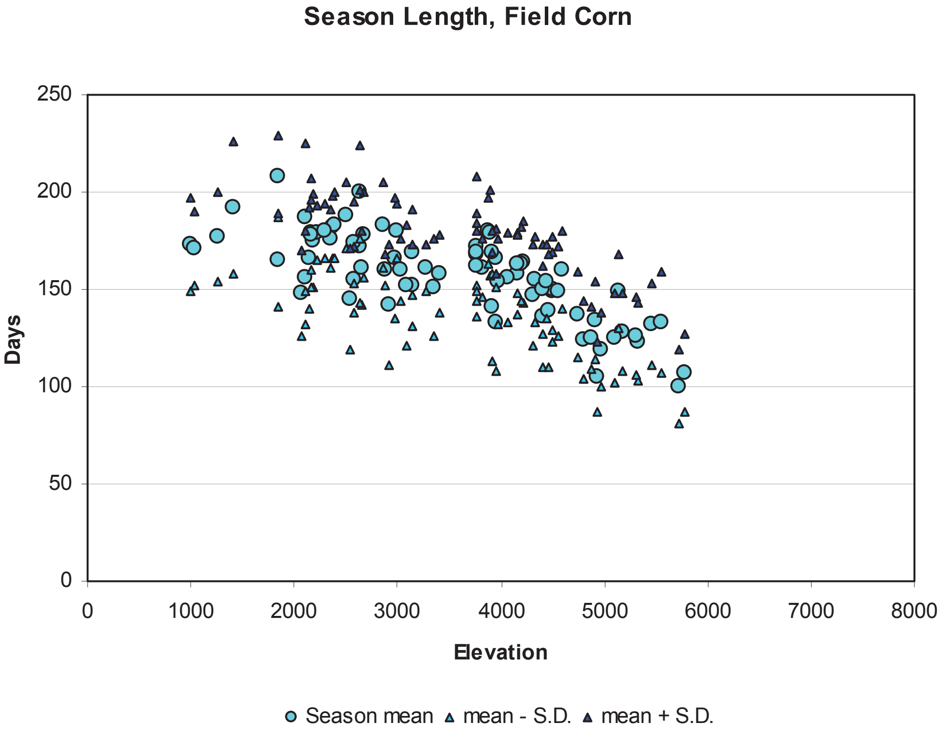
7000
8000
Elevation
Season mean
mean - S.D.
mean + S.D.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8000
Elevation
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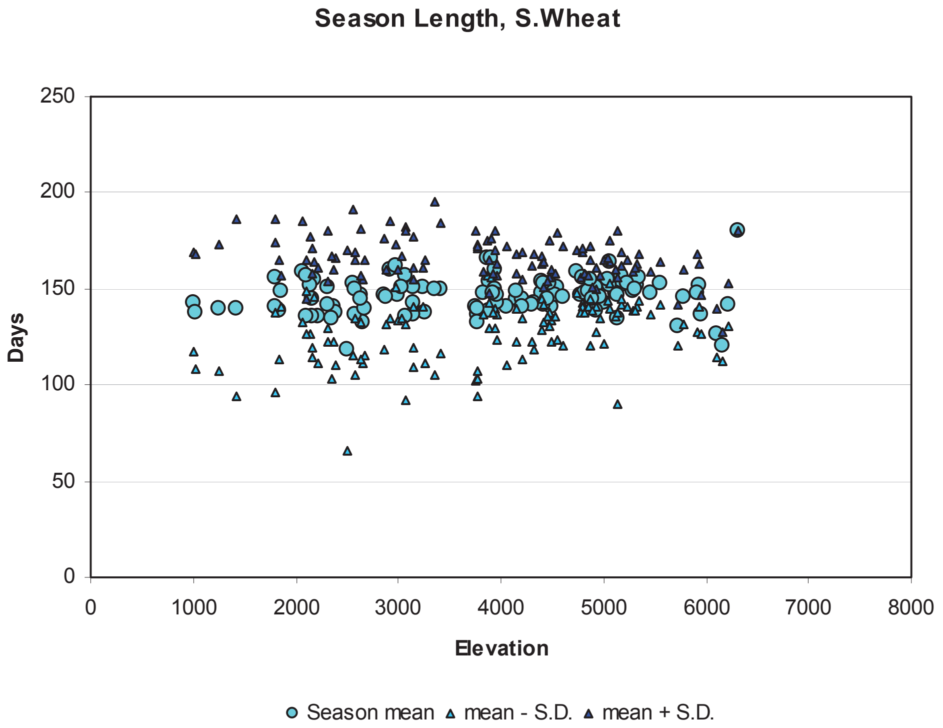
mean + S.D.


Season Length, S.Wheat
Days
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200
150
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2000
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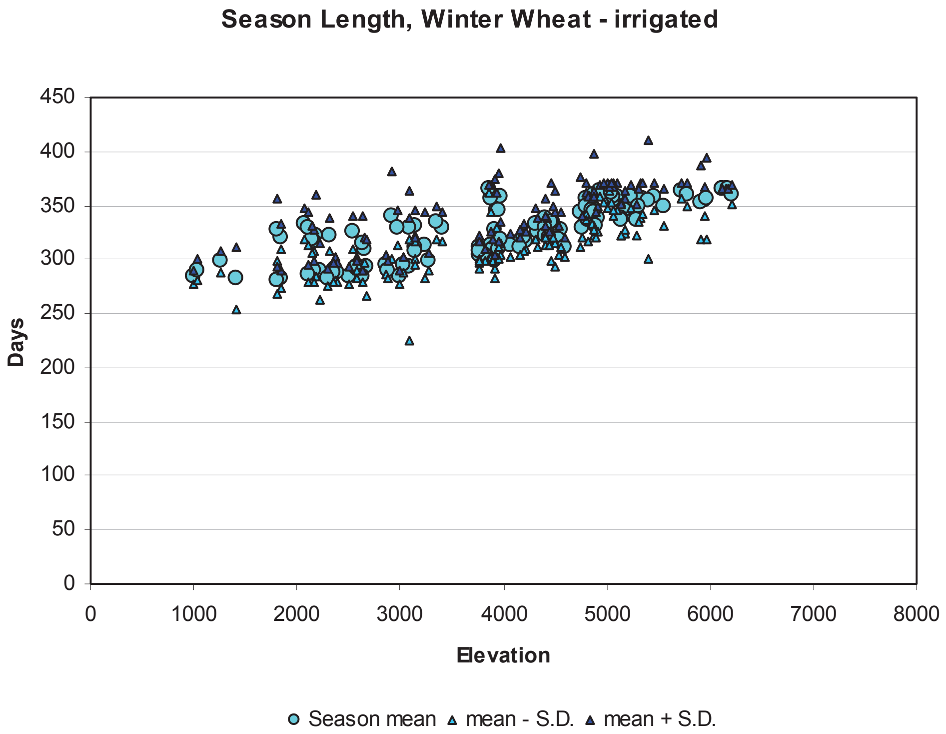
6000
7000
8000
Elevation
Season mean
mean - S.D.
mean + S.D.


Season Length, Winter Wheat - irrigated
Days
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400
350
300
250
200
150
100
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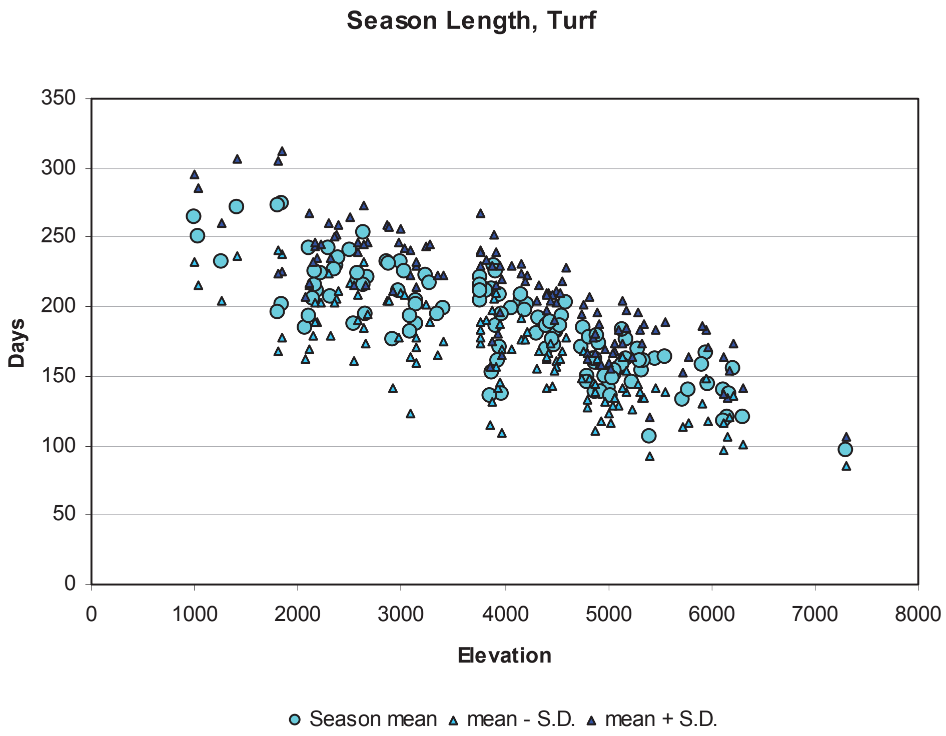
4000
5000
6000
7000
8000
Elevation
Season mean
mean - S.D.
mean + S.D.


Season Length, Turf
Days
350
300
250
200
150
100
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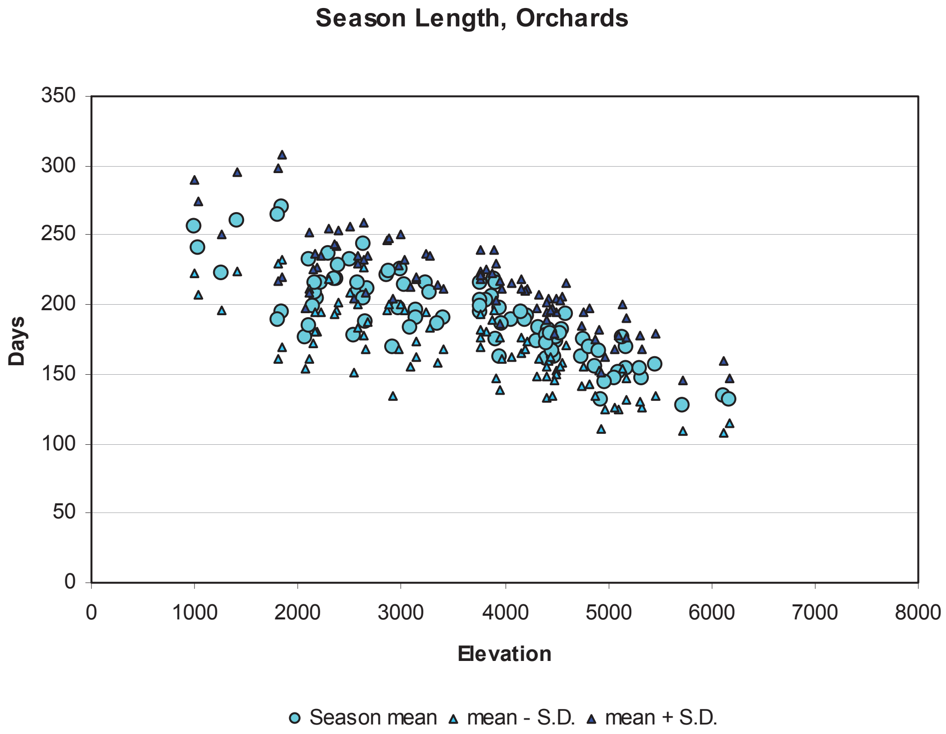
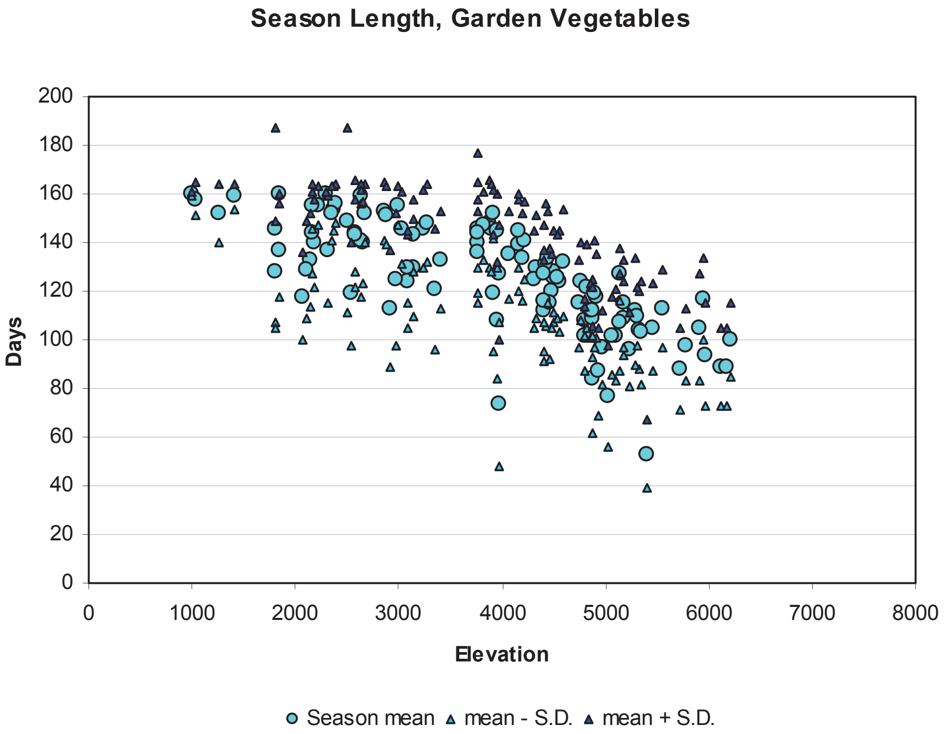
1000
2000
3000
4000
5000
6000
7000
8000
Elevation
Season mean
mean - S.D.
mean + S.D.


Season Length, Orchards
Days
350
300
250
200
150
100
50
0
0
1000
2000
3000
4000
5000
6000
7000
8000
Elevation
Season mean
mean - S.D.
mean + S.D.


Season Length, Garden Vegetables
Days
200
180
160
140
120
100
80
60
40
20
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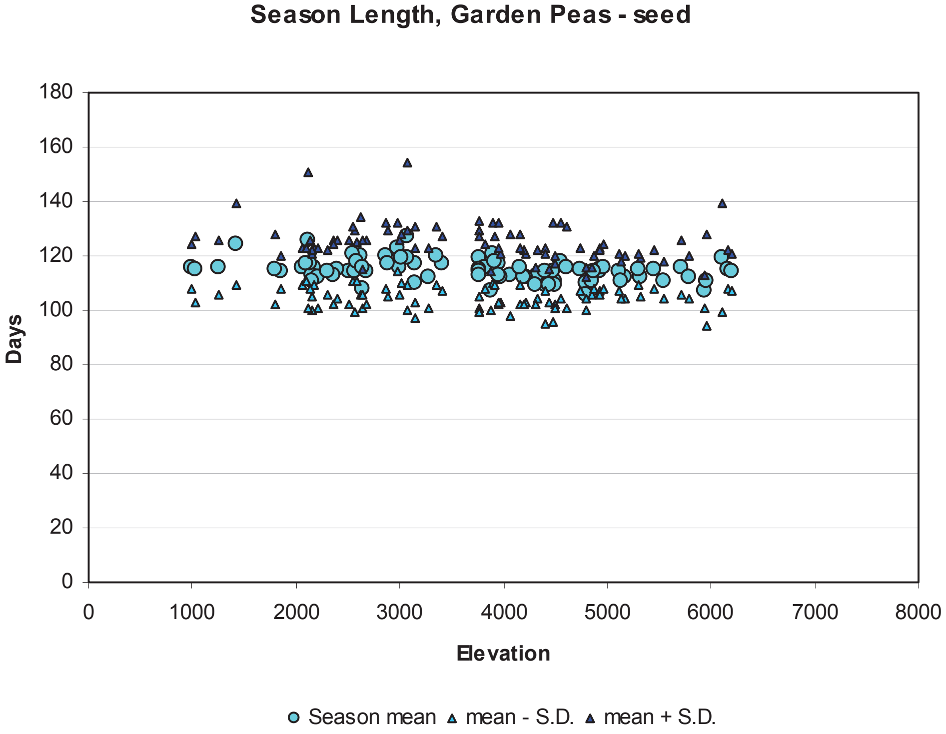
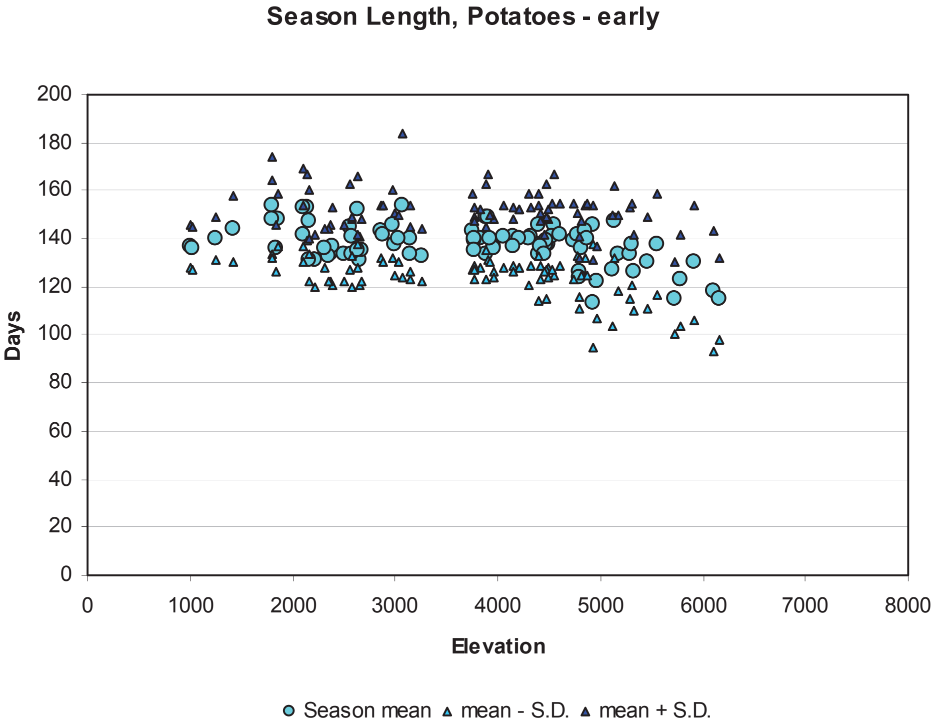
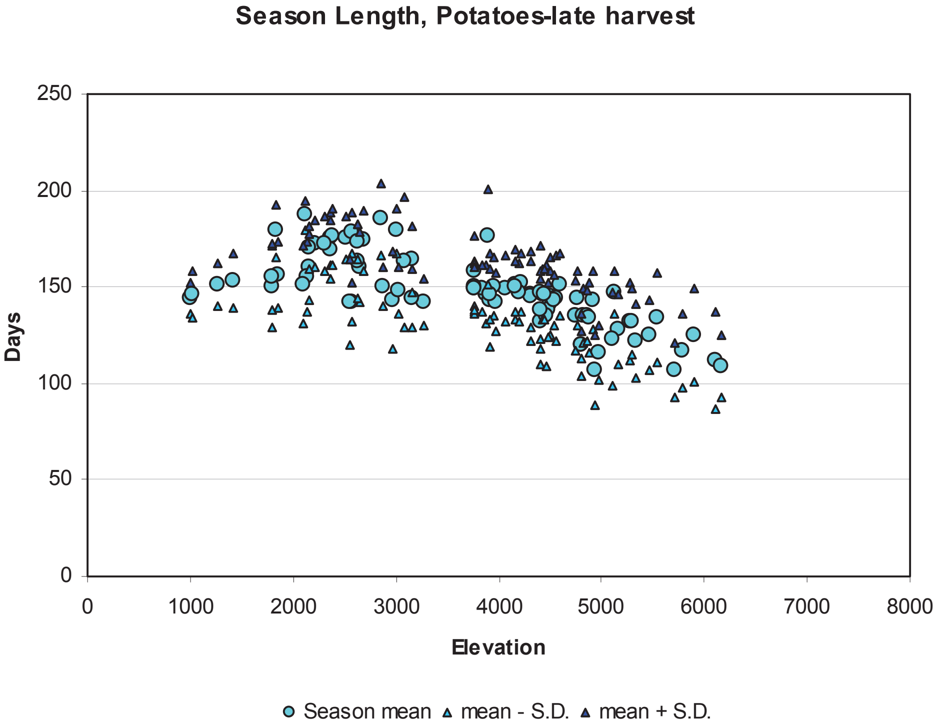
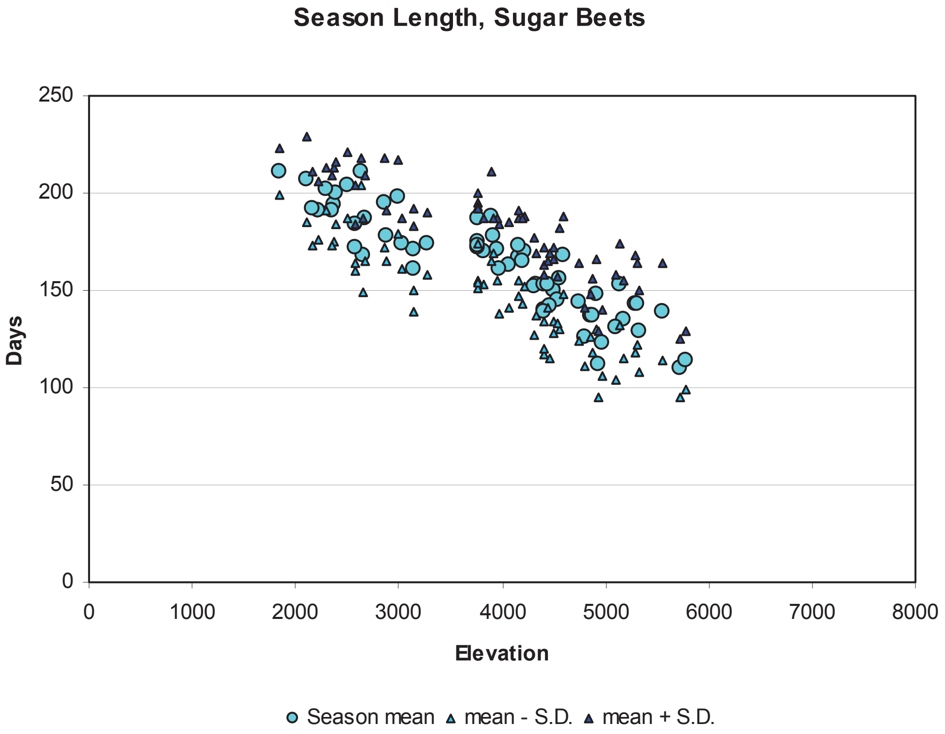
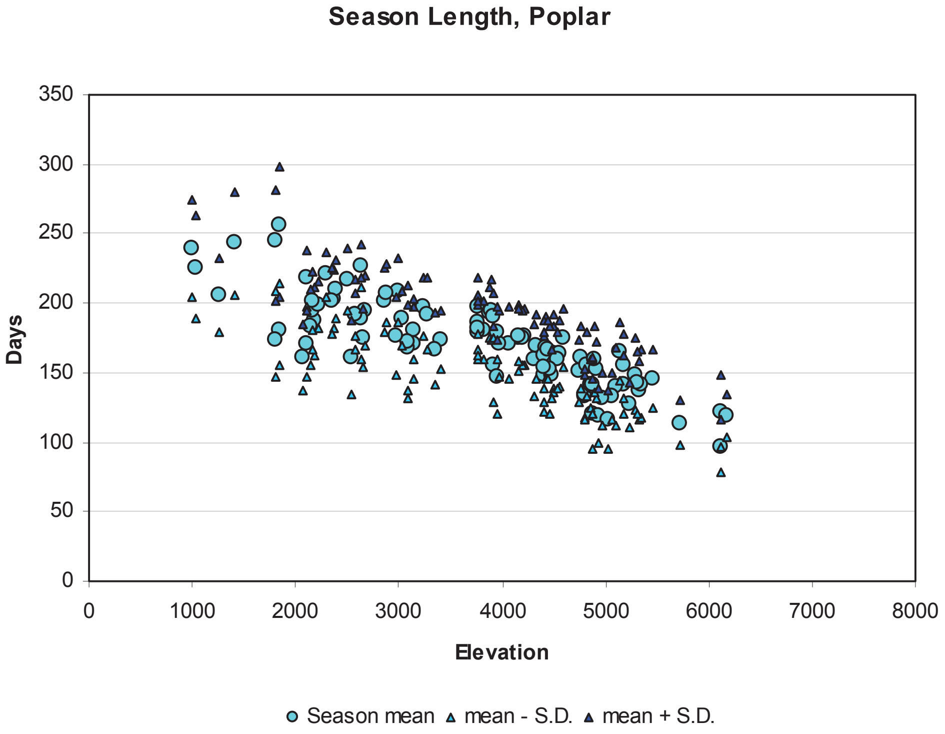
0
1000
2000
3000
4000
5000
6000
7000
8000
Elevation
● Season mean ▲ mean - S.D. ▲ mean + S.D.


Season Length, Garden Peas - seed
Days
180
160
140
120
100
80
60
40
20
0
0
1000
2000
3000
4000
5000
6000
7000
8000
Elevation
● Season mean ▲ mean - S.D. ▲ mean + S.D.

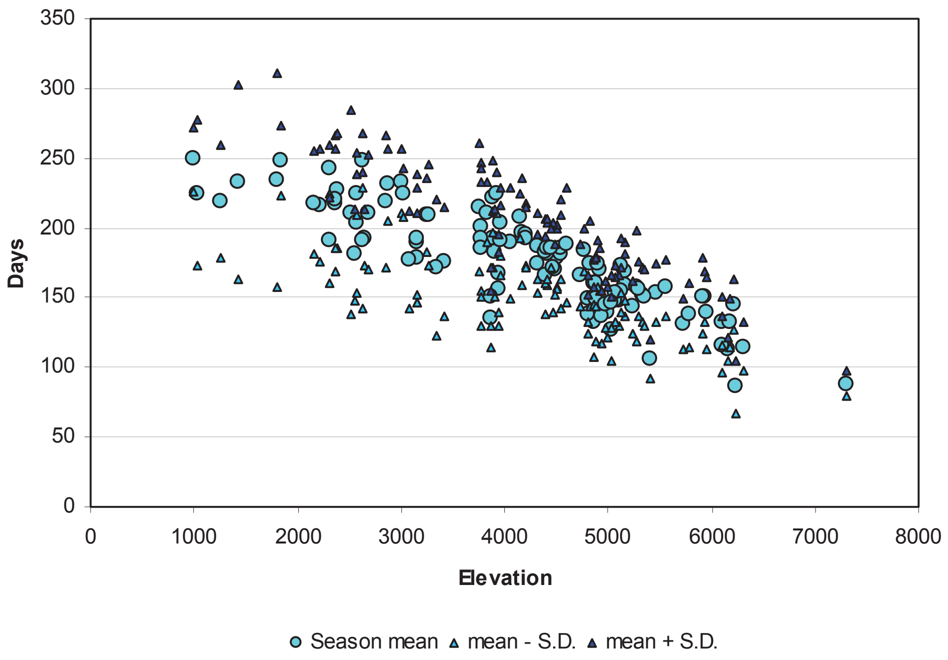

Season Length, Potatoes - early


Season Length, Potatoes-late harvest

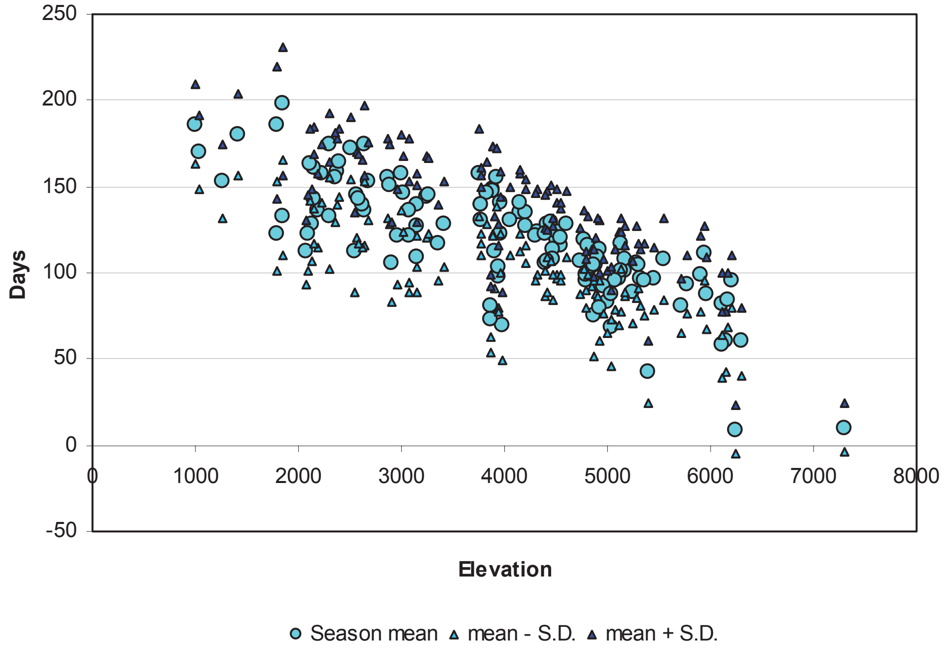

Season Length, Sugar Beets
Days
250
200
150
100
50
0
0
1000
2000
3000
4000
5000
6000
7000
8000
Elevation
Season mean
mean - S.D.
mean + S.D.


Season Length, Poplar
Days
350
300
250
200
150
100
50
0
0
1000
2000
3000
4000
5000
6000
7000
8000
Elevation
Season mean
mean - S.D.
mean + S.D.

Season Length, Sage brush



Season Length, Wetlands



APPENDIX 9

COMPARISON OF ALFALFA ET_R BY THE 1982 KIMBERLY PENMAN TO ALFALFA ET_R BY THE ASCE STANDARDIZED PENMAN-MONTEITH METHOD

The ASCE Penman-Monteith and 1982 Kimberly Penman equation both estimate alfalfa reference evapotranspiration ET_r. Differences between the two methods are small during the middle of the growing season, generally less than a few percent (Wright et al., 2000). The two methods deviate more during winter, early spring and late fall, where the ASCE-PM estimates as much as 50% higher than the 1982 Kimberly Penman method during December and January (Figure 9.1) and about 20% greater during March and November. The reason for the higher estimation by the ASCE-PM is the definition and standardization of the equation for 0.5 m tall, living alfalfa having leaf surface area that is 4 times that of the underlying ground surface. During Idaho winters, alfalfa becomes dormant and the hypothetical (living) standard definition can not exist in reality. However, ASCE-EWRI (2005) stressed the importance of retaining the living definition for the reference, even during dormant periods, in order to retain a consistant evapotranspiration index. This usage contrasts with the 1982 Kimberly Penman, where the empirical wind function in the equation was reduced by Wright (1996, Jensen et al., 1990) during nongrowing periods to produce smaller estimates during those periods. Generally, K_c values relative to ET_r from the ASCE-PM during wintertime will be less than 1.0 due to most winter covers being in a total or semi dormant state. The following figure shows monthly ratios of ASCE-PM to 1982 Kimberly penman over a 32 year period of record at Kimberly.

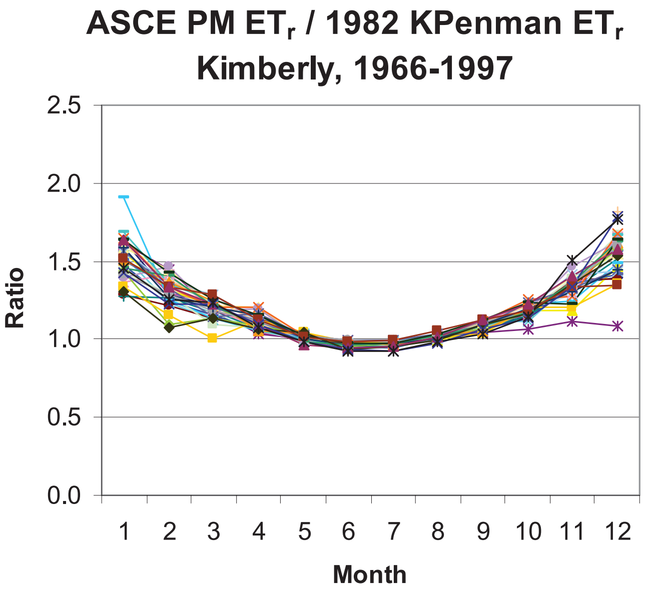


Figure 9.1. Monthly ratios of alfalfa reference ET_r calculated by the ASCE standardized Penman-Monteith equation to ET_r calculated by the 1982 Kimberly Penman method.

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APPENDIX 10

EVAPORATION FROM DEEP, OPEN WATER

Evaporation from deep, open water was estimated for this report 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 equipment was set up on the reservoir during the 2004 growing season (Allen and Tasumi, 2005). Measurements from this study were used to develop and calibrate aerodynamic procedures that can be applied with air temperature data, only, to estimate evaporation from deep water bodies.

A 2004 evaporation instrumentation study was conducted on American Falls Reservoir by Allen and Tasumi (2005) to produce independent measurements of evaporation derived from energy balance and aerodynamic micrometeorological methods (Bowen ratio, Eddy Covariance and infrared temperature). These measurements enabled the determination of monthly evaporative behavior of the reservoir with a relatively high level of confidence. Details on the study are provided in the 2005 paper by Allen and Tasumi (2005), which is reproduced as Annex 2.

One of the outcomes of the 2004 study was Table 3 of Allen and Tasumi (2005), shown as Table 10.1, that shows the basic components of the surface energy balance of American Falls Reservoir on a 24-hour basis by month (EC is eddy covariance, BREB is Bowen ratio energy balance, H is sensible heat flux, LE is latent heat flux (evaporation), β is the Bowen ratio (ratio of H to LE), R_n is net radiation to the water body, Q_t is the heat storage to the water body, and ET_rF is the ratio of evaporation to the alfalfa reference ET_r (ET_r was computed using the ASCE-EWRI Penman-Monteith equation (ASCE-EWRI, 2005):

Table 10.1 Observed monthly reservoir energy balance, 24-hour average based on the EC / BREB combination (from Table 3 of Allen and Tasumi, 2005).

Month	R_n (W/m2)	H (W/m2)	LE (W/m2)	Q_t (W/m2)[1]	β	Q_t/R_n	ET_rF
5	204	25	71	108	0.35	0.53	0.45
6	197	8	53	136	0.15	0.69	0.26
7	202	23	121	59	0.19	0.29	0.59[a]
8	187	24	74	89	0.32	0.48	0.35
9	120	11	40	69	0.27	0.57	0.30
10	77	18	43	16	0.42	0.21	0.60
11	39	18	26	-5	0.69	-0.14	0.76

[1] Q_t (water heat storage) was calculated as a residual of the energy balance.

[a] The LE calculated by the EC / BREB combination for July exceeded that by the two aerodynamic methods and is considered to be impacted by unknown error or bias. ET_rF for July (24-hour) probably averaged nearer to 0.35.

Aside from the month of July, which was an uncertain value, the ratio of evaporation (E) to ET_r (last column of Table 3) was relatively low, especially during summer, averaging about 0.35. As described in Allen and Tasumi (2005), these low values are due to the very high amount of solar radiation (a component of R_n) absorbed below the water surface and stored as heat. The values rise into fall as stored heat is transported to the water surface and used to support evaporation.

The ET_rF values from Allen and Tasumi (2005), available for May – November, have been used here to calibrate a fully aerodynamic method that is based on wind speed and water and air temperature, only. This latter method is developed to provide information for all months of the year as well as for application to historical data periods for which only air temperature data are available.

Aerodynamic Method. Allen and Tasumi (2005) tested and described several aerodynamic methods including a classical one of Kondo (1975) that utilizes water and air temperature to estimate the specific humidity gradient between water and air. In this bulk aerodynamic method, latent heat of evaporation (LE, where LE is equal to evaporation (E) in mm multiplied by the latent heat of vaporization λ) is calculated using using observed windspeed, air temperature and humidity at one height above the surface along with water surface temperature. Latent heat flux is expressed as:

$$LE = \lambda \, \rho_{air} \, C_E \, u \left(q_{satTs} - q_a \right) \tag{10.1}$$

where LE has units of W m^{-2}, ρ_{air} is density of moist air (Kg m^{-3}), u is wind speed (m s^{-1}), q_{satTs} is the saturated specific humidity (Kg Kg^{-1}) at surface temperature T_s, q_a is the specific humidity at observation height z, and C_E is a dimensionless bulk transfer coefficient for water vapor. C_E is equivalent to the classical aerodynamic expression:

$$C_E = \frac{k^2}{\ln(z/z_{om})\ln(z/z_{ov})} = \frac{1}{u \cdot r_{av}} \tag{10.2}$$

for near neutral stability conditions where z_{om} and z_{ov} are roughness lengths for momentum and vapor transfer, k is the von Karman constant (0.41) and r_{av} is bulk aerodynamic resistance for vapor transfer between the surface and z. C_E was recommended by Kondo as 0.0012 for neutral conditions. In addition, several literature reviews indicate that C_E=0.0012 for many applications to water. In equation 1, specific humidity, q, is calculated from vapor pressure, e, as (Allen et al., 1996):

$$q = \frac{0.622 \, e}{P - 0.378 e} \tag{10.3}$$

where q has units of Kg vapor per Kg of air, e is vapor pressure in kPa and P is atmospheric pressure in kPa. Vapor pressure of the water surface is computed as saturation pressure at water surface temperature and the air vapor pressure, e_a, used to calculate q_a via Eq. (10.3) is taken from a nearby weather station, in this case the Aberdeen AgriMet station. The functions for vapor pressure were then:

$$e_{surface} = 0.6108 \exp\left[\frac{17.27 \, T_s}{T_s + 237.3} \right] \tag{10.4}$$

$$e_{air} = 0.6108 \exp\left[\frac{17.27 \, T_{dew}}{T_{dew} + 237.3} \right] \tag{10.5}$$

where T_s is estimated water surface temperature and T_{dew} is mean dewpoint temperature.

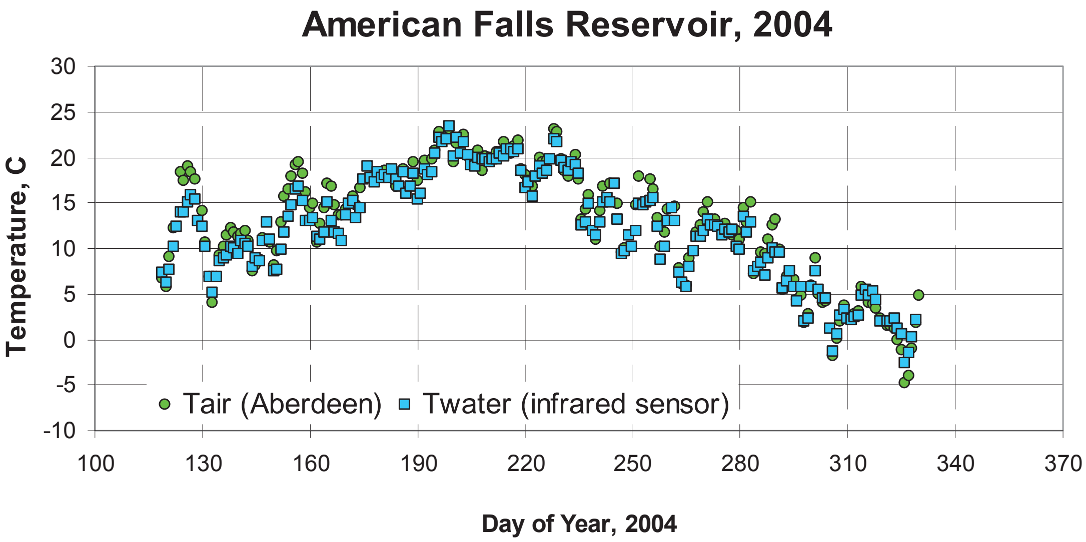
Evaporation depth, mm d^{-1}, is calculated by dividing LE from Equation 1 by latent heat of vaporization λ, where a mean value for λ of 2.45 MJ/kg is used:

$$E = \frac{LE}{2.45} (86400/10^6) \tag{10.6}$$

The 86,400 unit converts from seconds to days and 10^6 converts from MJ to Joules.

Modification of Aerodynamic Method to use only air temperature and wind speed. Water surface temperature is not routinely measured for water bodies in Idaho and therefore, other means are needed to estimate T_S. Allen and Tasumi (2005) observed, for American Falls Reservoir, that surface temperature of the reservoir corresponded closely with air temperature on a daily and even hourly basis. Mean daily water surface temperature measured by an infrared thermometer and corresponding mean daily air temperature at the Aberdeen AgriMet weather station are plotted in Figure 10.1 for the May – October 2004 period. Smoothed (10-day running average) data are plotted in the lower figure. The close correspondence of the surface and air temperature is remarkable and reflects the strong coupling between water skin temperature and air temperature caused by long-wave radiation exchange. For water bodies, long-wave radiation coupling between water and atmosphere dominates other energy exchange processes impacting surface temperature, such as cooling via latent heat exchange or conduction of heat to the surface from below. The latter two processes are constrained over water due to the typically aerodynamically smooth surface and near neutral boundary layer stability of the atmosphere and stable water layering.

Independent confirmation of the close relationship between (as measured by Landsat satellite (via the METRIC process)) was provided by comparing water temperature of reservoir releases (measured in the Snake River immediately below the reservoir) with surface temperature measured by Landsat (Figure 10a of Allen and Tasumi). The close correspondance between reservoir outlet temperature and surface temperature indicates that outlet water temperature can be used as a surrogate for mean surface temperature. In addition, outlet water temperature was closely related to mean air temperature recorded at the AgriMet Aberdeen weather station during the same year (2000) (Figure 10b of Allen and Tasumi). Therefore, it appears that a relatively robust relationship can be derived between mean daily air temperature recorded at Aberdeen and surface temperature of American Falls Reservoir.



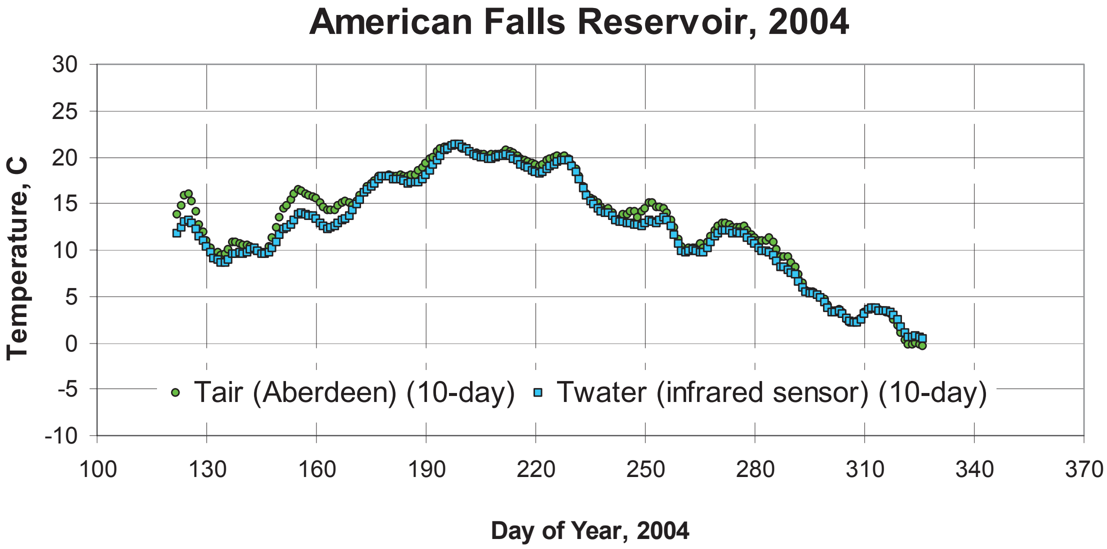
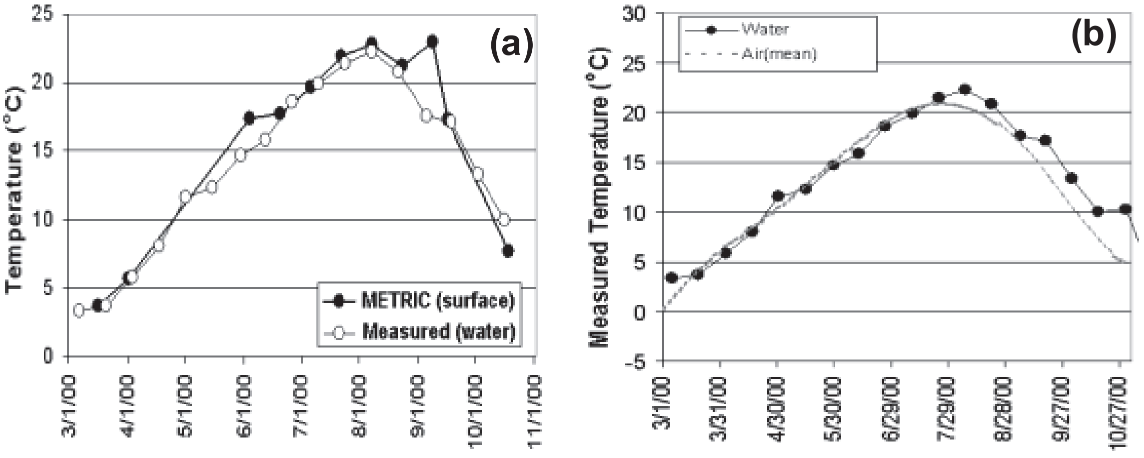


Figure 10.1. Water surface temperature of American Falls Reservoir measured by infrared thermometer (mounted on shore) and mean daily air temperature recorded at the Aberdeen AgriMet station during 2004.



(Figure 10 of Allen and Tasumi, 2005). (a) Satellite measured reservoir surface temperature and water temperature at downstream of the AMF dam (from Univ. Idaho); (b) the same water temperature and smoothed air temperature from the Aberdeen station of AgriMet (BOR, 2005).

Figure 10.2 below is a similar plot to Figure 10b of Allen and Tasumi, but for year 2004 and with 10-day running average mean daily air temperature rather than the smoothed air temperature curve of Allen and Tasumi. The water temperature in Figure 10.2 is for the Snake River below American Falls reservoir, collected by the University of Idaho. The relationship between T_s and T_{air} is similar between the two years (2000 and 2004).

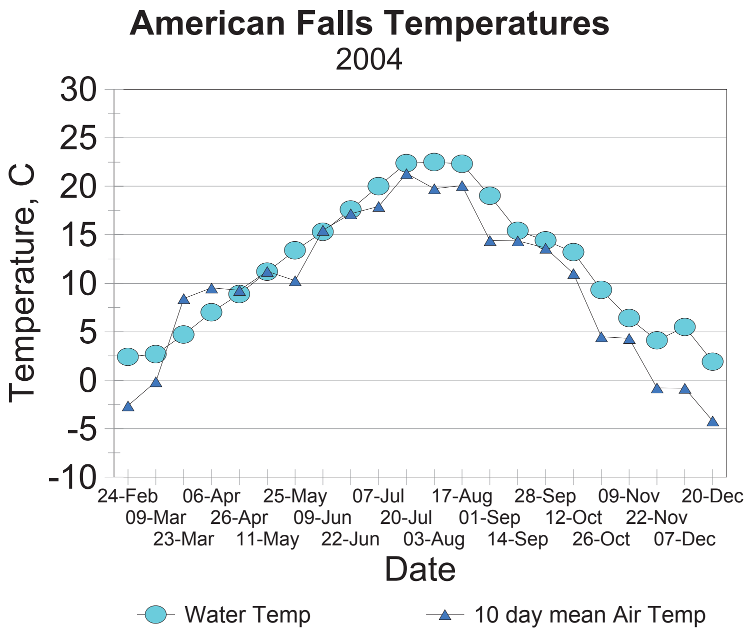


Figure 10.2. Water temperatureof Snake River downstream of the AMF dam (from Univ. Idaho, 2006) and 10-day average mean daily air temperature at the Aberdeen station of AgriMet (BOR, 2005).

Based on the above figures and an evaporation analysis described next, Table 10.2, containing smoothed, mean differences between T_s and T_{air} has derived for use in estimating water surface temperature from mean daily air temperature. These temperature differences reflect general relationships between multiple-day mean air temperature and water surface temperature of American Falls Reservoir. These mean differences are used to estimate T_s given 10 to 30 day average mean daily air temperature:

$$T_s = T_{air} + D_{month} \tag{10.7}$$

where D_{month} is the value taken from Table x.

Table 10.2. Monthly difference (D) between water surface temperature (T_s) and daily mean air temperature at Aberdeen AgriMet station.

Month	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept	Oct.	Nov.	Dec.
$D = T_s - T_{air}$, °C	4	3	1	0	0	0	0	1	1	3	4	4

Application to American Falls, 2004

Evaporation from American Falls Reservoir was estimated on a daily time step using Eq. 10.1-7 and mean daily air temperature and mean daily wind speed from the Aberdeen AgriMet station. Daily estimates were summed over each month and ratios of evaporation to reference ET_r were determined. These 'ET_rF' fractions are plotted in Figure 10.3 for all twelve months of 2004 along with ET_rF fractions determined by Allen and Tasumi (2005) using micrometeorological measurements from the reservoir in 2004. The Values for D in Table 10.2 were refined, based on Figures 10.2-10.4 and based on comparison of ET_rF estimates by the aerodynamic model and those by Allen and Tasumi. Other than for the month of July, which was noted to be an uncertain value by Allen and Tasumi, the agreement is relatively good. A constant value for an effective $z_{om} \sim z_{ov} = 0.00005$ m was applied to all months, which resulted in a value for $C_E = 0.0015$, which is similar to the value recommended by Kondo (1975).

Values for ET_rF rise during winter time due to the effect of warmer water, relative to air, and lower humidity of the air as compared to the ET_r reference. Total rates of evaporation during winter are relatively low, however, as illustrated in Figure 10.4. The estimates for winter assume no ice coverage. Error caused by ice coverage would be relatively small, since evaporation estimates during winter are small, even for open water (Figure 10.4).

For year 2004, the total estimated evaporation from American Falls reservoir over the 12 month period was 620 mm whereas total calculated alfalfa reference ET_r (ASCE Penman-Monteith method) was 1470 mm. The ratio of evaporation to ET_r for the year was 0.42.

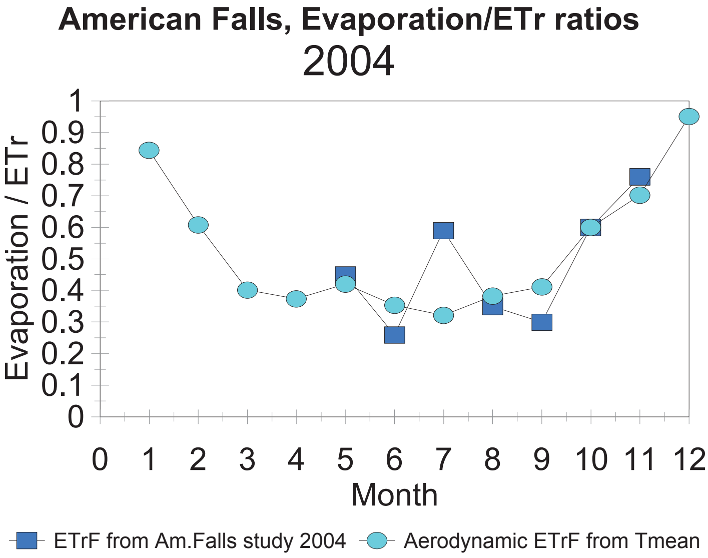


Figure 10.3. Monthly ratios of evaporation from American Falls Reservoir relative to alfalfa reference ET_r for year 2004, based on Equations 1-7 and Tables 10.1 and 10.2. ET_r is based on the ASCE standardized Penman-Monteith equation.

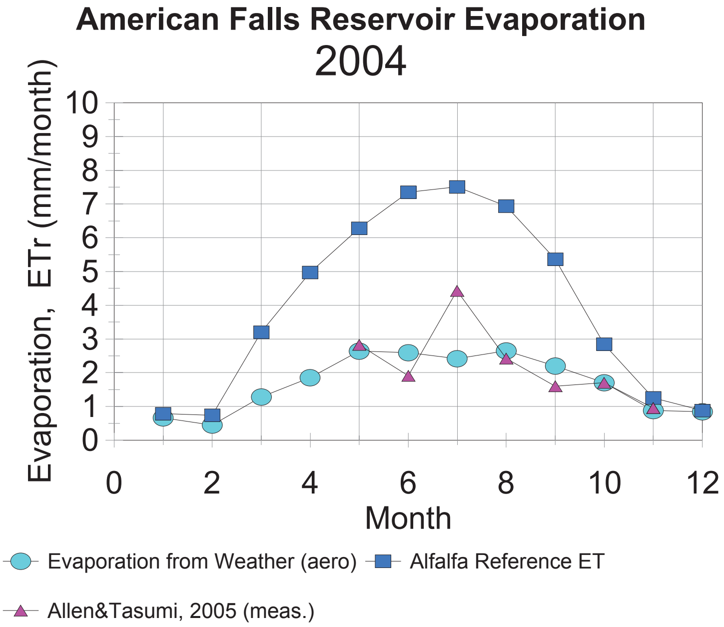


Figure 10.4a. Monthly evaporation rates from American Falls reservoir as estimated from Eq. 10.1-7 ('aero' method) and as estimated from ET_rF values of Allen and Tasumi (2005). Also plotted is the alfalfa reference ET_r.

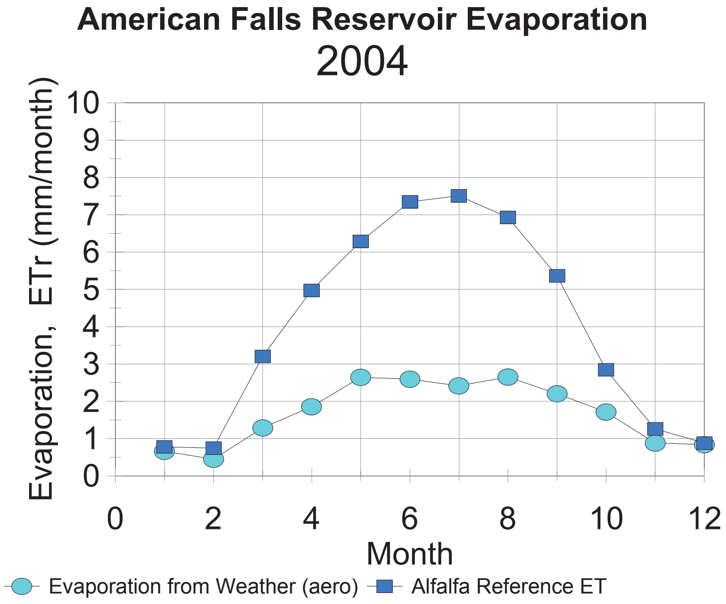


Figure 10.4b. Monthly evaporation rates from American Falls reservoir as estimated from Eq. 10.1-7 ('aero' method) along with the alfalfa reference ET_r.

Sensitivity of Aerodynamic Estimates to Estimated Water Surface Temperature. Some uncertainty exists in the estimate for T_s derived from air temperature, especially during fall, winter and spring periods. Figures 10.5a and b show impacts on estimated ET_rF and evaporation rates from American Falls Reservoir when the estimates for T_s are elevated or de-elevated by 3°C (5° F) each month. Impacts on evaporation rates are largest during summer, however, during this period, the close coupling between T_s and T_{air} is the most certain, and therefore, estimation error in T_s is probably less than 1°C on average. Impacts of 3°C bias are less pronounced during winter, early spring and late fall, since total evaporation rates are lower during those periods due to lower T_s values. Impacts on ET_rF during winter appear large, since ET_rF is based on small values for ET_r in winter.

In total, error in applying the method described in Eq. 1-7 and estimating T_s from T_{air} is estimated to be less than +/- 15% to 20% (+/- 100 mm) on an annual basis.

Application to historical periods. Equations 101-7 and values for D in Table 10.2 were applied to historical periods dating back to the 1800's. Wind speed for the applications was assigned to historical periods using mean monthly values from a local AgriMet weather station or airport station (in northern Idaho). Monthly wind speed values for Aberdeen are summarized in Table 10.3

Table 10.3. Mean monthly wind speed (m/s) at the Aberdeen AgriMet station for period 1991 – 2002.

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
3.0	2.9	3.0	3.2	2.9	2.6	2.1	2.0	2.1	2.7	2.7	2.8

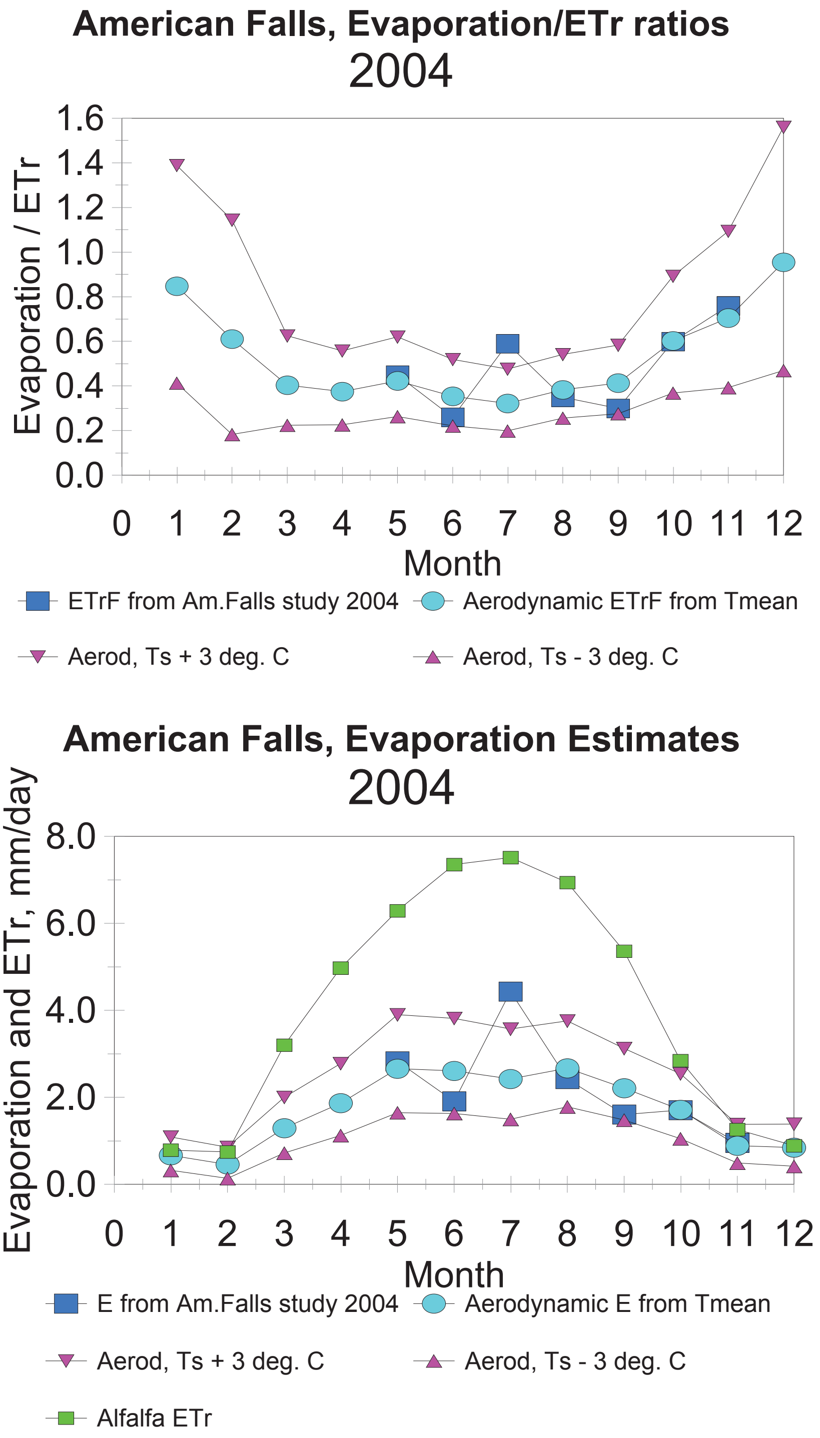


Figure 10.4. Impacts of elevating or de-elevating water surface temperature T_s by 3°C (5° F) each month on a) estimated ET_rF and b) evaporation rate from American Falls Reservoir.

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APPENDIX 11

FORMATTING AND CONTENT OF CROP AND LAND-USE EVAPOTRANSPIRATION PRODUCT FILES

Daily Evapotranspiration Files

The daily ET_c “time series” files are assembled as one or two files per station and contain daily information for entire periods of record. Each of the two files per station has ET_c information for up to 34 crops or land use conditions. For weather stations having more than 34 crop or land use conditions, a second file was created to contain the additional crops or land use conditions. The primary file was limited to 34 crops to limit the total number of data columns in the file to 256. This provides the ability to import the files directly into most common spreadsheet systems.

The names of the ET_c files for the National Weather Service (NWS) stations contain the National Climatic Data Center “Coop ID” number, for example, 109303 for Twin Falls 6 E station plus the letters “*ETc*” plus either an ‘a’ for the first file of 34 or fewer crop/land use types or a ‘b’ for the second file containing crop/land use types in excess of 34. The extension to these files is ‘*.dat*.’ For example, the names of the two daily ET_c files for the Twin Falls 6 E station are 109303ETca.dat and 109303ETcb.dat.

The daily ET_c files are ‘flat’ text (i.e., ‘ASCII’) files with all columns of data separated by one or more blank spaces. The daily ET_c files contain daily ET_c data for the full period of record for the particular station, with some files dating to the 1800’s. All NWS files conclude at 12/31/2004 (or earlier), as the end of 2004 was the last period for which data were obtained.

ET_c files are also available for sixteen AgriMet weather stations across southern Idaho. Periods of record for these stations typically begin in the late 1980’s or 1990’s and end on 12/31/2005. The names for the files for the AgriMet stations range from 1 to 16 plus “*ETca.dat*” or “*ETcb.dat*” .

The full list of weather station names along with assigned file numbers are provided in Tables 3 and 4 of the main report. The ID numbers used in file names for the NWS stations are contained in the “NCDC Coop no” column of Table 3 and the ID numbers used for Agimet stations are contained in the column of Table 4 labeled “Internal AgriMet Sta. no.”.

The daily files contain reference ET and reported precipitation in units of mm/day, along with the computed 30-day average daily mean air temperature (T30). The value for T30 is for the 30-day period ending on the particular date. T30 was used to estimate starts of growth periods for many types of crops.

The file header is comprised of five lines that describe the date of computation, the station ID number and internal station ‘ET number’ as well as the station latitude, longitude and elevation (in decimal degrees and feet). The fourth line of the header lists the number of crop/land use types in the specific file as well as the total number of crop/land use types for the station in total. Following these values, each crop/land use type is listed beginning with its specific number (1 through 57) followed by a short 41 character description of the crop or land use.

The last line in the header describes each data column. The first seven columns, headed by “*Year DoY Mo Dy PMETr Pr.mm T30*” represent the year, day of year (1-366), month, day of month, alfalfa reference ET computed by the ASCE Penman-Monteith ET_r method, gross precipitation, and 30-day mean air temperature. Following these seven columns, seven columns appear for each crop: "*ETact ETpot ETbas Irrn Seasn Runof DPerc*" These columns are defined as follows:

ETact – *Actual daily* ET_c. *ETact* represents the total estimated flux of ET given any reduction in potential ET caused by soil water shortage or soil surface dryness. *ETact* is computed as $ETact = K_s\, ETbas + K_e\, ET_r$, where ET_r is alfalfa reference ET, K_s is a stress factor (0 – 1 where 1 means no stress) and K_e is the evaporation coefficient. *ETbas* is defined below. <u>*ETact* is often less than *ETpot*</u> for rainfed crops and occasionally for irrigated crops prior to the growing season when a low-level, basal crop coefficient for the nongrowing season cover can not be sustained by precipitation, or early in the growing season prior to initiation of irrigation. *ETact* includes evaporation from the soil surface from both precipitation and any simulated irrigation.

ETpot – *Potential daily* ET_c. *ETpot* represents the total estimated flux of ET that would occur <u>if</u> there were no moisture stress imposed by soil water shortage in the 'root zone.' *ETpot* includes evaporation from the soil surface from both precipitation and any simulated irrigation. *ETpot* is computed as $ETpot = ETbas + K_e\, ET_r$, where ET_r is alfalfa reference ET.

ETbas – *Basal ET*. *ETbas* represents the ET that would occur under no water stress and with no surface wetting by precipitation or irrigation. In other words, *ETbas* represents potential ET for a dry soil surface. *ETbas* should not be used to estimate irrigation water requirements, and is included to provide an indication of the amount of *ETpot* that is primarily 'transpiration', as opposed to any amount that is from evaporation of water from the soil surface layer. *ETbas* is calculated as $K_{cb}\, ET_r$ where K_{cb} is the basal crop coefficient and ET_r is the alfalfa reference ET representing climatic demand.

Irrn – *Irrigation*. Irrigation timing and amount is simulated using a daily soil water balance. Irrigations are scheduled when the root zone dries to the threshold point where stress will begin to occur (*MAD* point). Therefore, the irrigation frequency and depth per irrigation represent that for surface and fixed grid types of sprinkler systems such as wheelline and handlines. The frequency would be greater than that estimated for center pivot and solid set types of sprinkler systems where smaller depths are applied each irrigation. These latter systems could have somewhat greater *ETact* and *ETpot* than was simulated due to somewhat greater evaporation losses from the more frequent event. For crops that have nearly full ground cover, however, the increase would be small, since the full crop cover essentially utilizes all available energy for transpiration and thus little remaining energy is available to support evaporation.

Seasn – The '*Seasn*' column contains a 'flag' that is 1 when the date is inside the estimated growing period and 0 when outside the growing season. The growing period is defined as the time from first green-up or planting of the crop or land-use type until the time of harvest or senescence or killing frost. The season start and end may vary from year to year for some crops or vegetation types where the season start is estimated using T30 or cumulative growing degree days and/or where season length is estimated using cumulative growing degree days or is terminated by frost. In the case of the three primary 'land cover' types (bare soil, mulch and 'dormant turf'), the season flag is always on.

Runof – *Surface runoff* from precipitation. Surface runoff is estimated during precipitation events using the NRCS curve number as described elsewhere.

DPerc – *Deep percolation below the root zone. DPerc* represents water, in mm/day, percolating below the maximum root zone depth for the crop or land-use cover. This water is considered to be unrecoverable for fulfilling any ET requirements and is assumed to enter a ground-water system. There are no estimates for upward capillary fluxes into the root zone from below the root zone. The *DPerc* during irrigation events may contain 10% of the irrigation depth (the amount of water required to refill the rootzone). This 10% was included in the ET computations to provide recharge to depths in the soil profile that are above the maximum rooting depth but that are below the current rooting depth of the crop. This was necessary to simulate buildup of soil water during irrigation events that is used later in the season as roots may deepen. This phenomenon is typical in practice.

Any missing data in the daily ET_c files are denoted as –99. Generally, missing data occurred due to missing air temperature data for a day that precluded the calculation of ET_r. Often, entire months were missing from NWS files obtained from the NOAA-NCDC system (via the Inside Idaho archive).

The daily ET_c files can be large, exceeding 60 mb for some stations having long periods of record and many crop/land use conditions.

The total crop and land use condition types that may be included in a ET_c file are listed in the following table. Some crops or land-use types are never irrigated even at stations that are in traditionally irrigated areas. For example, mustard and canola crops and desert grasses and sage brush are never irrigated. Crops near stations in traditionally rainfed areas (those without an irrigation flag = 1 in the station file (Tables 5.2 and 5.3 of Appendix 5) and in the header of the time series and statistics files) were assumed to not be irrigated, for example for many stations in northern Idaho such as Grangeville or Moscow. At these stations, crop stress and reduction in *ETact* below *ETpot* were simulated whenever accumulated precipitation in the root zone fell below levels necessary to supply full ET demands. Irrigation of a crop when near a weather station in a traditionally irrigated area (irrigation flag = 1) is noted in the following Table 11.1.

Table 7 in the main text includes a numeric 'Irrigation Flag' in Table 7 that indicates whether the crop was assumed to be irrigated and therefore some increased evaporation from wet soil. An irrigation flag equal to 0 indicated that the crop or land-use condition was never irrigated, regardless of location and a flag equal to 3 indicated that the crop was always irrigated. An irrigation flag equal to 1 or 2 indicated that the crop or surface was irrigated if in an irrigated region (see Tables in Appendix 5 for station environment information) and was not irrigated if in a region that does not generally have irrigation, for example in much of northern Idaho.

The land use types of wetlands, cottonwoods, willows and open water were assumed to always have full access to water supply due to the nature of their typical locations near shallow ground-water and growing conditions.

Table 11.1. Crop or Land Use Name and Brief Description.

Crop/ Land -use No.	Crop or Land Use Name and Brief Description	Irrigated ? (if in irrig. region)
1	Alfalfa Hay - peak (no cutting effects (i.e., alfalfa reference except early and late))	y
2	Alfalfa Hay – frequent cutting - dairy style ~4 cuttings	y
3	Alfalfa Hay – less frequent cutting - beef cattle style ~3 cuttings	y
4	Grass Hay	y
5	Snap and Dry Beans - fresh	y
6	Snap and Dry Beans - seed	y
7	Field Corn having moderate lengthed season	y
8	Silage Corn (same as field corn, but with truncated season)	y
9	Sweet Corn--early plant	y
10	Sweet Corn--late plant	y
11	Spring Grain—Irrigated	y
12	Spring Grain—Rainfed	
13	Winter Grain--Irrigated	y
14	Winter Grain—Rainfed	
15	Grass Pasture – high management	y
16	Grass Pasture – low management	y
17	Grass - Turf (lawns)—Irrigated	y
18	Grass - Turf (lawns)--Rainfed	
19	Orchards - Apples and Cherries w/ground cover	y
20	Orchards - Apples and Cherries no ground cover	y
21	Garden Vegetables – general	y
22	Carrots	y
23	Onions	y
24	Melons	y
25	Grapes--wine	y
26	Alfalfa Seed	y
27	Garden Peas--fresh	y
28	Garden Peas--seed	y
29	Potatoes--processing (early harvest)	y
30	Potatoes--cold pack (late harvest)	y
31	Sugar beets	y
32	Hops	y
33	Mint	y
34	Poplar (third year and older)	y
35	Lentils	
36	Sunflower—Irrigated	y
37	Sunflower—Rainfed	
38	Safflower—Irrigated	y
39	Safflower--Rainfed	
40	Canola	
41	Mustard	
42	BlueGrass Seed	
43	Asparagus	y
44	Bare soil	
45	Mulched soil, including wheat stubble	
46	Dormant turf (winter time)	
47	Range Grasses- early, short season (cheat, etc.)	
48	Range Grasses- long season (bunch, wheatgrass, etc.)	
49	Range Grasses- bromegrass	
50	Sage brush	
51	Wetlands--large stands	
52	Wetlands--narrow stands	
53	Cottonwoods	
54	Willows	
55	Open water – shallow systems (large ponds, streams)	
56	Open water – deep systems (lakes, reservoirs)	
57	Open water – small stock ponds	

Monthly Time Series

Files for monthly ET_c time series have names that follow the same convention for daily ET_c files. The latter portion of the name carries the label '*ETc_monthly.dat*', for example, for Twin Falls 6 E, the name for the monthly file is "*109303ETc_monthlya.dat*". The monthly files are assembled as one or two files per station. Each file has ET_c information for up to 41 crops or land use conditions. For weather stations having more than 41 crop or land use conditions, a second file was created to contain the additional crops or land use conditions. The primary file was limited to 41 crops to limit the total number of data columns in the file to 256. This provides the ability to import the files directly into most common spreadsheet systems. The names of the ET_c files terminate with either an 'a' for the first file of 41 or fewer crop/land use types or a 'b' for the second file containing crop/land use types in excess of 41. The extension to these files is '*.dat*.'

The monthly ET_c time series files have 10 lines of header information that contain similar information as for the daily time series files. The header notes the time and date of computation of the original daily ET_c information as well as the time and date of computation of the monthly summaries (series).

The first three columns of data contain the year, the month number (1-12) and the number of 'valid' days in the month (*V.Dys*). *V.Dys* represents valid days (that do not have a –999 flag in the daily ET_c file caused by lack of weather data). The next two columns are average reference ET_r (*ETr*) and average daily precipitation (*Prec.*), both expressed as mm/day averaged over the month.

Any missing data in the monthly ET_c time series files are denoted as –999. Generally, a monthly period in a time series was marked as missing if air temperature data were missing for all days in that month. Entire months were frequently missing from NWS files obtained as from the NOAA-NCDC system (via the Inside Idaho archive).

There are six columns of data presented for each crop or land use cover that are defined as follow:

ETact – *Actual* ET_c averaged over the month. This is the same parameter as *ETact* in the daily ET_c files. *ETact* represents the total estimated flux of ET given any reduction in potential ET caused by soil water shortage or soil surface dryness. *ETact* is computed as $ETact = K_s\, ET_{bas} + K_e\, ET_r$, where ET_r is alfalfa reference ET, K_s is a stress factor (0 – 1 where 1 means no stress) and K_e is the evaporation coefficient. ET_{bas} is the 'basal' ET representing a dry soil surface and is defined above in the daily ET_c section. *ETact* is often less than *ETpot* for rainfed crops and occasionally for irrigated crops prior to the growing season when a low-level, basal crop coefficient for the nongrowing season cover can not be sustained by precipitation, or early in the growing season prior to initiation of irrigation. *ETact* includes evaporation from the soil surface from both precipitation and any simulated irrigation.

ETpot – *Potential daily* ET_c averaged over the month. *ETpot* represents the total estimated flux of ET that would occur if there were no moisture stress imposed by soil water shortage in the 'root zone.' *ETpot* includes evaporation from the soil surface from both precipitation and any simulated irrigation. *ETpot* is computed as $ETpot = ETbas + K_e\, ET_r$, where ET_r is alfalfa reference ET.

P_def – *Precipitation deficit*. The precipitation deficit is the difference between the potential ET (*ETpot*) and the amount of precipitation that infiltrates the root zone. *P_def* is calculated as *ETpot* – *P_rz* and is synonymous with the ***irrigation water requirement*** when applied during the growing season for an irrigated crop. *P_def* represents the amount of additional water that the crop would consume (evapotranspire) beyond *P_rz* if that water were made available at the right time during the growing or nongrowing season. The *ETpot* estimate includes soil evaporation for known precipitation and simulated irrigation events. The *P_def* (i.e., irrigation water requirement), if summed only during the growing season, does not include the impact of *P_def* during the nongrowing season in providing stored soil moisture that may offset irrigation during the growing season.

P_rz – *Precipitation residing in the root zone.* *P_rz* is the amount of gross reported precipitation that infiltrates into the soil (i.e., less any surface runoff) and that remains in the root zone for consumption by evaporation or transpiration. *P_rz* is computed as *P – Runoff – DPerc* where *P* is gross reported precipitation, *Runoff* is estimated surface runoff and *DPerc* is deep percolation of any precipitation below the maximum rootzone for the crop or land-use condition. The difference between *P_rz* and *ETact* during the nongrowing season represents the amount of 'recharge' or 'build-up' of moisture to the root zone during the nongrowing season (i.e., increase in soil water storage) that would be available at the start of the growing season to later partially fulfill plant water requirements. The ratio of (*P_rz – ETact*)/*P* computed during the nongrowing period represents the 'efficiency' or effectiveness of gross precipitation, including snow, in building soil water for use during the growing season.

P_efT – *Precipitation residing in the root zone that is available for transpiration (rather than for evaporation).* *P_efT* is the amount of gross reported precipitation that infiltrates into the soil (i.e., less any surface runoff) and that remains in the root zone for use in supplying *transpiration* by the crop or land use cover. *P_efT* does not include the amount of infiltrated precipitation that evaporates from the surface evaporation layer (upper 100 mm of soil). The *P_efT* parameter is useful in estimating the amount of precipitation during the nongrowing season that is stored over the long term and made available for transpiration requirements during the growing season. *P_efT* is always less than *P_rz*. *P_efT* is useful during the growing season to determine how 'efficient' precipitation is in fulfilling transpiration requirements of crops, as opposed to simply 'burning off' as evaporation from the soil surface. *P_efT* was calculated as *P_efT = P_rz - surface evaporation losses = P – Runoff – DPerc - surface evaporation losses*, where *P_rz* is precipitation infiltrating and residing in the maximum root zone for the crop, *P* is gross reported precipitation, *Runoff* is estimated surface runoff and *DPerc* is deep percolation of any precipitation below the maximum rootzone for the crop or land-use condition.

SeDys – The number of *growing season days* within the particular month. *SeDys* was computed by summing the *Seasn* flag contained in the daily ET_c files.

ETact, ETpot, P_rz and *P_def* are all reported in units of mm/day averaged over the month.

Annual Time Series

The annual ET_c time series files contain the same information as the monthly ET_c time series files. The annual files have names that follow the same convention for daily ET_c files previously described. The latter portion of the name carries the label '*ETc_annual.dat*', for example, for Twin Falls 6 E, the name for the monthly file is "*109303ETc_annuala.dat*". The annual files are assembled as one or two files per station. Each file has ET_c information for up to 41 crops or land use conditions. For weather stations having more than 41 crop or land use conditions, a second file was created to contain the additional crops or land use conditions. The primary file was limited to 41 crops to limit the total number of data columns in the file to 256. This provides the ability to import the files directly into most common spreadsheet systems. The names of the ET_c files terminate with either an 'a' for the first file of 41 or fewer crop/land use types or a 'b' for the second file containing crop/land use types in excess of 41. The extension to these files is '*.dat*.'

The annual ET_c time series files have 10 lines of header information that contain similar information as for the monthly and daily time series files. The header notes the time and date of computation of the original daily ET_c information as well as the time and date of computation of the annual summaries (series).

The first four columns of data contain the year and the number of 'valid' days in the year (*V.Days*). *V.Days* represents those days that do not have a –999 flag in the daily ET_c file caused by lack of weather data. The next two columns are total reference ET_r (*ETr*) and total precipitation (*Prec.*) for the calendar year, both expressed as mm over the year. It is important to note that both *ETr* and *Prec.* represent the entire calendar year (365 or 366 days), including winter periods.

Units for ET and precipitation are all in mm/year. Any years that had less than 350 days of valid data or more than 5 days of missing data during the growing season (defined as the growing period for grass hay) were reported as –999. Years having one to fifteen missing days during the year (and fewer than 6 missing days during the growing season) had annual values for ET and precipitation deficit adjusted by multiplying by 365 or 366 divided by the number of valid days. Any years that had more than 5 days of missing data during the growing season for a crop were reported as –999 for the seasonal ET totals. Years having one to five missing days had growing values for ET and precipitation deficit (used later in the statistics files) adjusted by multiplying by the length of the growing season divided by the number of valid days in the season.

There are six columns of annual data presented for each crop that are defined as follow:

ETac – *Actual* ET_c summed over the year. This is the same parameter as *ETact* in the daily ET_c files. *ETac* (or *ETact*) represents the total estimated flux of ET given any reduction in potential ET caused by soil water shortage or soil surface dryness. *ETact* is computed for daily timesteps as $ETact = K_s\, ET_{bas} + K_e\, ET_r$, where ET_r is alfalfa reference ET, K_s is a stress factor (0 – 1 where 1 means no stress) and K_e is the evaporation coefficient. ET_{bas} is the 'basal' ET representing a dry soil surface and is defined above in the daily ET_c section. *ETact* is often less than *ETpot* for rainfed crops and occasionally for irrigated crops prior to the growing season when a low-level, basal crop coefficient for the nongrowing season cover can not be sustained by precipitation, or early in the growing season prior to initiation of irrigation. *ETact* includes evaporation from the soil surface from both precipitation and any simulated irrigation.

ETpt – *Potential daily* ET_c summed over the year. *ETpt* (or *ETpot*) represents the total estimated flux of ET that would occur if there were no moisture stress imposed by soil water shortage in the 'root zone.' *ETpot* includes evaporation from the soil surface from both precipitation and any simulated irrigation. *ETpot* was computed for daily timesteps as $ETpot = ETbas + K_e\, ET_r$, where ET_r is alfalfa reference ET.

P_Df – *Precipitation deficit.* The precipitation deficit is the difference between the potential ET (*ETpot*) and the amount of precipitation in the root zone. *P_Df* (or *P_def*) is calculated as *ETpot* – *P_rz* and is synonymous with the *irrigation water requirement* for an irrigated crop (as summed over the calendar year). *P_Df* represents the amount of additional water that the crop would evaporate beyond *P_rz* if that water were made available at the right time during the growing or nongrowing season. It is important to note that in general, *ETpot* during the nongrowing season increases in response to *P_Df* due to evaporation associated with precipitation events.

P_rz – *Precipitation residing in the root zone*. *P_rz* is the amount of gross reported precipitation that infiltrates into the soil (i.e., less any surface runoff) and that remains in the root zone for use in evaporation or transpiration. *P_rz* was computed on a daily basis as *P – Runoff – DPerc* where *P* is gross reported precipitation, *Runoff* is estimated surface runoff and *DPerc* is deep percolation of any precipitation below the maximum rootzone for the crop or land-use condition.

P_efT – *Precipitation residing in the root zone that is available for transpiration (rather than for evaporation)*. *P_efT* is the amount of gross reported precipitation that infiltrates into the soil (i.e., less any surface runoff) and that remains in the root zone for use in supplying transpiration by the crop or land use cover. *P_efT* does not include the amount of infiltrated precipitation that evaporates from the surface evaporation layer (upper 100 to 150 mm of soil). The *P_efT* parameter is useful in estimating the amount of precipitation that is stored over the long term and made available for transpiration requirements. *P_efT* is useful to determine how 'efficient' precipitation is in fulfilling transpiration requirements of crops, as opposed to simply 'burning off' as evaporation from the soil surface. *P_efT* was calculated as *P_efT = P_rz - surface evaporation losses = P – Runoff – DPerc - surface evaporation losses*, where *P_rz* is precipitation infiltrating and residing in the maximum root zone for the crop, *P* is gross reported precipitation, *Runoff* is estimated surface runoff and *DPerc* is deep percolation of any precipitation below the maximum rootzone for the crop or land-use condition.
DSn – The *number of growing season days* within the calendar year. *DSn* was computed by summing the *Seasn* flag contained in the daily ET_c files over the calendar year.

As a reminder, all ET and precipitation parameters reported in the annual file are for the full calendar year, including the nongrowing season. This was done to provide information required to conduct full hydrologic-types of water balances. To determine ET and precipitation parameters during the growing period only, one can sum parameters over the months in the growing season (from the 'monthly' files). Endpoint months (for planting and harvest) can be proportioned according to the number of growing period days in the month, or perhaps more accurately and realistically, by including the entire month's values, since the majority of ET reported for a partial month will probably have occurred within the portion of the month residing within the growing period, and impacts of pre-planting and post-harvest activities can generally be considered to be included in the 'growing period'.

Statistics Files

There are four 'statistics' files per weather station. These files contain statistical summaries for 1) *actual ET*; 2) *potential ET*; 3) *'basal' ET*; and 4) *Precipitation deficit* (i.e., *irrigation water requirement*). The files have names beginning with the station coop number or, in the case of AgriMet stations, numbers ranging from 1 to 16, and ending with '*ETcact_stats.dat*', '*ETcpot_stats.dat*', '*ETcbas_stats.dat*' or '*Prec_def_stats.dat*'. For example, in the case of Twin Falls 6 E station, the four files are named *109303ETcact_stats.dat*, *109303ETcpot_stats.dat*, *109303ETcbas_stats.dat* and *109303Prec_def_stats.dat*. The *ETcact* represents actual ET, *ETcpot* represents potential ET, *ETcbas* represents 'basal' ET and *Prec_def* represents the precipitation deficit. All of these terms have been defined under the daily, monthly or annual time series sections above. The *Prec_def* is the same as the net irrigation water requirement when occurring during the irrigation season and if any beneficial carryover storage of precipitation during the nongrowing season is considered.

The four files all contain headers comprised of 12 lines containing similar information including the time and date of the original calculation of daily ET and the time and date of the calculation of the statistical summaries. The headers also contain the station latitude and longitude in decimal degrees and station elevation in feet.

Each crop or land-use type that was processed for a station is contained in the statistics files in sequential order, following a single entry for reference ET (in the '*ETcact_stats*' file), for gross precipitation (in the '*ETcpot_stats*' file), or for 30 day average daily mean air temperature (in the '*ETcact_stats*' file).

The values for the parameters have been averaged over four different lengths of averaging periods during each month. These averaging periods have lengths of 3, 7, 15 and 30 (monthly) days. These period lengths were selected to represent possible lengths of irrigation intervals or drying periods of interest. For example, if a potato crop is irrigated each 3 days during July, then the user would be interested in reviewing the statistics describing the 3 day periods within the month of July for irrigation system design. If a crop of sugar beets having a deeper effective root zone is irrigated on average each two weeks during August, then the user would be interested in reviewing the statistics describing the 15 day periods within the month of August for irrigation system design.

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 span of the 30 year 'normals' (i.e., first and last year) are listed for each crop. The span of the normal periods could poentitally change with crop type, depending on the timing of any missing data (inside or outside growing periods). The span of the normal period can exceed 30 years if some intervening years were omitted due to missing data.

The 30 year normal periods were used to generate means and other 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 (1966-1795) 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 specific station location, 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 record 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.

For each crop, the following data columns are reported for each month, for the calendar year ('Ann.' row) and for the growing season ('Sea.' row):

Mean – *Mean value* for the month and over the 'normal' period of record for the location. *Mean* represents either *ETcact, ETcpot, ETcbas* or precipitation deficit, depending on the file. Units are in mm/day for monthly periods and mm for annual and seasonal periods. The '*nyr*' column represents the number of years that had 'valid' entries for the month (i.e., a minimum of missing data) and that were included in the mean. Generally, if a full normal period was available, *nyr* = 30. The actual period of record for the station may have been much longer and is preserved in the time series files.

Values for means are reported for the monthly, 15 day, 7 day and 3 day averaging periods within each month. In general, these four means are nearly the same, and are reported only for documentation. Means for the 15, 7 and 3 day periods can deviate from those for the entire month because some information from near the beginning and end of the month may not have the same weight. This was caused by the requirement that each 3, 7 or 15 day period considered for a month must have all of its member days residing within the month evaluated. For example, for the 15 day statistics, generally 13 to 16 separate 15 day averages were computed and considered for a specific month and year. The member days for the 15-day averages were days 1-15, days 2-16, days 3-17, ……, days 14-28, days 15-29, days 16-30, and days 17-31. Therefore, days nearer to the beginning and end of a period appeared fewer times in the computed means for the month. Thus, some differences in monthly means occurred between the 3, 7, 15 and monthly periods. Differences were generally small.

Stdev – *Standard deviation* of the variable for the month over the normal period of record. The *Stdev* entry for a particular month was computed using one value (the observation mean) per year for the month. Units are in mm/day for monthly periods and mm for annual and seasonal periods.

Skew – The *skew of the distribution of values* is shown for the variable for each month for the monthly means (only) over the period of record. The skew for a particular month was computed using one value (the observation mean) per year for the month. A value for skew near zero indicates that the underlying distribution approximates a normal (Gaussian) and symmetrical distribution. A skew near 1.0 indicates that the underlying distribution approximates a lognormal distribution. The values for skew, standard deviation and mean can be used to parameterize a variety of probability density functions such as the normal, lognormal, Pearson, and Gamma distributions.

Kurt. – *Kurtosis* is a measurement of the 'slenderness' of the underlying distribution; in other words, the 'height to width ratio' of the probability density function. A normal (Gaussian) distribution has a kurtosis of 3. The higher the number, the more tall and slender the distribution. A high kurtosis indicates that many of the observations in the distribution have very similar values. Kurtosis was calculated for monthly averages only over the normal period.

20%Ex – The *20%Ex* value represents the *value* for the parameter (actual, potential or basal ET or the precipitation deficit) *that has a 20% chance of being exceeded* that month during any particular year. Conversely, there is an 80% chance that the value of the parameter (for the particular length of averaging period) will be less than the *20%Ex* value. The *20%Ex* value is commonly used in design of capacity for irrigation and water supply systems. Units for *20%Ex* are in mm/day for monthly periods and mm for annual and seasonal periods. The *20%Ex* values were computed assuming a 'distribution free' probability density function. The values were selected by ranking the highest 3-, 7-, 15- or 30-day value within the month for *ETact, ETpot, ETbas* or *P_def* for each year of the 30 year normal period and selecting the value that was positioned 20% of the way down from the highest value. There were '*nyrs*' values that were ranked (one for each year). In this way, the *20%Ex* value represents that value for the parameter (*ETact, ETpot, ETbas* or *P_def*) that, when averaged over any 3-, 7-, 15- or 30- day period within the month, would have only a 20% chance of being exceeded at any time during that month for the given year. Thus, if an irrigation system were designed with capacity to provide the *20%Ex* amount of *P_def* over a 7-day period, for example, the system's 'net' output (less any incidental leakage, spray drift or uniformity 'losses') would exceed the actual precipitation deficit (i.e., the ET less any infiltrating precipitation) 8 years out of 10. During two years out of any 10 year period, the

ET less any infiltrating precipitation would exceed the net system capacity during at least one 7 day period during the particular month by some amount. The amount of the exceedence might range from only a millimeter to perhaps 15 to 20 mm over the period.

AveHi – The *AveHi* parameter complements the *20%Ex* parameter, where *AveHi* represents the average (over the 30 year normal period) of the highest value for the parameter within the 3, 7, or 15 day period for each month. Therefore, each month of each year was assigned one 'highest' value for the parameter for the 3, 7 or 15 day averaging length. Then, for each month of the year, the 30 values over the normal period were averaged to obtain *AveHi*. The value for *AveHi* for 3, 7 and 15 day periods is always greater than the average for the month itself (i.e., the 'mean'), since the *AveHi* is the mean of the highest value for the 3, 7, or 15 day period within the month. The value for *AveHi* increases as the length of the averaging period (3, 7 or 15 days) decreases. The same 30 values used to calculate *AveHi* were used in calculating the *20%Ex* value.

80%Ex – The *80%Ex* value represents the *value* for the parameter (actual, potential or basal ET or the precipitation deficit) *that has an 80% chance of being exceeded* that month during any particular year. Conversely, there is a 20% chance that the value of the parameter (for the particular length of averaging period) will be less than the *80%Ex* value. The *80%Ex* value is commonly used in design of land application systems where water application may need to be limited to amounts that have at least 80% chance of being evaporated. Units for *80%Ex* are in mm/day for monthly periods and mm for annual and seasonal periods. The *80%Ex* values were computed assuming a 'distribution free' probability density function. The values were selected by ranking the lowest 3-, 7-, 15- or 30-day value during the month for *ETact, ETpot, ETbas* or *P_def* for each year and selecting the value that was positioned 80% of the way down from the highest value. There were 'nyrs' values that were ranked (one for each year). In this way, the 80%Ex value represents that value for the parameter (*ETact, ETpot, ETbas* or *P_def*) that, when averaged over any 3-, 7-, 15- or 30- day period within the month, would have an 80% chance of being exceeded at all times during that month for the given year. Thus, if a land application system were designed with capacity to provide the *80%Ex* amount of *P_def* over a 7-day period, for example, then the systems 'net' output (less any incidental leakage, spray drift or uniformity 'losses') would exceed the actual precipitation deficit (i.e., the ET less any infiltrating precipitation) during 2 years out of a 10 year period. During eight years out of any 10 year period, the ET less any infiltrating precipitation would exceed the application amount during all 7 day periods during the particular month by some amount. The amount of the exceedence might range from only a millimeter to perhaps 15 to 20 mm.

AveLo – The *AveLo* parameter complements the *80%Ex* parameter, where *AveLo* represents the average (over the 30 year normal period) of the lowest value for the parameter within the 3, 7, or 15 day period for each month. Therefore, each month of each year was assigned one 'lowest' value for the parameter for the 3, 7 or 15 day averaging length. Then, for each month of the year, the 30 values over the normal period were averaged to obtain *AveLo*. The value for *AveLo* for 3, 7 and 15 day periods is always less than the average for the month itself (i.e., the 'mean'), since the *AveLo* is the mean of the lowest value for the 3, 7, or 15 day period within the month. The value for *AveLo* decreases as the length of the averaging period (3, 7 or 15 days) decreases. The same 30 values used to calculate *AveLo* were used in calculating the *80%Ex* value.

On an annual or growing season basis, the mean, *20%Ex* and *80%Ex* values are computed only for annual or growing season totals and represent the distribution of annual or growing season values (rather than for specific months). The *seasonal* values for *P_def* (in the 'xxxxxx*Prec_def_stats.dat*' files) represent net irrigation water requirements (*NIR*) for a particular crop during the defined growing season only. These values represent the amount of water required in excess of infiltrating precipitation (and less any precipitation that deep percolates) to fulfill the potential ET requirements during the growing season. The value for *P_def* is not discounted for soil water that is stored during the nongrowing season prior to the growing season. This amount of water can be approximated by summing differences between *P_rz* and *ETact* on a daily basis over the nongrowing season periods using data contained in the daily ETc files.

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APPENDIX 12

DESCRIPTION OF COMPUTER PROGRAMS USED IN PROCESSING

Program Files and Applications for Reference ET and Crop ET Calculations – 2006, 2007

Reference ET

The following lists computer program files used to calculate Reference ET in support of this 2007 report "Evapotranspiration and Consumptive Irrigation Water Requirements for Idaho" by Allen and Robison. Some of the programs were written in Quickbasic (QB.exe) and others in Visual Basic, version 6.

1. ***Names3.bas*** – Quickbasic language – Finds National Weather Service stations and names within the Inside Idaho 'macro' NWS weather data file and creates a summary file of station names and station ID numbers.

Reads: ALLID04.csv -- large single file of weather data obtained from Inside Idaho

Writes: STANOS.dat

2. ***UIFirst.bas*** – Quickbasic language – Splits the single large file from Inside Idaho into two files that contain "official" NWS weather data and weather data housed by UI (typically the UI housed data date earlier than the formal NWS data set and there may be some overlap) and then recombines the two files with the UI data first, since it is typically the oldest. (The ALLID04.csv file was created by Inside Idaho with the UI data placed last.

Reads: ALLID04.csv -- large single file of weather data from Inside Idaho
Reads: Results.csv
Writes: 3200.csv – "official" NWS weather data
Writes: 32UI.csv – Inside Idaho 'unique' weather data that may predate 3200.csv
Reads: 3200.csv
Reads: 32UI.csv
Writes: UI32.csv – similar to ALLID04.csv, but with UI data first.

3. ***RecSum2.bas*** - Quickbasic language - not an essential program. – finds the first and last dates in a NWS weather data file

Reads: StationF.txt
Writes: datamont.txt, startstp.txt

4. ***Split4.bas*** – Quickbasic language – splits the 'macro' file of NWS weather data received from Inside Idaho that contained data from all stations, that was rearranged by the *UIFirst.bas* program into one (or two) large text tiles, and creates individual files for each station and for each parameter type.

Reads: Stanos.dat
Writes: StaStat2.dat
Writes: StaRecs.dat
Reads: UI32.csv (macro data file from Inside Idaho)
Reads: UI32_dup.csv (duplicate of UI32.csv)
Writes: ------pr.csv, ------sd.csv, ------sw.csv, ------tx.csv, ------tn.csv, where 'pr' is precipitation, 'sd' is cumulative snow depth on ground, 'sw' is daily snow depth received, 'tx' is daily maximum air temperature and 'tn' is daily minimum air temperature. The '------' is the WBN station number.

5. ***CFiles2.bas*** – Quickbasic language – Reads the stations.txt and -----pr etc. files and notes the availability of data

Reads: stations.txt
Reads: ------pr.csv, ------sd.csv, ------sw.csv, ------tx.csv, ------tn.csv
Writes: FilesN2.txt

6. ***Create4u.bas*** – Quickbasic language – Synchronizes daily Tx, Tn, P, SD, SW data files and creates "-------d2.dat" files.

Reads: stations.txt
Writes: flushd2b.txt
Reads: ------pr.csv, ------sd.csv, ------sw.csv, ------tx.csv, ------tn.csv
Writes:------da.dat

where 'pr' is precipitation, 'sd' is cumulative snow depth on ground, 'sw' is daily snow depth received, 'tx' is daily maximum air temperature and 'tn' is daily minimum air temperature. The '------' is the WBN station number.

Create4u.bas was modified from Create4T.bas in March 2007 to shift daily Tmax and P one day back in time to adjust for the reporting format of NWS stations where yesterday's Tmax and P are reported for the date recorded (next day) rather than the actual day of occurrence.

7. ***ETr_calc5c.frm*** – Visual Basic language – Reads the -----da.dat NWS data files, estimates solar radiation and dewpoint temperature from air temperature data (on a daily basis), assigns a long-term monthly wind speed, and **calculates alfalfa reference evapotranspiration (ETr)**. VisualBasic files are: ETr_calc5c.frm for the primary code and ETr_Calc_5project3.vbp for the Visual Basic project.

Reads:Stationf.txt
Reads:Windmon.txt
Reads:Txnmon.txt (longterm monthly Tmax and Tmin)
Reads:------da.dat
Writes:Txnmon2.txt (creates new Txnmon.txt file each run (file does not change))
Writes: TxTnLog3.txt – log file showing days when Tmax < Tmin
Writes: ------ET.dat – daily reference ET by station where '------' is the WBN.

8. ***Order4.frm*** -- Visual Basic language – (see comments in file for full description) – Orders the computed ETr data chronologically (the data as received from Inside Idaho were sometimes out of order or had missing data at the beginning). VisualBasic files are: Order4.frm for the primary code and Order4.vbp for the Visual Basic project.

Reads: stationf.txt
Reads: ------ET.dat
Writes: ------E2.dat

Crop ET and Irrigation Water Requirements

The *UI_KcETr* computer program was developed to calculate crop ET and irrigation water requirements in support of this 2007 report "Evapotranspiration and Consumptive Irrigation Water Requirements for Idaho" by Allen and Robison. The program, ***UI_KcETr42.frm*** was coded in Visual basic, version 6 and is contained in Visual basic project UI_KcETr25.vbp.

Reads: *Final_Kcs_for_IDWR_17.csv* for crop curve information. File extracted from xls spreadsheet having the same name.
Reads: *Idaho_Crop_parameters28.csv* for parameters associated with each crop type. File extracted from xls spreadsheet having the same name.
Reads: *Idaho_Stations_Crops_i.csv* for list of crops associated with each weather station. File extracted from QuattroPro spreadsheet *Final_stations_Data_file_setup_v.qpw*
Reads: *Final_stations_Properties_b.csv* for weather station parameters. File extracted from QuattroPro spreadsheet *Final_stations_Data_file_setup_q.qpw*
Reads: *ETrfilename$* containing daily ETr, Precipitation, snow depth, air temperature.
For station numbers < 108 (NWS), *ETrfilename$* = ETrfilespath$ & station_IDno(ns) & "E2.dat"
For station numbers > 107 (AgriMet), *ETrfilename$* = AgriMetpath$ & "Aberdeen" & "_final_ETr_precip.dat" (where "Aberdeen" is name of AgriMet station). The AgriMet stations were created with Excel spreadsheets, based on *REF-ET* output.

Writes and Reads: *tempETc.dat* -- temporary file that contains daily ETc (row by row), with one set of seven columns per crop (*ETactual, ETpotential, ETbasal, net irrigation, growing season flag, runoff, deep percolation*). These files have columns added for each successive crop that is processed for a particular station.

Writes: *ETcfilename$* and *ETcfilename2$* -- Final files for daily ETc and NIR for all crops at a station. *ETcfilename$* contains results for the first 34 crops (to keep no. columns < 256) and *ETcfilename2$* contains the second half of crops for the station.
*ETcfilename$* = ETcfilespath$ & station_IDno(ns) & "ETc.dat" *ETcfilename2$* = ETcfilespath$ & station_IDno(ns) & "ETcb.dat" (second half of ETc file if more than 34 crops).

Filter_missing_daily7b.frm in project Filter_daily_project4b.vbp is used to clean up the start of the 'ETc.dat' and 'ETcb.dat' daily ETc data files so that the files begin on Jan. 1 of the first full year of data. *Filter_missing_daily7b.frm* also rearranges crops in the two files to start with crop no. 1 and to run sequentially.

Reads: *ETrfilename$* containing daily ETr, Precipitation, snow depth, air temperature.
For station numbers < 108 (NWS), *ETrfilename$* = ETrfilespath$ & station_IDno(ns) & "E2.dat"
For station numbers > 107 (AgriMet), *ETrfilename$* = AgriMetpath$ & "Aberdeen" & "_final_ETr_precip.dat" (where "Aberdeen" is name of AgriMet station). The AgriMet stations were created with Excel spreadsheets, based on *REF-ET* output.
Reads: *ETcfilename$* = ETcfilespath$ & station_IDno(ns) & "ETc.dat" *ETcfilename2$* = ETcfilespath$ & station_IDno(ns) & "ETcb.dat" (second half of ETc file if more than 34 crops).
Writes: *ETcfinished$* and *ETcfinished2$* -- Final files for daily ETc and NIR for all crops at a station. *ETcfinished$* contains results for the first 30 crops (to keep no. columns < 256) and *ETcfinished2$* contains the second half of crops for the station.
*ETcfinished$* = ETcfilespath$ & station_IDno(ns) & "ETca.dat" *ETcfinished2$* = ETcfilespath$ & station_IDno(ns) & "ETcb.dat" (second half of ETc file if more than 30 crops).

Statistics Calculation Program

UI_ETc_Stats22frm.frm in project Stats_project3.vbp calculates monthly and annual time series from daily time series for the periods of record and statistics describing the most current 30 year normal period. Computations are done for each crop and land cover type as well as for reference ET, 30 day mean air temperature and precipitation.

Reads: "*Idaho_Stations_Crops_i.csv*" file for the number of crops per station and other station data (irrigationflag, etc.).
Reads: "*Final_stations_Properties_b.csv*" for waterholding capacity information (used in calculating P_efT where P_efT is the component of precipitation effective in supplying transpiration).
Reads: "*xxxxxxETca.dat*" ("*xxxxxxETcb.dat*" if no. crops > 30) for the daily ETc time series, where xxxxxx is the station no.

Writes: "*xxxxxxETc_monthly.dat*" and "*xxxxxxETc_annual.dat*" files that contain monthly and annual time series for the entire periods of record and for each crop (in parallel columns)

Writes: "*xxxxxxETcact_stats.dat*", "*xxxxxxETcpot_stats.dat*", "*xxxxxxETcbas_stats.dat*", and "*xxxxxxPrec_def_stats.dat*" containing statistics (mean, standard deviation, skew, kurtosis and 20 and 80% exceedance values) for 30, 15, 7 and 3 day periods in each month as well as annual and seasonal statistics. Statistics are computed for only the last 30 years of data (30 year normals). The four files contain information on 'actual ETc', 'potential ETc', 'basal ETc' and 'precipitation deficit (i.e., net irrigation water requirement)'. These parameters are described in Appendix 11 of the final report.

UI_ETc_Monthly_Parse2.frm in project Monthly_Parse2.vbp is used to split the monthly and annual time series files created by the statistics program into two sets of files (a and b) so that the number of data columns in each file are less than 256. This allows the files to be imported into spreadsheets.

Reads: the "*xxxxxxETc_monthly.dat*" and "*xxxxxxETc_annual.dat*"files created by the statistics program where xxxxxx is the station number.
Reads: "*xxxxxxETca.dat*" which is the daily time series file to confirm the number of crops per station
Reads: "*Idaho_Stations_Crops_i.csv*" file for the number of crops per station
Writes: "*xxxxxxETc_monthlya.dat*" and "*xxxxxxETc_monthlyb.dat*" (if needed) and "*xxxxxxETc_annuala.dat*" and "*xxxxxxETc_annualb.dat*" (if needed (if there are more than 41)).

APPENDIX 13

CHANGES TO THE 2007 REVISION (SINCE 2006)

Changes in Evapotranspiration Calculations

The October 2006 verions of this report was revised in April 2007 to implement refinements in some calculations and parameter estimates. The daily, monthly and annual ET_c files were recomputed under the revision, with the following significant modifications. The procedures to invoke these modifications are described elsewhere:

Estimation of daily solar radiation – A procedure by Thornton and Running (1999) was adopted to replace the more simple procedure of Hargreaves used in the 2006 version.

Estimation of daily dewpoint temperature – The offset from daily minimum air temperature used to estimate dewpoint temperature was varied by month based on an analysis of humidity data at a number of AgriMet stations (described in Appendix 2), as opposed to a constant value for all months used in 2006.

Shifting of daily T_{max} and precipitation back one day for NWS stations. The values for daily maximum air temperature and precipitation are reported at NWS stations for the date that they are recorded. This is typically at 7 or 8 am. In nearly all cases, the T_{max} recorded occurred on the previous day. It is likely that the precipitation recorded also occurred on the previous day (between 7 am and midnight) rather than between midnight and 7 am of the current day. Therefore, T_{max} and precipitation values were moved back in time by one day in the NWS data sets. T_{min} and snow depth values were not moved. This shifting had little impact on ET estimates.

Calculation of P_efT – *Precipitation residing in the root zone that is available for transpiration (rather than for evaporation).* *P_efT* is the amount of gross reported precipitation that infiltrates into the soil (i.e., less any surface runoff) and that remains in the root zone for use in supplying transpiration by the crop or land use cover. This calculation was included in this revision. *P_efT* does not include the amount of infiltrated precipitation that evaporates from the surface evaporation layer (upper 100 to 150 mm of soil). The *P_efT* parameter is useful in estimating the amount of precipitation that is stored over the long term and made available for transpiration requirements. *P_efT* is also useful to determine how 'efficient' precipitation is in fulfilling transpiration requirements of crops, as opposed to simply 'burning off' as evaporation from the soil surface. *P_efT* was calculated as *P_efT = P_rz - surface evaporation losses = P – Runoff – DPerc - surface evaporation losses*, where *P_rz* is precipitation infiltrating and residing in the maximum root zone for the crop, *P* is gross reported precipitation, *Runoff* is estimated surface runoff and *DPerc* is deep percolation of any precipitation below the maximum rootzone for the crop or land-use condition.

Lengths of growing seasons for spring wheat as predicted by the cumulative growing degree day (thermal unit) procedure were post adjusted at high elevation sites in SE Idaho to compensate for the likely use of shorter season varieities and to obtain more typical season lengths. The adjustment factors are summarized in Table 8 of the main body (for crops 11-14). The adjustment multiplied the standard estimation for season length by [1 – 0.6 (1-160/x)] where x is the season length, in days, estimated by the standard method. Spring grain was dropped as a viable crop at very high elevation stations including Elk City, New Meadows, Cascade, Kilgore, Leadore, Galena and Three Creek.

A maximum length for the growing season was invoked for some crops, for example, for spring wheat, to insure that the length of the season terminated prior to mid fall at high elevations. This value is listed in

Table 7 on the row labeled 'Harvest, days after EFC (neg til frost)'. Negative values directed the calculations to maintain the crop and K_c curve computation (i.e., season length) until the occurrence of a killing frost. Crops extended until killing frost (Table 7) included grapes, apples, asparagus, turf, pasture, wetlands, and native trees.

Cumulative growing degree days (heat units) used to estimate the time of effective full cover and harvest for some crops were reduced in the revision for some crops to estimate season lengths that were more typical of observed conditions. In addition, the value for the 30-day mean air temperature required for planting or greenup were adjusted for some crops, also, in the revision, based on comparisons in Kc curves between those estimated by T30 and those observed in south-central Idaho during 2000 and 2003 using the METRIC satellite-based ET procedure (Tasumi et al., 2005). Crops for which values were adjusted were beans (T_{30} changed from 12 to 14°C), sugar beets (T_{30} changed from 5 to 8°C and GDD for effective full cover (EFC) changed from 820 to 970 and GDD for harvest changed from 2200 to 2600), and corn (T_{30} changed from 8 to 10°C and GDD for EFC changed from 460 to 540 and GDD for harvest changed from 1200 to 1400 for field corn and from 800 to 1000 for sweet corn).

An irrigated and a rainfed condition was created for spring grain (wheat and barley), winter grain, turfgrass and sunflower and safflower crops. This change created ET_{act} estimates for both irrigated and nonirrigated conditions at the same location, for example in parts of SE Idaho where both irrigated and dryland grains are cultivated. The estimates of ET_{act} for irrigated and nonirrigated turf are useful in Northern Idaho during evaluation of the increase in ET caused by irrigation of landscapes.

Changes in Calculation of Statistics

In the 2006 version, statistics (means, standard deviations, 20% and 80% exceedence values) were calculated using the full periods of record. For some locations, the period spanned from 1880 to 2004 and for other locations, the period of record began only in the 1960's. In addition, some trends in estimated reference ET and in reported precipitation were visually apparent over the 100 year periods of record. Therefore, for consistency and to produce statistics that are descriptive of recent conditions, a 30 year normal period was established for each location that was comprised of the most recent 30 years of data. Statistics were computed from this 30 year normal period. More description is given in Appendix 11.

During calculation of statistics, values for the mean of the highest 3, 7 or 15 day period and for the mean of the lowest 3, 7 or 15 day period were calculated over the 30 year normal. These parameters are described in Appendix 11.

APPENDIX 14

COMPARISON OF CALCULATED DAILY CROP COEFFICIENTS WITH THOSE FROM METRIC AND AGRIMET

The University of Idaho, in partnership with Idaho Department of Water Resources, applied the METRIC satellite-based evapotranspiration calculation procedure to most of southern Idaho for year 2000 (Tasumi et al., 2005, Allen et al., 2007b). The METRIC process (Allen et al., 2007a) estimates actual ET_c from 'pixels' that are 30 m in size using surface temperature measured by the Landsat satellite and images of reflected solar energy. The ET from the satellite images processed for year 2000 was sampled for thousands of fields in Magic Valley (from approximately Buhl on the west to Rupert on the east, and from approximately Wendell on the north to Twin Falls on the south) that had been classified for the type of crop (Tasumi et al., 2005). ET from fields of the same crop type were averaged and converted into the form of crop coefficients that could then be compared to crop coefficients estimated in this report and estimated by the AgriMet weather and ET system.

Results of comparisons by crops are shown in the following figures for the NWS weather stations in Buhl and Hazelton. These two stations represent near 'endpoints' (west and east) for the areas of Magic Valley sampled from the METRIC-derived images. For these two stations, the "Allen-Robison" values represent values calculated for this report using a daily water balance and calculation timestep and weather data from the Buhl and Hazelton stations. The "AgriMet for 2000" values represent crop coefficient (Kc) curves derived from ET information reported by AgriMet for the Twin Falls station (located near Kimberly) for year 2000. The K_c curves were derived by dividing reported ET from AgriMet by ET_r computed from the 1982 Kimberly Penman equation employed by AgriMet. The AgriMet K_c values are 'mean' K_c values the include the soil surface evaporation component and many of the K_c curves employed by AgriMet are traceable to K_c curves developed by Dr. J.L. Wright (1981, 1982) of the USDA-ARS, Kimberly. The AgriMet system typically updates the starting and ending dates for their K_c curves each year to account for specific weather.

The METRIC-2000 K_c values shown in the figures represent values calculated on 12 Landsat satellite overpass dates beginning in March 2000 and ending in October 2000. The METRIC derived K_c values are 'actual' values averaged over typically 100 or more fields and the values include evaporation from soil, averaged over these same fields.

The bottom figures shown for each crop include K_c values from AgriMet (for 2000), from METRIC (for 2000) and from this report (for 2000). The daily K_c values calculated in this study (Allen-Robison) include the effects of evaporation from individual wetting events (either precipitation or an estimated irrigation) on the specific daily K_c value. Therefore, the values tend to be somewhat more 'spikey' than the smoother K_c curves of AgriMet or the 12 discrete values from METRIC.

The top figures shown for each crop show AgriMet-2000 and METRIC-2000 derived K_c values, along with K_c calculated by Allen-Robison averaged over a 14-year period spanning 1991-2004. The 14-year averages for K_c are not directly comparable to those specifically for year 2000 (AgriMet and METRIC). However, they are included in the top figures because the averaging over 14 years tends to average (smooth) out the individual spikes caused by evaporation from individual wetting events (either precipitation or an estimated irrigation).

For the most part, K_c 'curves' from all three sources show good agreement for the southern Idaho location(s). The figures for **alfalfa** show K_c (by METRIC and Allen-Robison) to vary as cuttings take place (these have been averaged over a few hundred fields with METRIC). The AgriMet K_c curve for alfalfa hay plots as a constant value during the growing season since specific cutting dates are not known by field. The K_c curve generated for alfalfa hay by Allen-Robison is based on growing degree units and represents an 'expected' cutting schedule. In the same way, the variation in K_c due to evaporation from wetting events is for a specific irrigation schedule (based on a daily soil water balance) that represents an 'expected' irrigation schedule for alfalfa hay during 2000. The relatively high K_c values during winter result from winter-time precipitation resulting in a relatively moist soil surface. The actual ET during these winter periods is quite low, however, since the reference ET_r is low.

The length and trends in the K_c curve for **dry beans** generated during this study agreed well with those by AgriMet and METRIC (second set of figures), especially at Hazelton. The drying trend in March and April 2000 prior to planting that was predicted by the daily model of this study agreed well with observed K_c from METRIC. The AgriMet curve for annual crops begins only at crop emergence and ends at estimated crop harvest.

As with dry beans, the K_c curve generated for **sugar beets** agreed well with both AgriMet and METRIC. The Allen-Robison curve corresponded better with METRIC than did the AgriMet curve during the last part of the growing season, whereas the Allen-Robison K_c curve peaked about one week early for 2000 (at the end of the crop development period) as compared to the METRIC curve.

The fourth set of figures at each station are for typical **field corn** crops. Here the K_c curve generated during this study (Allen-Robison) agreed well with both METRIC observations and AgriMet K_c for year 2000 (bottom figures), especially at Hazelton. The K_c curve by Allen-Robison was developed automatically for 2000 weather conditions, based on cumulative growing degree days, as described in other appendices. As with other crops, the relatively high K_c values during winter result from winter-time precipitation resulting in a relatively moist soil surface. The actual ET during these winter periods is quite low, however, since the reference ET_r is low.

The K_c curves and data generated for **potatoes** (baking category) for this study agreed closely with both METRIC and with AgriMet K_c curves at both locations. The impact of simulated, frequent irrigations for potatoes in the Allen-Robison model have large impact on the day to day variation in K_c due to spiking of the curve following wetting events and subsequent drying back to the basal K_{cb} curve. Even though the basal K_{cb} curve trended well below the AgriMet and METRIC 'mean' K_c curves during mid and late season, the addition of the evaporation component from frequent irrigation resulted in an average K_c from this study that was similar to that for AgriMet and METRIC. At the Buhl location, the K_{cb} curve tended to develop somewhat earlier than as observed by METRIC and to reduce, prior to harvest, earlier. Some of this may be due to the lower elevation of the Buhl station relative to the majority of the area sampled from METRIC.

The fifth set of figures at each station are for **spring grain** (wheat, barley, oats, triticale). The K_{cb} curve generated during this study (using cumulative growing degree days and 30 day mean air temperature to trigger planting date) estimated similarly to the AgriMet K_c curve, but tended to estimate higher (as did the AgriMet curve) than the observed K_c using METRIC. The fields sampled during the METRIC analysis may have included some fields that were less than fully irrigated or that had sparse planting. The reasons for the lower K_c from METRIC is not known. The K_c observed by METRIC during late August and September, following harvest, was higher than that estimated by the Allen-Robison model that is based on a daily soil water balance. The Allen-Robison model assumes that each crop follows itself from year to year (due to uncertainty in crop rotations). Therefore, the model assumes that the spring grain field(s) lies dormant (and dry) during the late summer, with little evaporation and essentially no transpiration. In practice, however, spring grain fields are often disked and/or irrigated to prepare to a follow-on crop the next year or may even be used to 'nurse' an alfalfa crop. Therefore, the actual K_c during late summer, as observed by METRIC (via satellite) averaged between 0.2 and 0.3.

The last set of figures are for **winter grain** crops (wheat and barley). In the application of the Allen-Robison model with the Hazelton data set, the generated K_c curve during 2000 for winter grain closely mimicked that used by AgriMet. Both curves (Allen-Robison and AgriMet) developed earlier than that observed by METRIC and both curves began to decline during crop maturity earlier than observed by METRIC. The Allen-Robison curves were simulated using cumulative growing degree days beginning November 1 of 1999. It is possible that the METRIC K_c curve includes some 'contamination' by information from fields that were actually planted to spring grains rather than winter grains, but that were 'misclassified' (i.e., falsely identified) as winter grain. Inclusion of information from the later developing and maturing spring grains would tend to shift the 'average' K_c curve for winter grains later in the spring and summer as is seen in the figures. This postulation, however, is speculative, as no accuracy information was directly available to independently test the classification accuracy for year 2000.

In general, the crop curves shown in this suite of figures compare well among the three largely independent sources of K_c (and therefore ET) information. The good comparisons provides relatively good corroborative confirmation of accuracy for each of the estimation methods.

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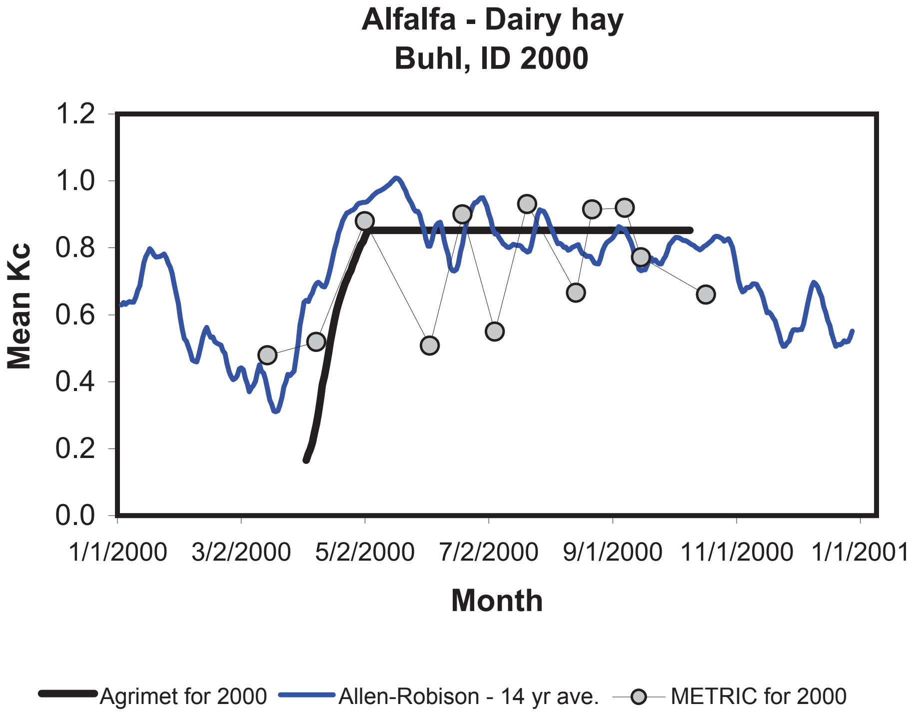
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1/1/2001
Month
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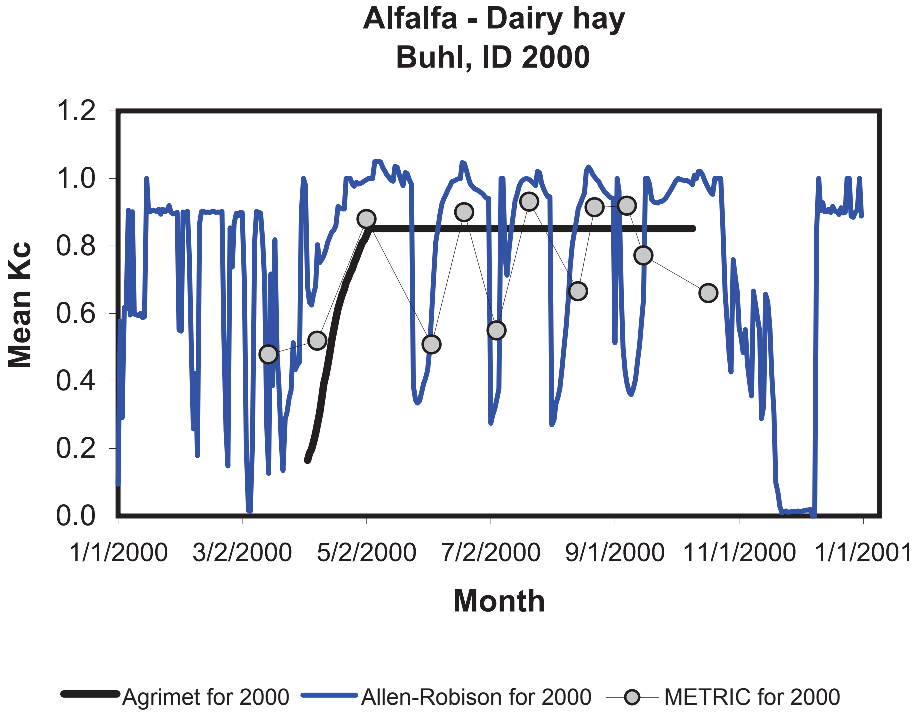
Allen-Robison - 14 yr ave.
METRIC for 2000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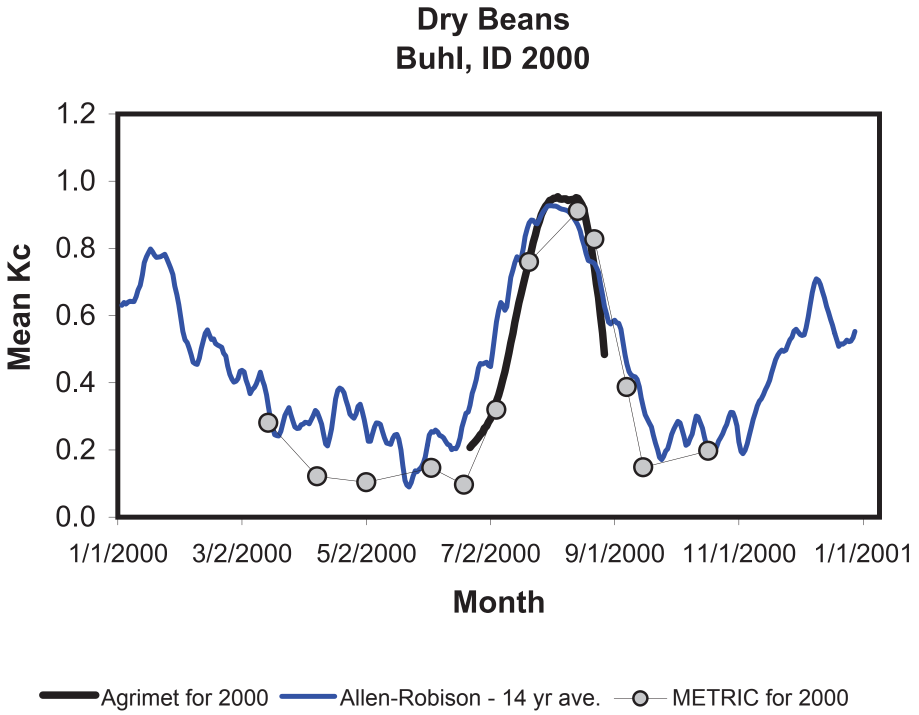
METRIC for 2000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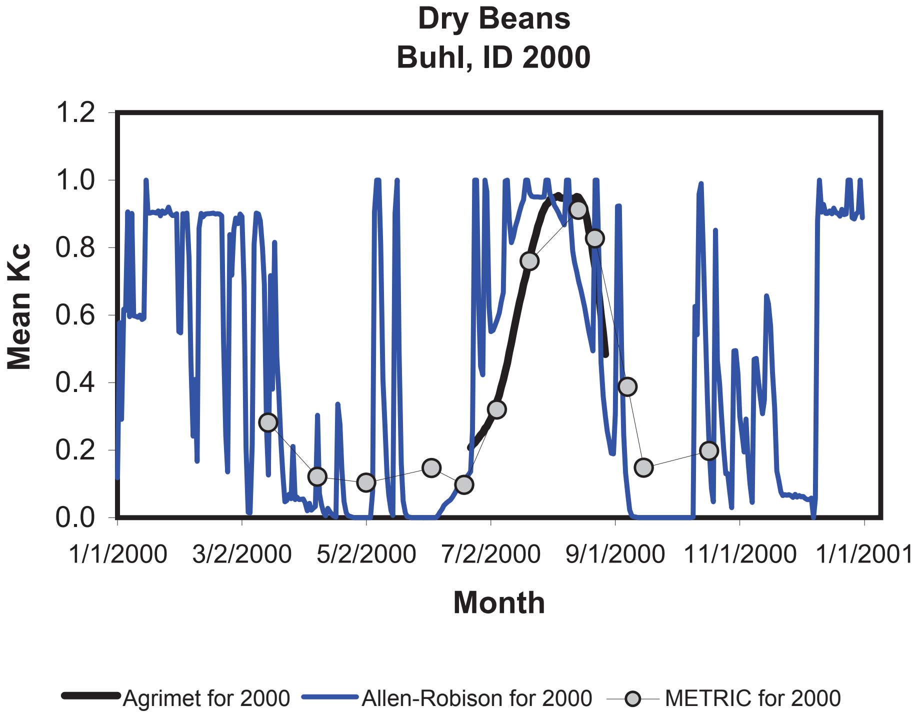
Agrimet for 2000
Allen-Robison - 14 yr ave.
METRIC for 2000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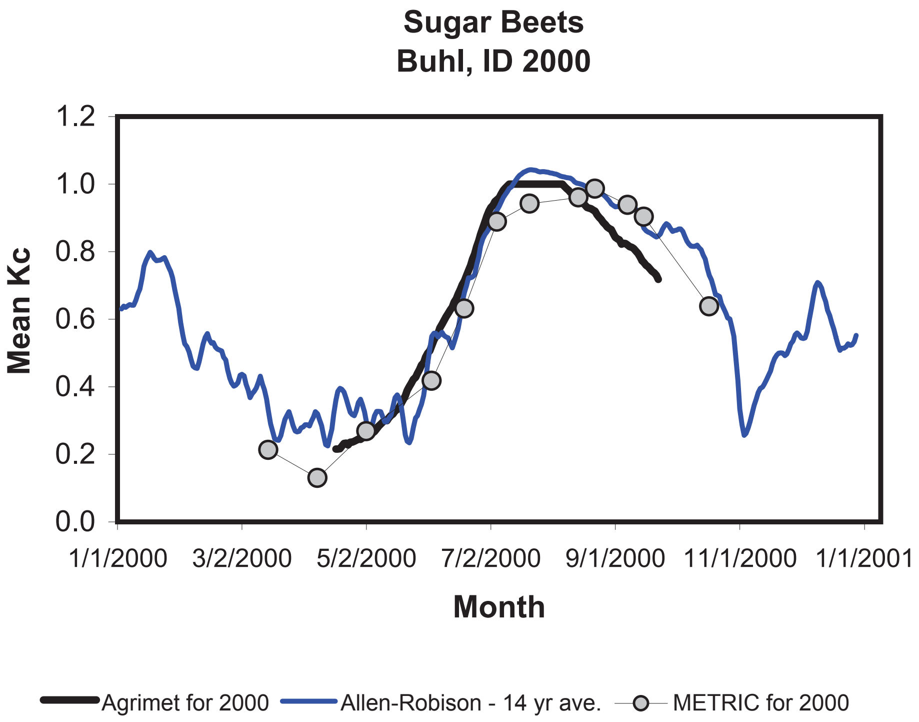
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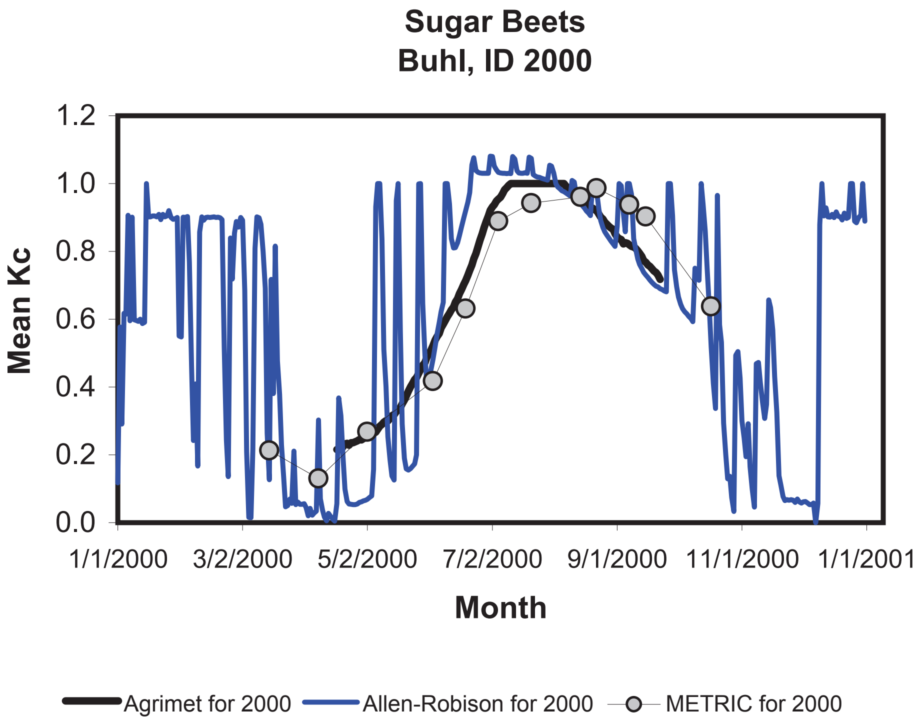
Allen-Robison - 14 yr ave.
METRIC for 2000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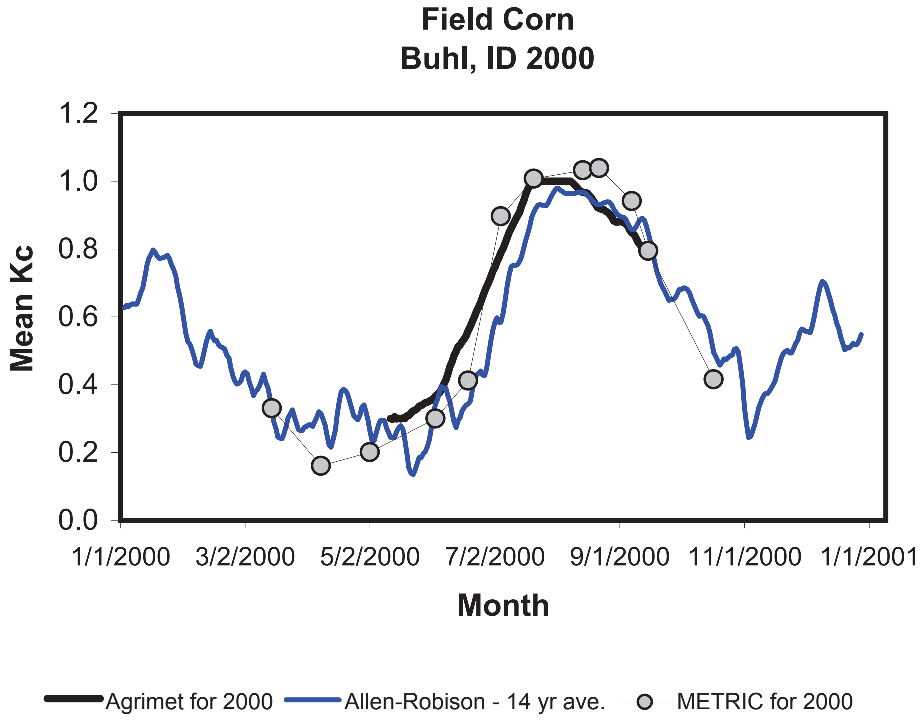
Allen-Robison for 2000
METRIC for 2000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11/1/2000
1/1/2001
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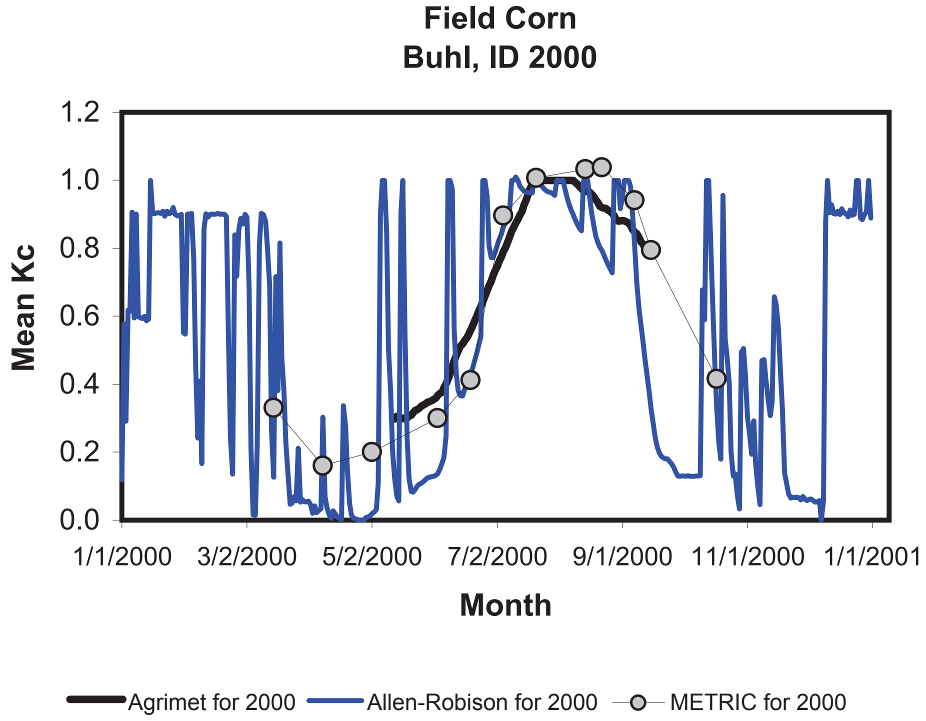
Allen-Robison - 14 yr ave.
METRIC for 2000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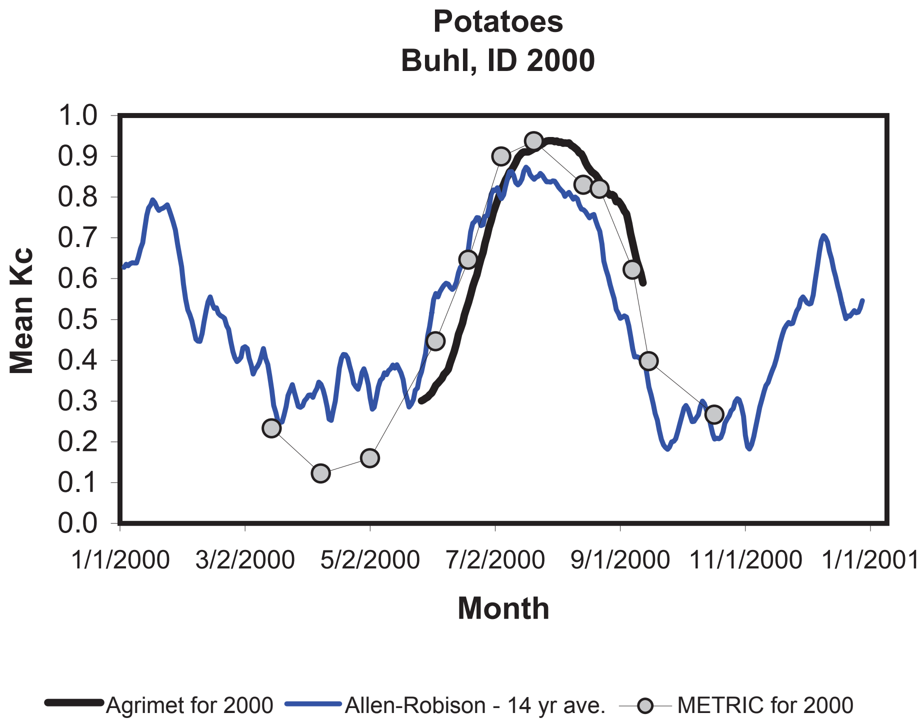
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0.1
0.0
1/1/2000
3/2/2000
5/2/2000
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1/1/2001
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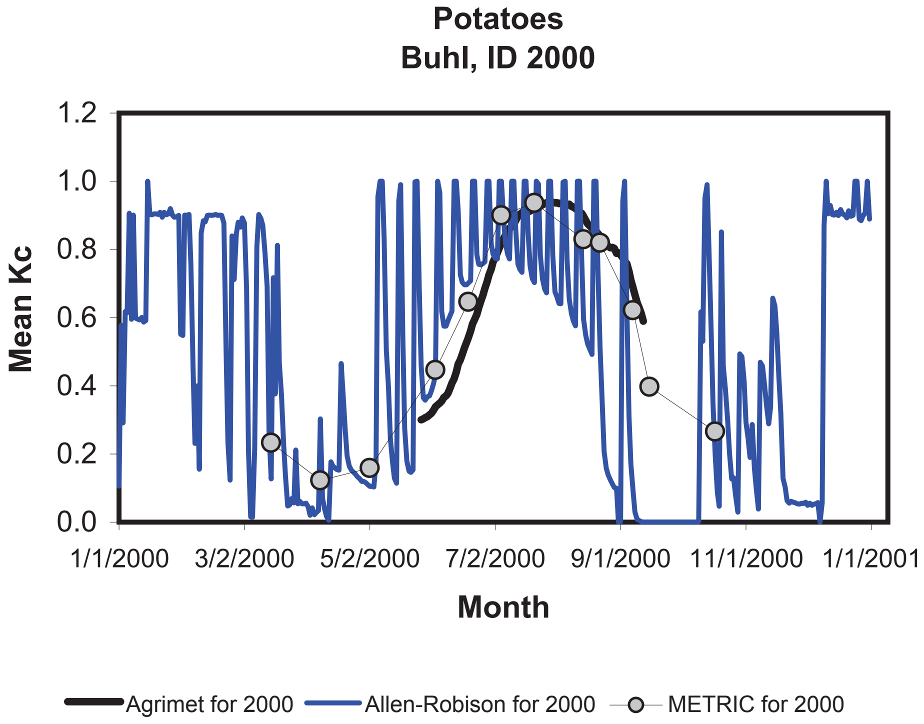
Allen-Robison - 14 yr ave.
METRIC for 2000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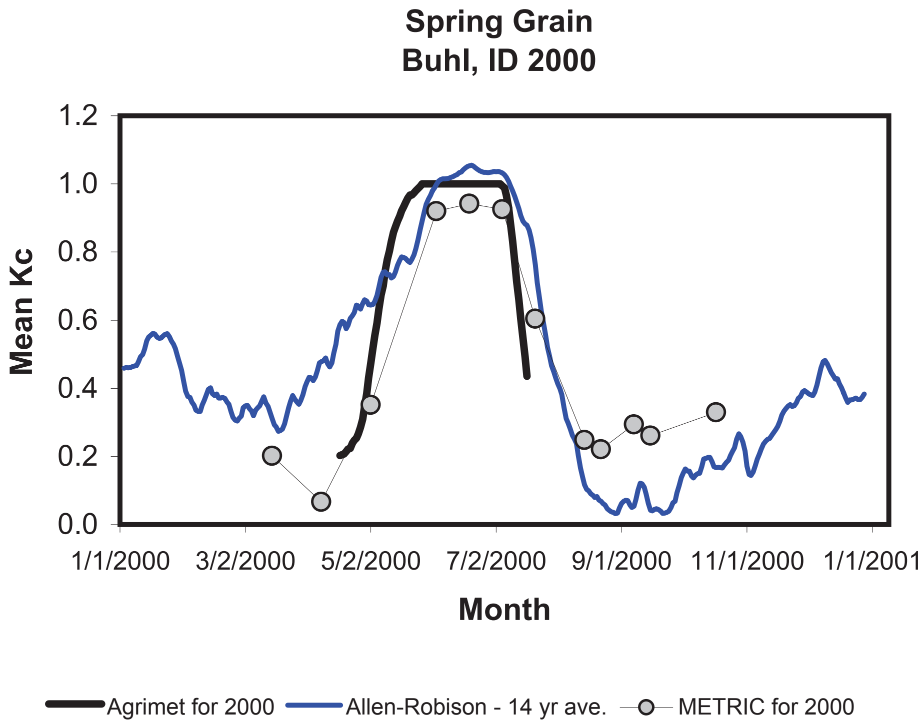
METRIC for 2000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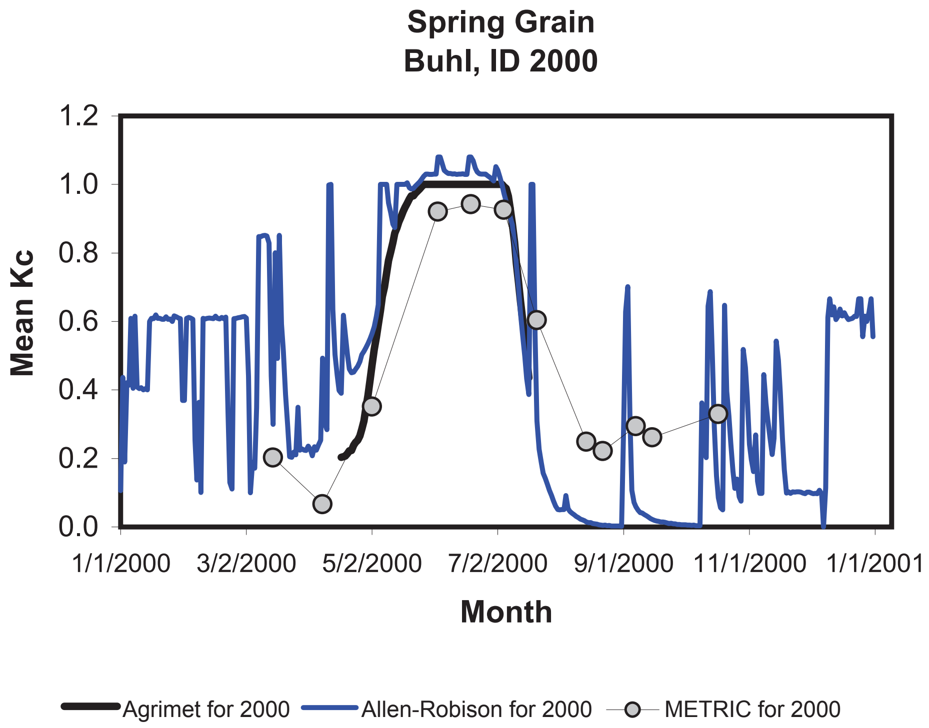
METRIC for 2000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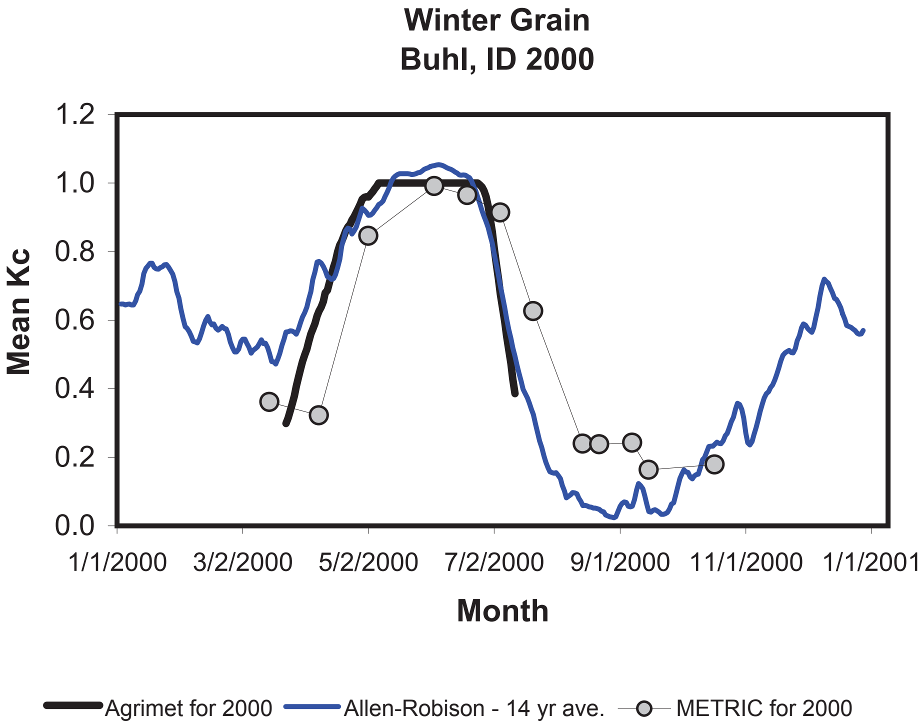
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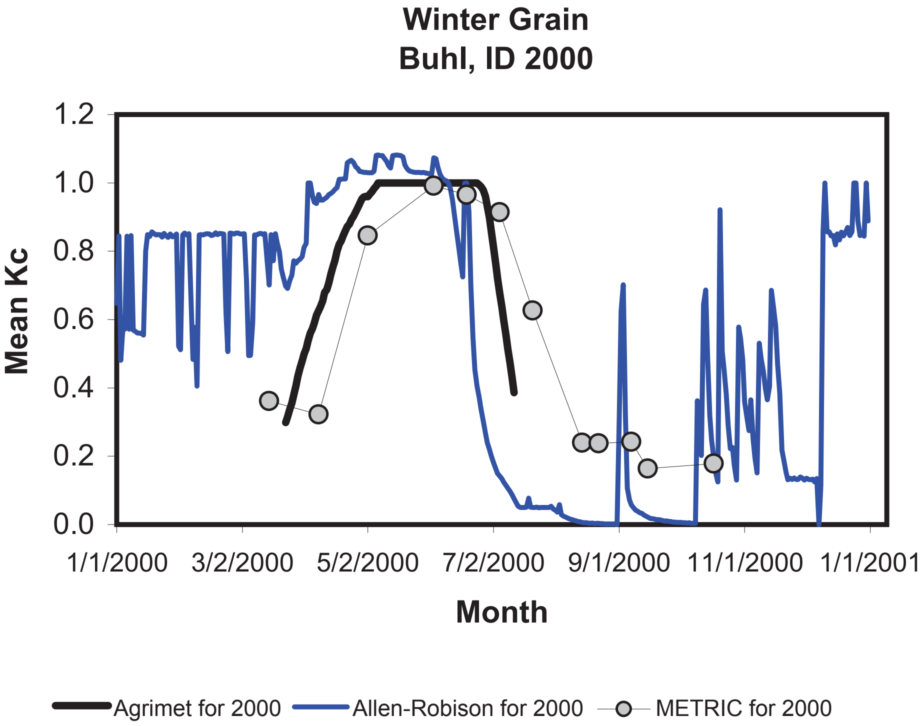
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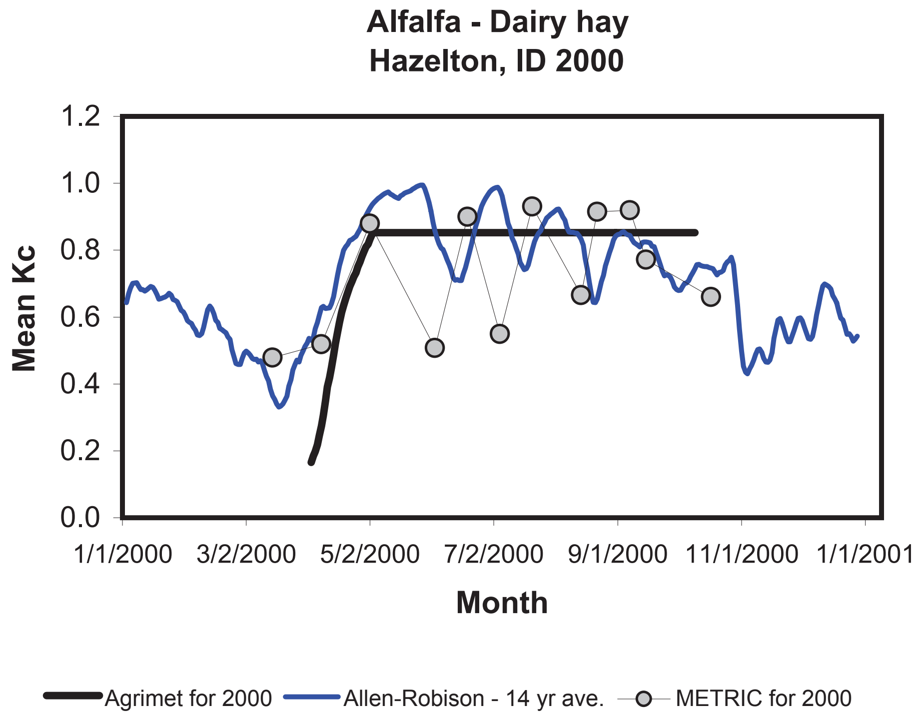
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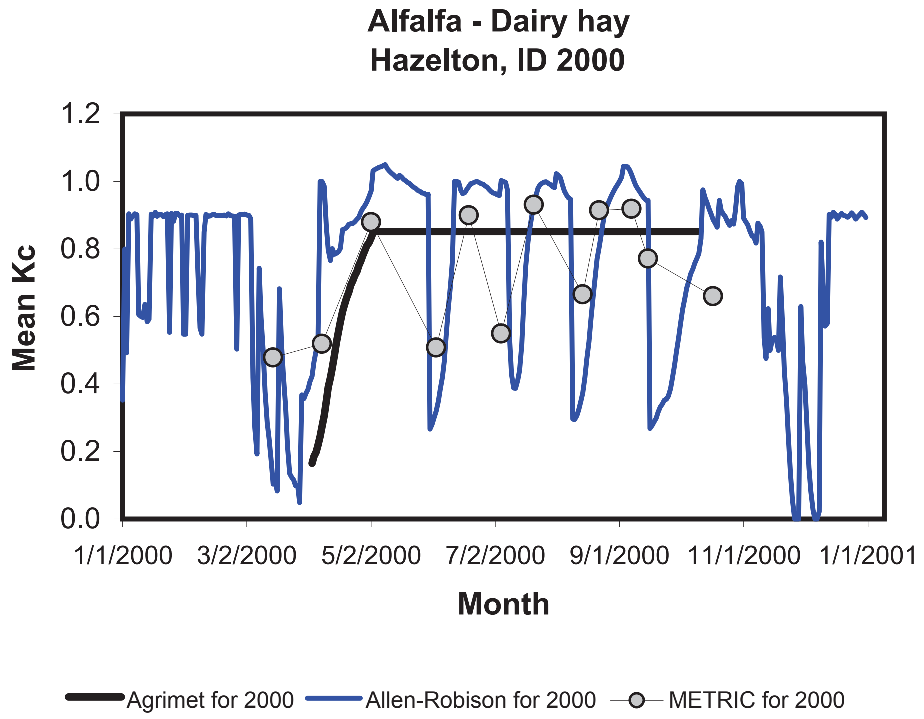
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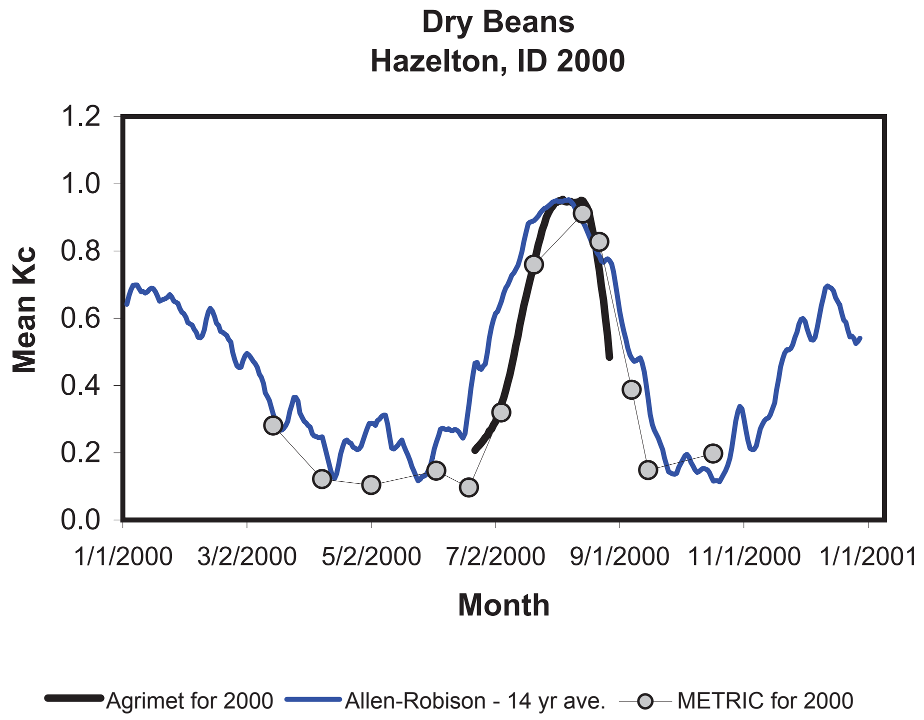
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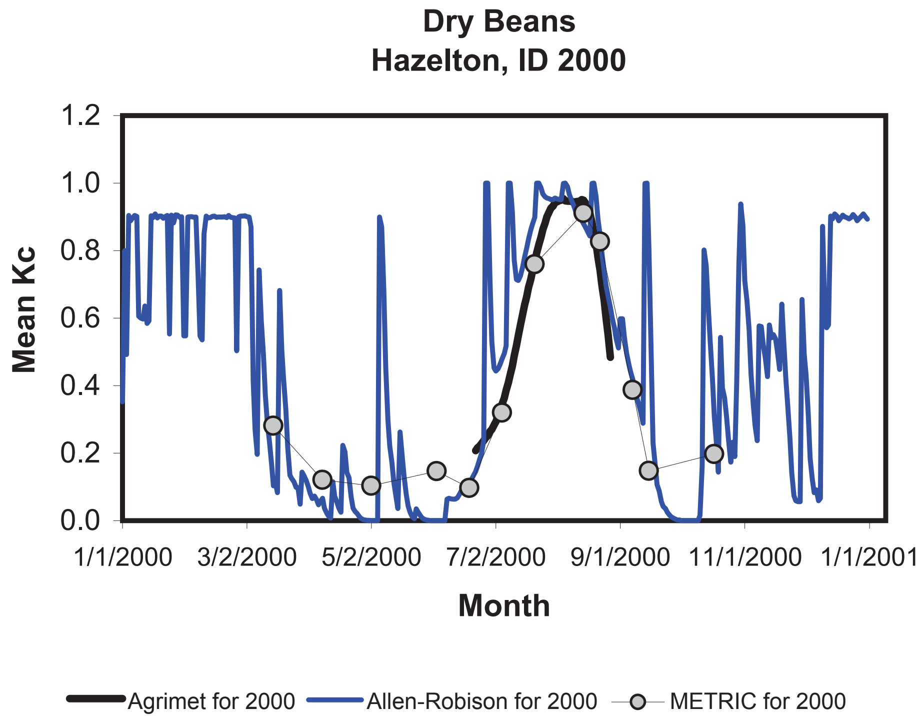
Allen-Robison - 14 yr ave.
METRIC for 2000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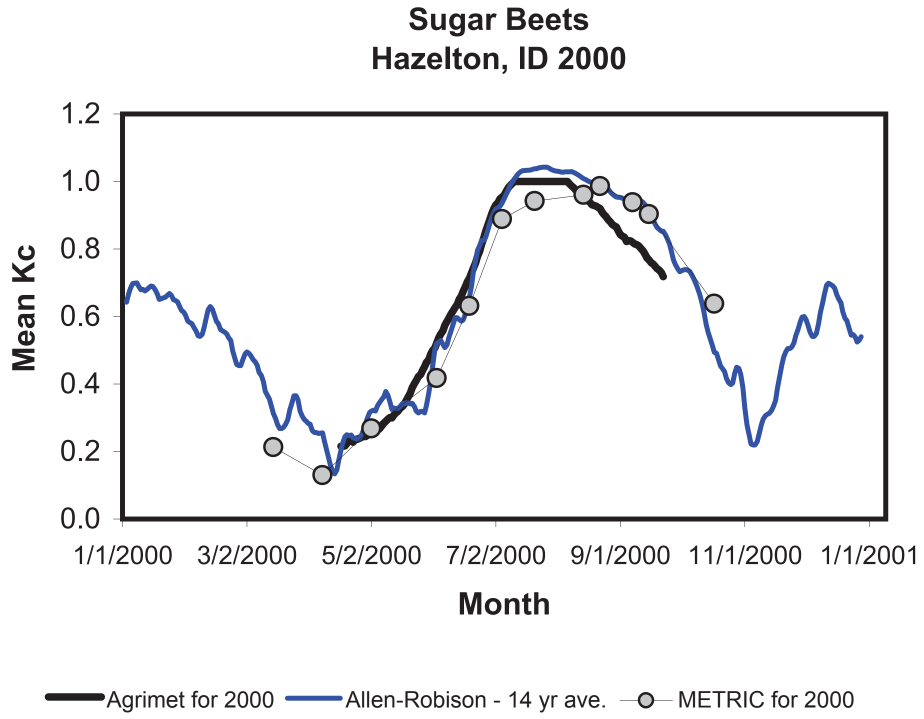
Allen-Robison for 2000
METRIC for 2000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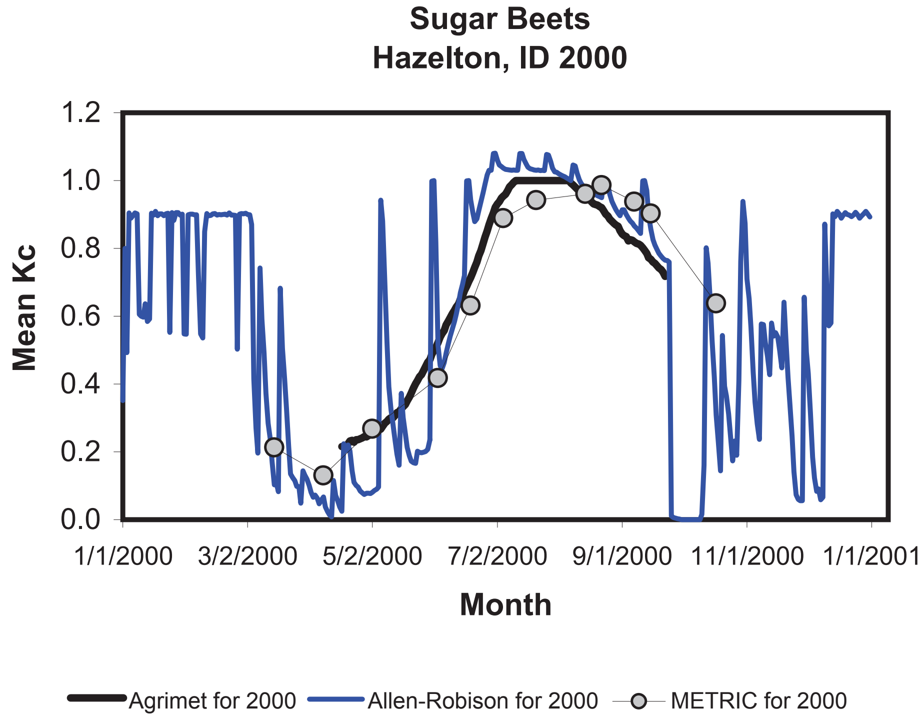
METRIC for 2000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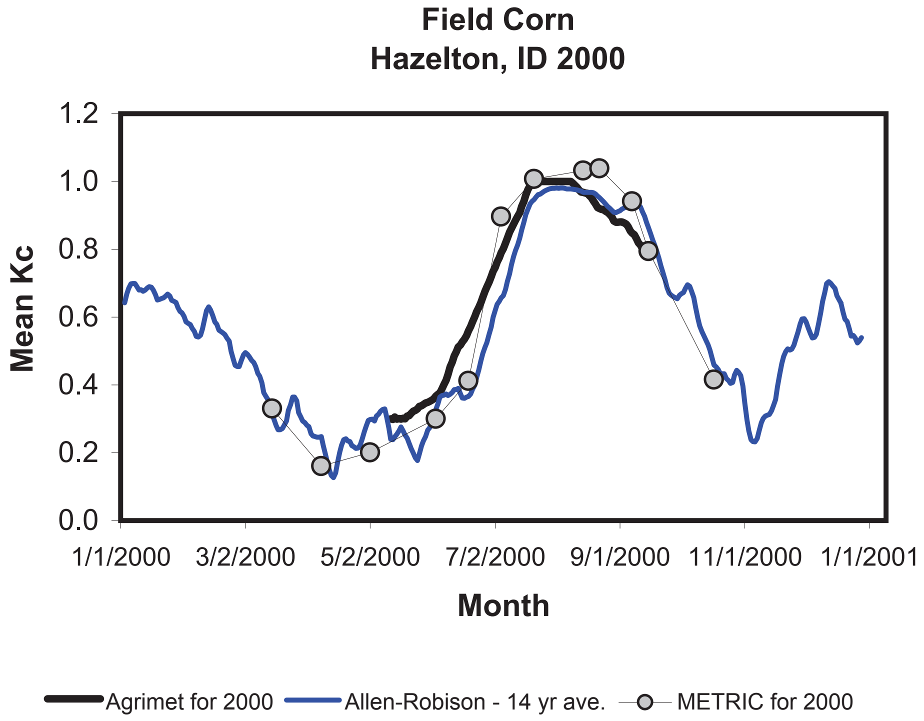
METRIC for 2000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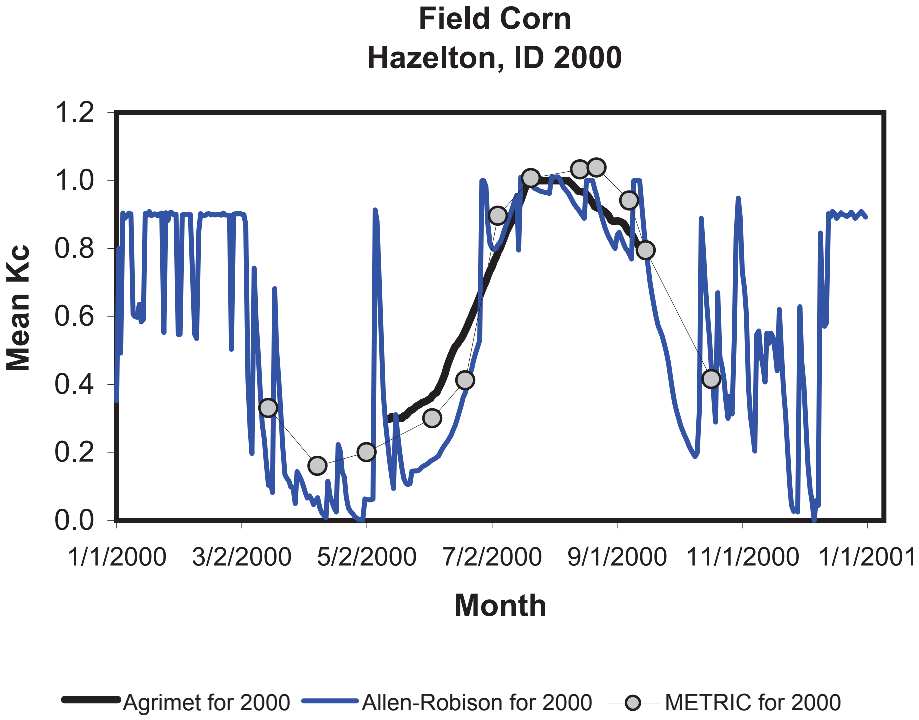
Allen-Robison - 14 yr ave.
METRIC for 2000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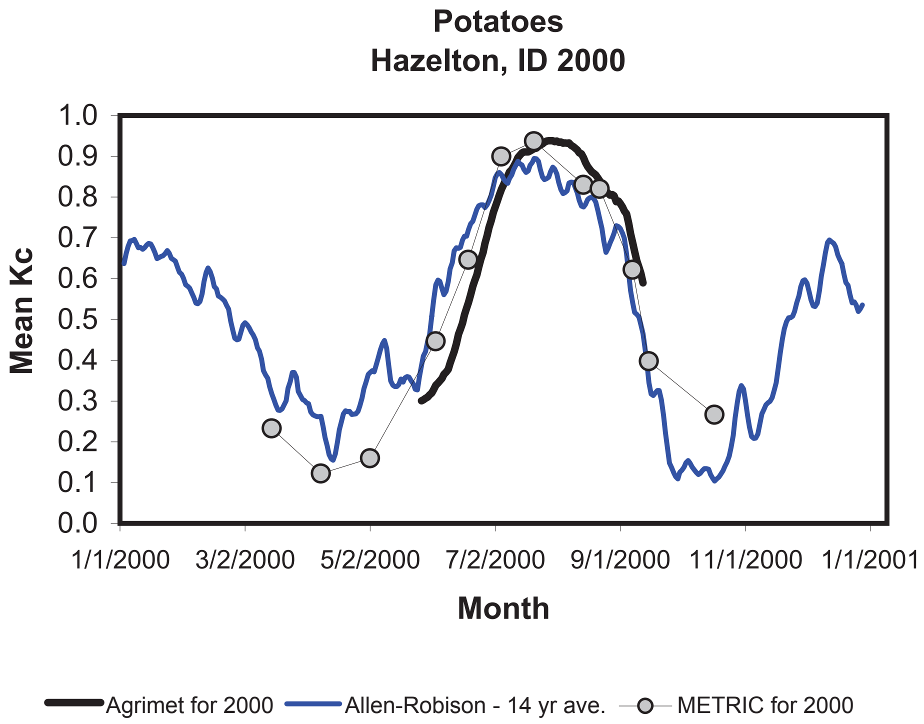
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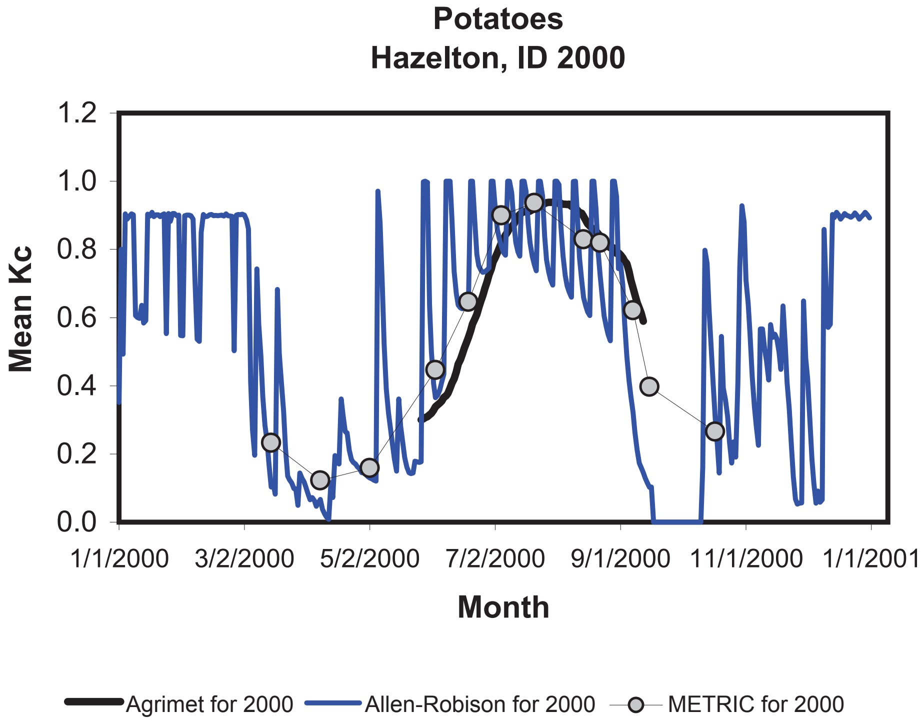
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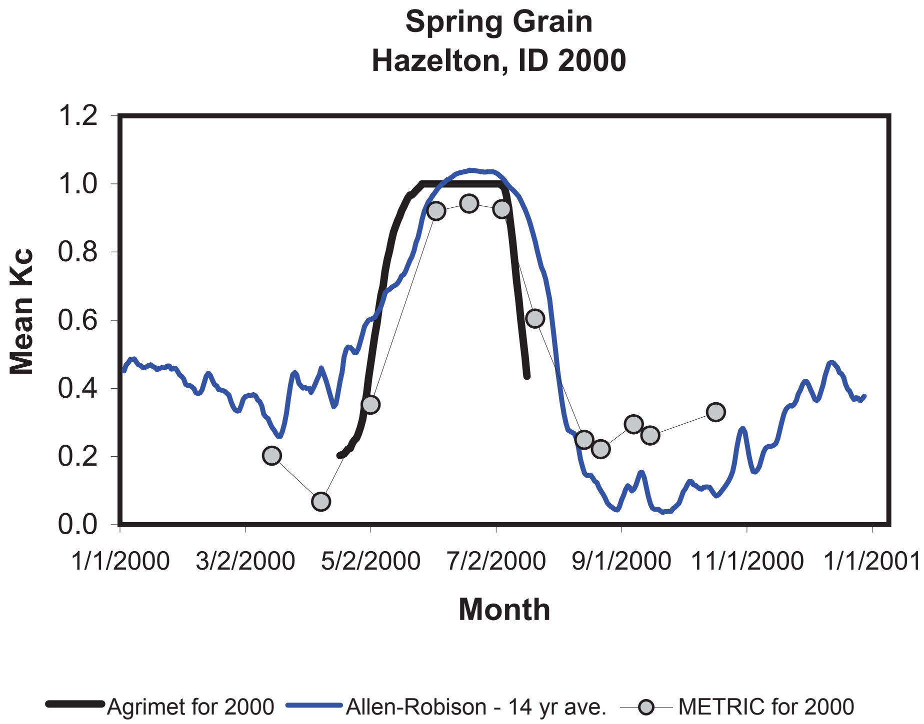
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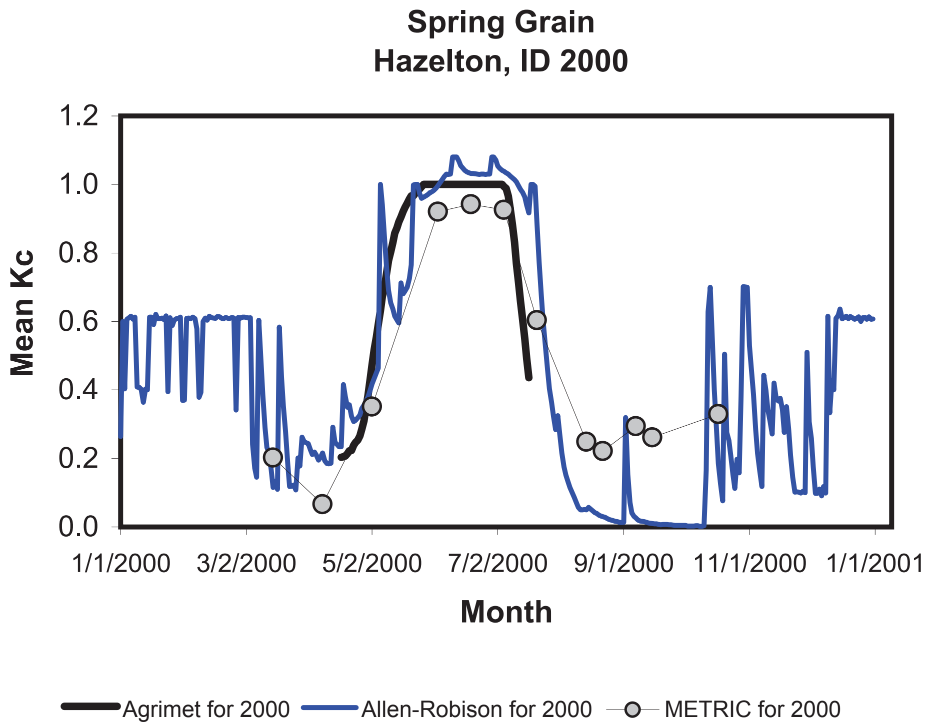
METRIC for 2000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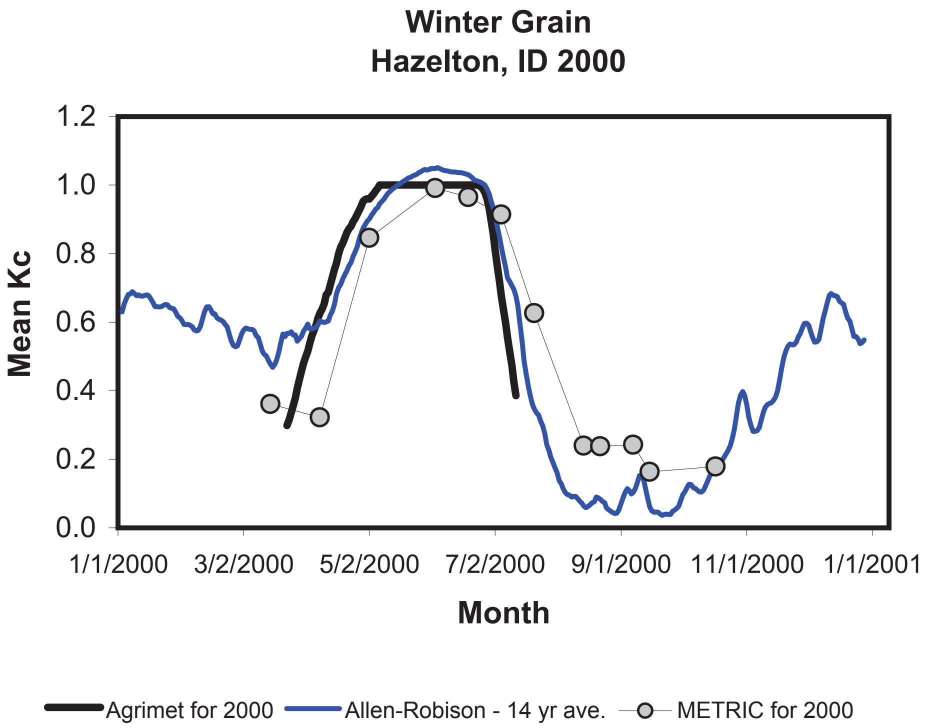
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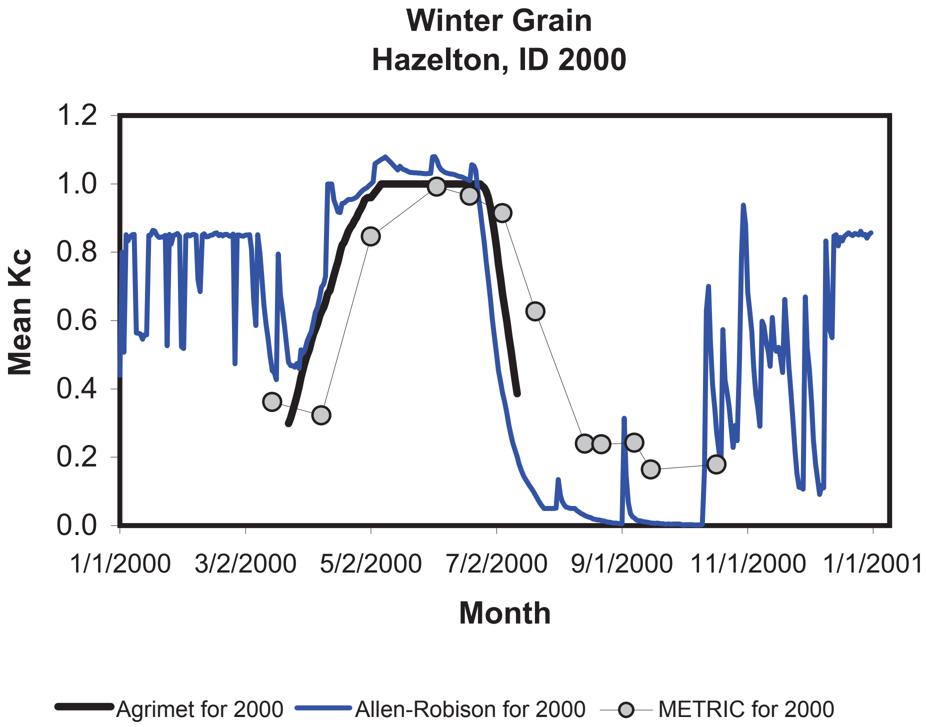
METRIC for 2000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5/2/2000
7/2/2000
9/1/2000
11/1/2000
1/1/2001
Month
Agrimet for 2000
Allen-Robison for 2000
METRIC for 2000

APPENDIX 15

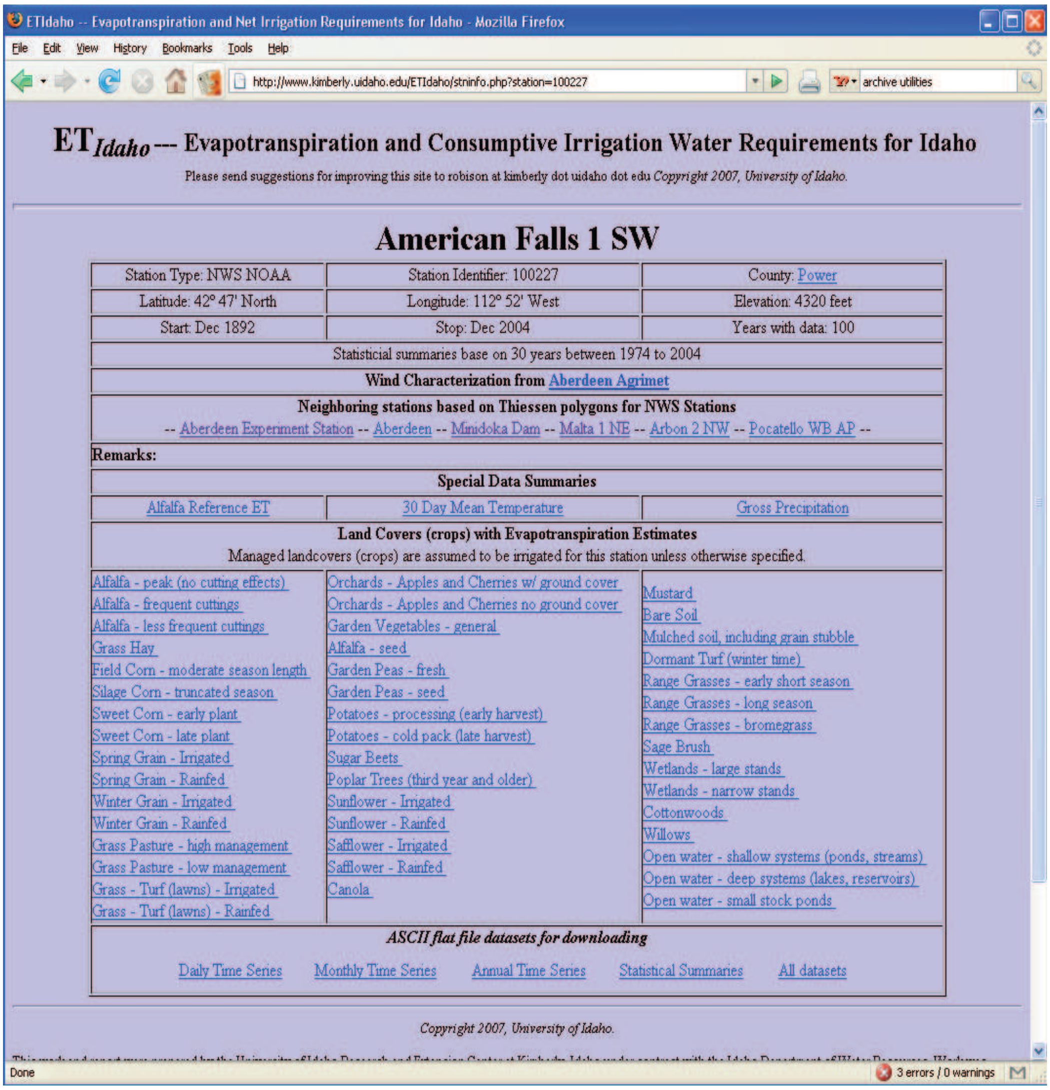
DESCRIPTION OF THE ETIDAHO WEB SITE (WWW.KIMBERLY.UIDAHO.EDU/ETIDAHO)

All evapotranspiration files computed during this analysis are available from the University of Idaho "ETIdaho" web site. The URL (uniform resource locater) for the site is http://www.kimberly.uidaho.edu/ETIdaho/ and the ETIdaho is case sensitive. The ASCII "flat file" data sets (i.e., 'text files') as described in Appendix 11 are available individually for download by station for each of the time series of crop ET related information (daily, monthly, and annual), for the statistical summaries and the daily reference evapotranspiration file as a single compressed archive (zip) (for each weather station). The entire group of data sets for an individual station may be downloaded as a single compressed archive file. The uncompressed data sets are fairly large, for example the daily time series for American Falls (100227) is 76 megabytes in size. By compressing the ASCII data files, the size was reduced to 6.8 megabytes. The compressed archives allow for a single download of the multiple individual files (for each station, a group of 10 files consist of potentially two files each for daily, monthly, and annual time series and statistical summaries for actual ET, potential ET, basal ET and precipitation deficit). These 10 files can have an aggregated size before compression of 80 megabytes, whereas, the single compressed archive is only 7.4 megabytes, shortening the download time. An archive compression utility such as WinZip™ (http://www.winzip.com/) or PicoZIP™ (http://www.picozip.com/) is required for the user to uncompress the archives.

The ETIdaho web site allows the user to explore the 123 stations throughout Idaho by station name. For each station the location information and period of record are displayed, as shown in Figure 15.1. Using a hot link for the station's county, other stations located with the county can be pursued and explored. Hot links to adjoining stations as based on the Thiessen-type polygons from Figure 5.1 of Appendix 5 are displayed along with any remarks associated with the station. Hot links to the statistical summaries for ET_r (Alfalfa Reference ET), 30 Day Mean Temperature, and Gross Precipitation are presented for all stations. A summary of the land surface conditions (crops) for which ET estimates were computed are shown with associated links to the four statistical data summaries. At the bottom of the station information table are links for downloading the compressed ASCII flat file data sets for the station.

Upon selection of a land surface condition, the user must select the type of statistical summary desired. The page gives definitions for the four choices (Actual ET, Potential ET, Basel ET, and Precipitation Deficit) to assist in selecting the appropriate summary (page 41). These parameters are defined in Appendix 11. The layout of the statistical summary table is slightly different from that shown in Table 9 of the main text. Figure 15.2 exhibits a portion of the statistical summary for Alfalfa Reference Evapotranspiration for the Twin Falls WSO station via the ETIdaho web site. Figure 15.3 exhibits a portion of the statistical summary for actual evapotranspiration for winter grain for the Twin Falls WSO station via the ETIdaho web site. The user can capture these data by highlighting the data in the tables (by dragging the mouse across the screen and copying to the clipboard) and pasting them into Excel or OpenOffice spreadsheets for use. A hot link is available to graphs displaying the long-term means for actual evapotranspiration and precipitation deficit summaries of land surfaces (crops). This link will produce graphs similar to those shown in Figures 10 and 11 of the main text and Figure 15.4 following. Other links provide for graphical display of annual reference ET and precipitation (Figure 15.5).

Additional methods for retrieving data from the ETIdaho web site via spreadsheet generation are under development as well as are other graphical displays.



ET*Idaho* --- Evapotranspiration and Consumptive Irrigation Water Requirements for Idaho

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American Falls 1 SW

Station Type: NWS NOAA	Station Identifier: 100227	County: Power
Latitude: 42° 47' North	Longitude: 112° 52' West	Elevation: 4320 feet
Start: Dec 1892	Stop: Dec 2004	Years with data: 100
Statisticial summaries base on 30 years between 1974 to 2004		
Wind Characterization from Aberdeen Agrimet		
Neighboring stations based on Thiessen polygons for NWS Stations -- Aberdeen Experiment Station -- Aberdeen -- Minidoka Dam -- Malta 1 NE -- Arbon 2 NW -- Pocatello WB AP --		
Remarks:		
Special Data Summaries		
Alfalfa Reference ET	30 Day Mean Temperature	Gross Precipitation

Land Covers (crops) with Evapotranspiration Estimates

Managed landcovers (crops) are assumed to be irrigated for this station unless otherwise specified.

Alfalfa - peak (no cutting effects)
Alfalfa - frequent cuttings
Alfalfa - less frequent cuttings
Grass Hay
Field Corn - moderate season length
Silage Corn - truncated season
Sweet Corn - early plant
Sweet Corn - late plant
Spring Grain - Irrigated
Spring Grain - Rainfed
Winter Grain - Irrigated
Winter Grain - Rainfed
Grass Pasture - high management
Grass Pasture - low management
Grass - Turf (lawns) - Irrigated
Grass - Turf (lawns) - Rainfed

Orchards - Apples and Cherries w/ ground cover
Orchards - Apples and Cherries no ground cover
Garden Vegetables - general
Alfalfa - seed
Garden Peas - fresh
Garden Peas - seed
Potatoes - processing (early harvest)
Potatoes - cold pack (late harvest)
Sugar Beets
Poplar Trees (third year and older)
Sunflower - Irrigated
Sunflower - Rainfed
Safflower - Irrigated
Safflower - Rainfed
Canola

Mustard
Bare Soil
Mulched soil, including grain stubble
Dormant Turf (winter time)
Range Grasses - early short season
Range Grasses - long season
Range Grasses - bromegrass
Sage Brush
Wetlands - large stands
Wetlands - narrow stands
Cottonwoods
Willows
Open water - shallow systems (ponds, streams)
Open water - deep systems (lakes, reservoirs)
Open water - small stock ponds

ASCII flat file datasets for downloading

Daily Time Series Monthly Time Series Annual Time Series Statistical Summaries All datasets

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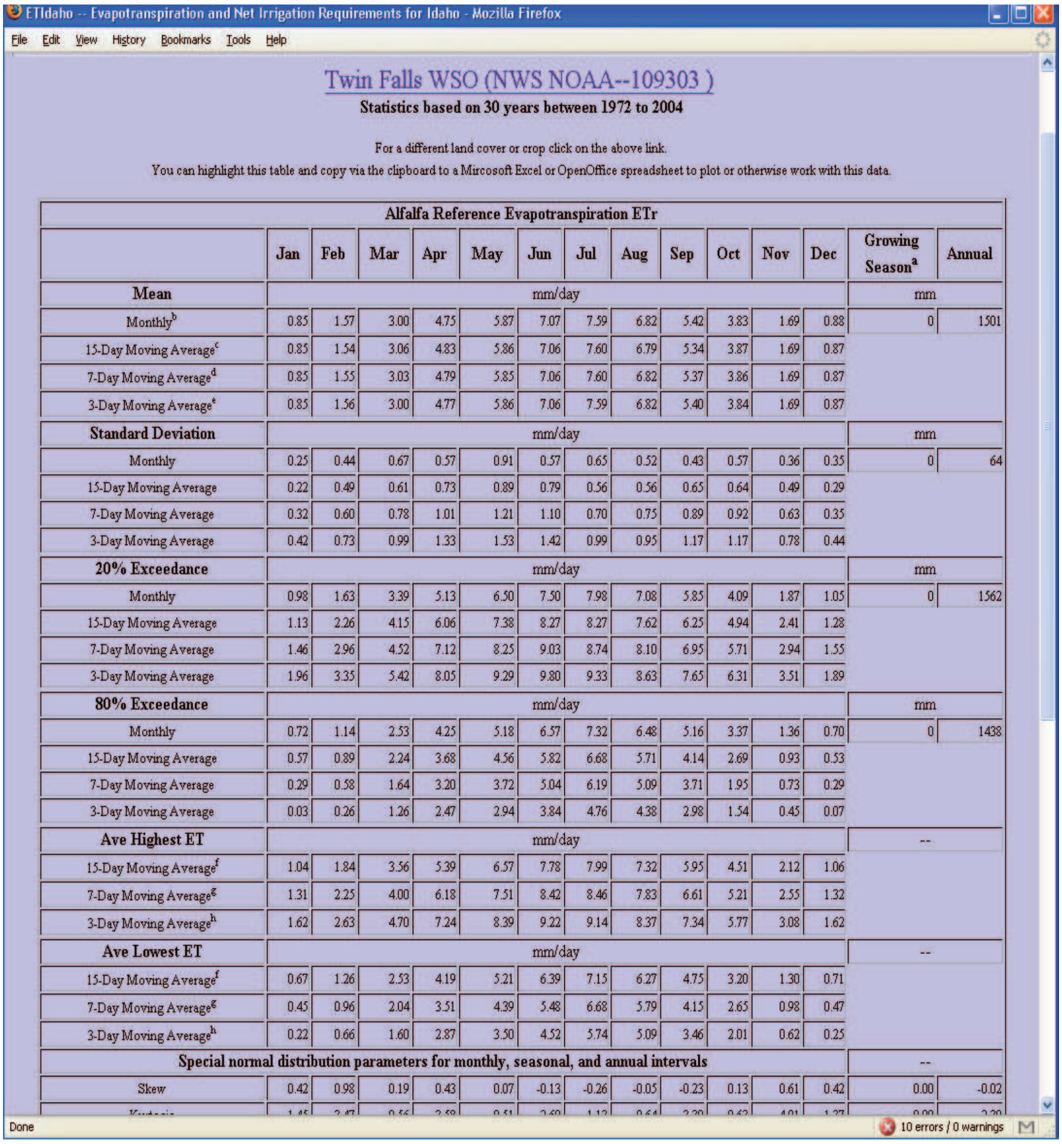
Figure 15.1: Example of Station Information display from the ETIdaho web site



Twin Falls WSO (NWS NOAA--109303)

Statistics based on 30 years between 1972 to 2004

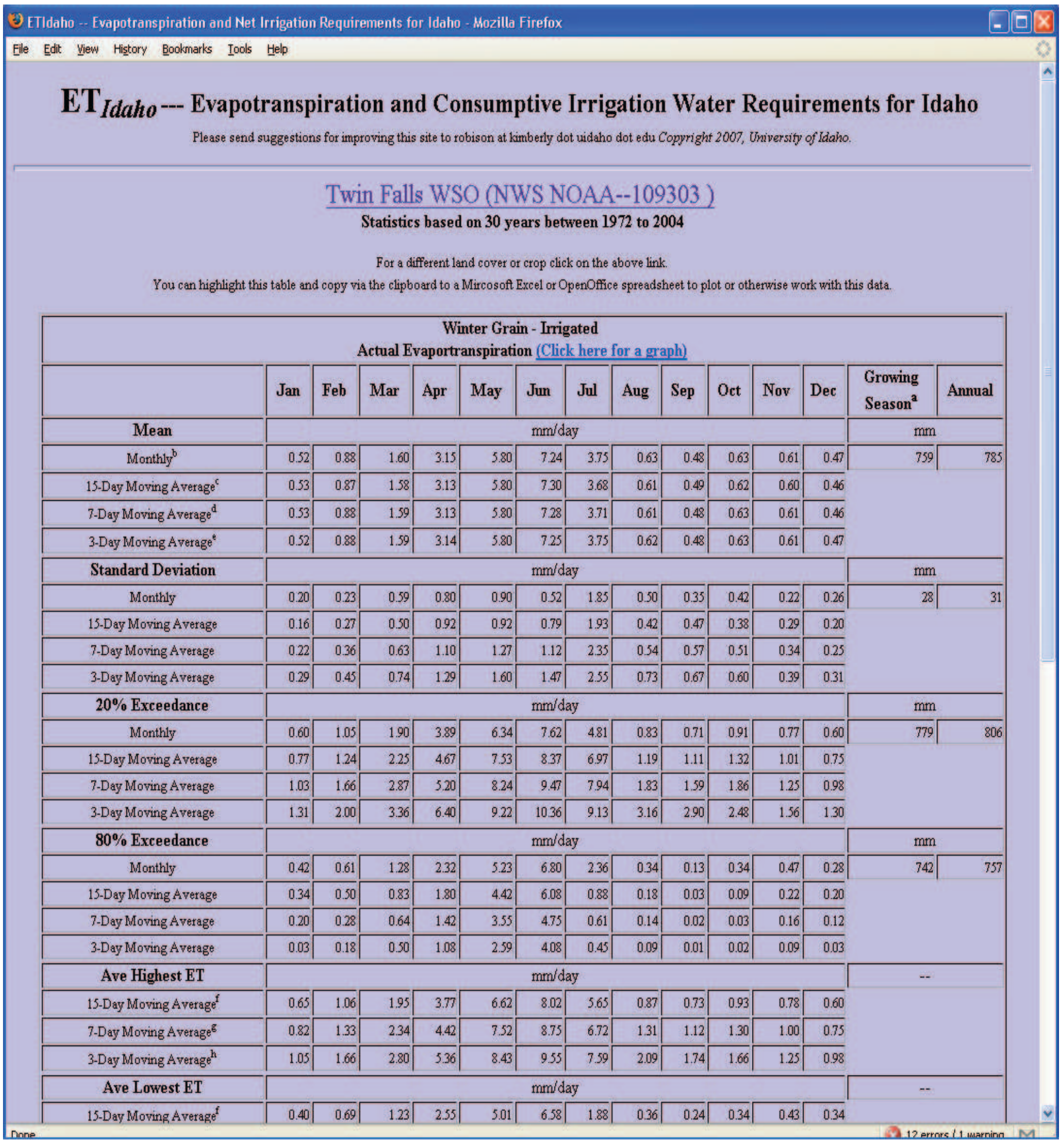
For a different land cover or crop click on the above link.

You can highlight this table and copy via the clipboard to a Mircosoft Excel or OpenOffice spreadsheet to plot or otherwise work with this data.

Alfalfa Reference Evapotranspiration ETr

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Growing Season[a]	Annual
Mean	mm/day												mm	
Monthly[b]	0.85	1.57	3.00	4.75	5.87	7.07	7.59	6.82	5.42	3.83	1.69	0.88	0	1501
15-Day Moving Average[c]	0.85	1.54	3.06	4.83	5.86	7.06	7.60	6.79	5.34	3.87	1.69	0.87		
7-Day Moving Average[d]	0.85	1.55	3.03	4.79	5.85	7.06	7.60	6.82	5.37	3.86	1.69	0.87		
3-Day Moving Average[e]	0.85	1.56	3.00	4.77	5.86	7.06	7.59	6.82	5.40	3.84	1.69	0.87		
Standard Deviation	mm/day												mm	
Monthly	0.25	0.44	0.67	0.57	0.91	0.57	0.65	0.52	0.43	0.57	0.36	0.35	0	64
15-Day Moving Average	0.22	0.49	0.61	0.73	0.89	0.79	0.56	0.56	0.65	0.64	0.49	0.29		
7-Day Moving Average	0.32	0.60	0.78	1.01	1.21	1.10	0.70	0.75	0.89	0.92	0.63	0.35		
3-Day Moving Average	0.42	0.73	0.99	1.33	1.53	1.42	0.99	0.95	1.17	1.17	0.78	0.44		
20% Exceedance	mm/day												mm	
Monthly	0.98	1.63	3.39	5.13	6.50	7.50	7.98	7.08	5.85	4.09	1.87	1.05	0	1562
15-Day Moving Average	1.13	2.26	4.15	6.06	7.38	8.27	8.27	7.62	6.25	4.94	2.41	1.28		
7-Day Moving Average	1.46	2.96	4.52	7.12	8.25	9.03	8.74	8.10	6.95	5.71	2.94	1.55		
3-Day Moving Average	1.96	3.35	5.42	8.05	9.29	9.80	9.33	8.63	7.65	6.31	3.51	1.89		
80% Exceedance	mm/day												mm	
Monthly	0.72	1.14	2.53	4.25	5.18	6.57	7.32	6.48	5.16	3.37	1.36	0.70	0	1438
15-Day Moving Average	0.57	0.89	2.24	3.68	4.56	5.82	6.68	5.71	4.14	2.69	0.93	0.53		
7-Day Moving Average	0.29	0.58	1.64	3.20	3.72	5.04	6.19	5.09	3.71	1.95	0.73	0.29		
3-Day Moving Average	0.03	0.26	1.26	2.47	2.94	3.84	4.76	4.38	2.98	1.54	0.45	0.07		
Ave Highest ET	mm/day												--	
15-Day Moving Average[f]	1.04	1.84	3.56	5.39	6.57	7.78	7.99	7.32	5.95	4.51	2.12	1.06		
7-Day Moving Average[g]	1.31	2.25	4.00	6.18	7.51	8.42	8.46	7.83	6.61	5.21	2.55	1.32		
3-Day Moving Average[h]	1.62	2.63	4.70	7.24	8.39	9.22	9.14	8.37	7.34	5.77	3.08	1.62		
Ave Lowest ET	mm/day												--	
15-Day Moving Average[f]	0.67	1.26	2.53	4.19	5.21	6.39	7.15	6.27	4.75	3.20	1.30	0.71		
7-Day Moving Average[g]	0.45	0.96	2.04	3.51	4.39	5.48	6.68	5.79	4.15	2.65	0.98	0.47		
3-Day Moving Average[h]	0.22	0.66	1.60	2.87	3.50	4.52	5.74	5.09	3.46	2.01	0.62	0.25		
Special normal distribution parameters for monthly, seasonal, and annual intervals													--	
Skew	0.42	0.98	0.19	0.43	0.07	-0.13	-0.26	-0.05	-0.23	0.13	0.61	0.42	0.00	-0.02

Figure 15.2: Example of Alfalfa Reference ET from the ETIdaho web site.



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Twin Falls WSO (NWS NOAA--109303)

Statistics based on 30 years between 1972 to 2004

For a different land cover or crop click on the above link.

You can highlight this table and copy via the clipboard to a Mircosoft Excel or OpenOffice spreadsheet to plot or otherwise work with this data.

Winter Grain - Irrigated

Actual Evaportranspiration (Click here for a graph)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Growing Season[a]	Annual
Mean	mm/day												mm	
Monthly[b]	0.52	0.88	1.60	3.15	5.80	7.24	3.75	0.63	0.48	0.63	0.61	0.47	759	785
15-Day Moving Average[c]	0.53	0.87	1.58	3.13	5.80	7.30	3.68	0.61	0.49	0.62	0.60	0.46		
7-Day Moving Average[d]	0.53	0.88	1.59	3.13	5.80	7.28	3.71	0.61	0.48	0.63	0.61	0.46		
3-Day Moving Average[e]	0.52	0.88	1.59	3.14	5.80	7.25	3.75	0.62	0.48	0.63	0.61	0.47		
Standard Deviation	mm/day												mm	
Monthly	0.20	0.23	0.59	0.80	0.90	0.52	1.85	0.50	0.35	0.42	0.22	0.26	28	31
15-Day Moving Average	0.16	0.27	0.50	0.92	0.92	0.79	1.93	0.42	0.47	0.38	0.29	0.20		
7-Day Moving Average	0.22	0.36	0.63	1.10	1.27	1.12	2.35	0.54	0.57	0.51	0.34	0.25		
3-Day Moving Average	0.29	0.45	0.74	1.29	1.60	1.47	2.55	0.73	0.67	0.60	0.39	0.31		
20% Exceedance	mm/day												mm	
Monthly	0.60	1.05	1.90	3.89	6.34	7.62	4.81	0.83	0.71	0.91	0.77	0.60	779	806
15-Day Moving Average	0.77	1.24	2.25	4.67	7.53	8.37	6.97	1.19	1.11	1.32	1.01	0.75		
7-Day Moving Average	1.03	1.66	2.87	5.20	8.24	9.47	7.94	1.83	1.59	1.86	1.25	0.98		
3-Day Moving Average	1.31	2.00	3.36	6.40	9.22	10.36	9.13	3.16	2.90	2.48	1.56	1.30		
80% Exceedance	mm/day												mm	
Monthly	0.42	0.61	1.28	2.32	5.23	6.80	2.36	0.34	0.13	0.34	0.47	0.28	742	757
15-Day Moving Average	0.34	0.50	0.83	1.80	4.42	6.08	0.88	0.18	0.03	0.09	0.22	0.20		
7-Day Moving Average	0.20	0.28	0.64	1.42	3.55	4.75	0.61	0.14	0.02	0.03	0.16	0.12		
3-Day Moving Average	0.03	0.18	0.50	1.08	2.59	4.08	0.45	0.09	0.01	0.02	0.09	0.03		
Ave Highest ET	mm/day												--	
15-Day Moving Average[f]	0.65	1.06	1.95	3.77	6.62	8.02	5.65	0.87	0.73	0.93	0.78	0.60		
7-Day Moving Average[g]	0.82	1.33	2.34	4.42	7.52	8.75	6.72	1.31	1.12	1.30	1.00	0.75		
3-Day Moving Average[h]	1.05	1.66	2.80	5.36	8.43	9.55	7.59	2.09	1.74	1.66	1.25	0.98		
Ave Lowest ET	mm/day												--	
15-Day Moving Average[f]	0.40	0.69	1.23	2.55	5.01	6.58	1.88	0.36	0.24	0.34	0.43	0.34		

Figure 15.3: Example of actual evapotranspiration statistics for winter grain from the ETIdaho site.

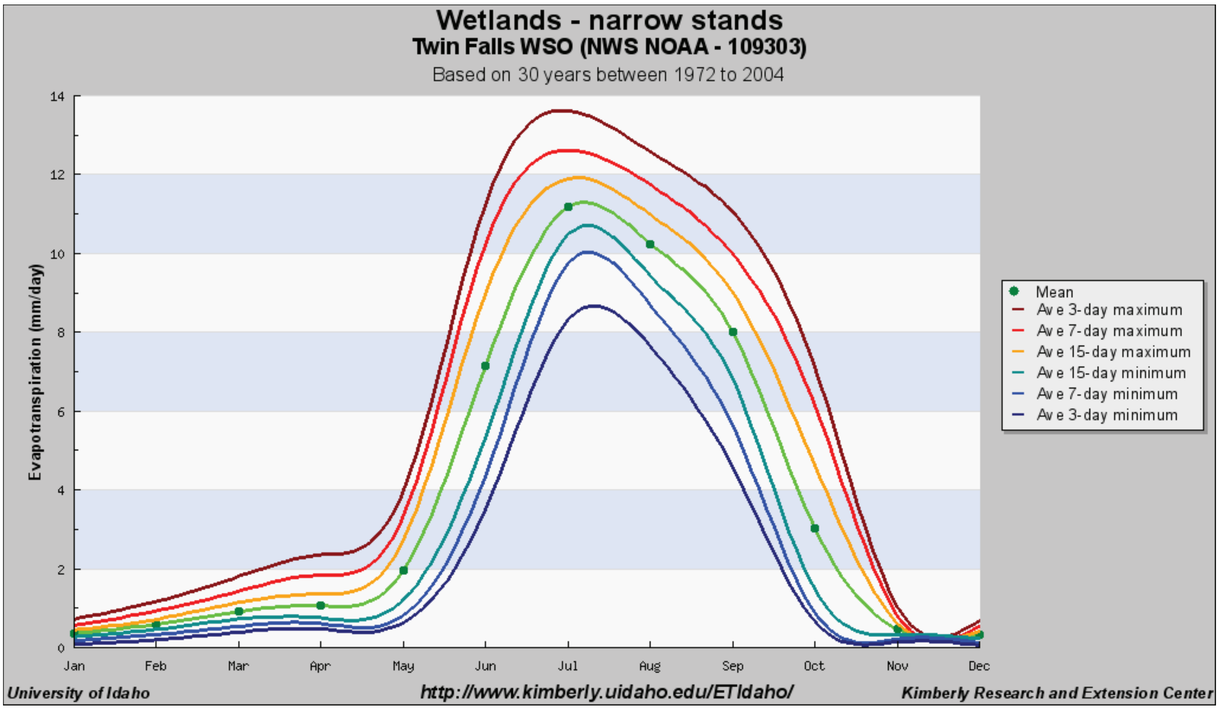

Figure 15.3: Image of long-term averages for actual evapotranspiration from wetlands near Twin Falls WSO created by the ETIdaho web site.

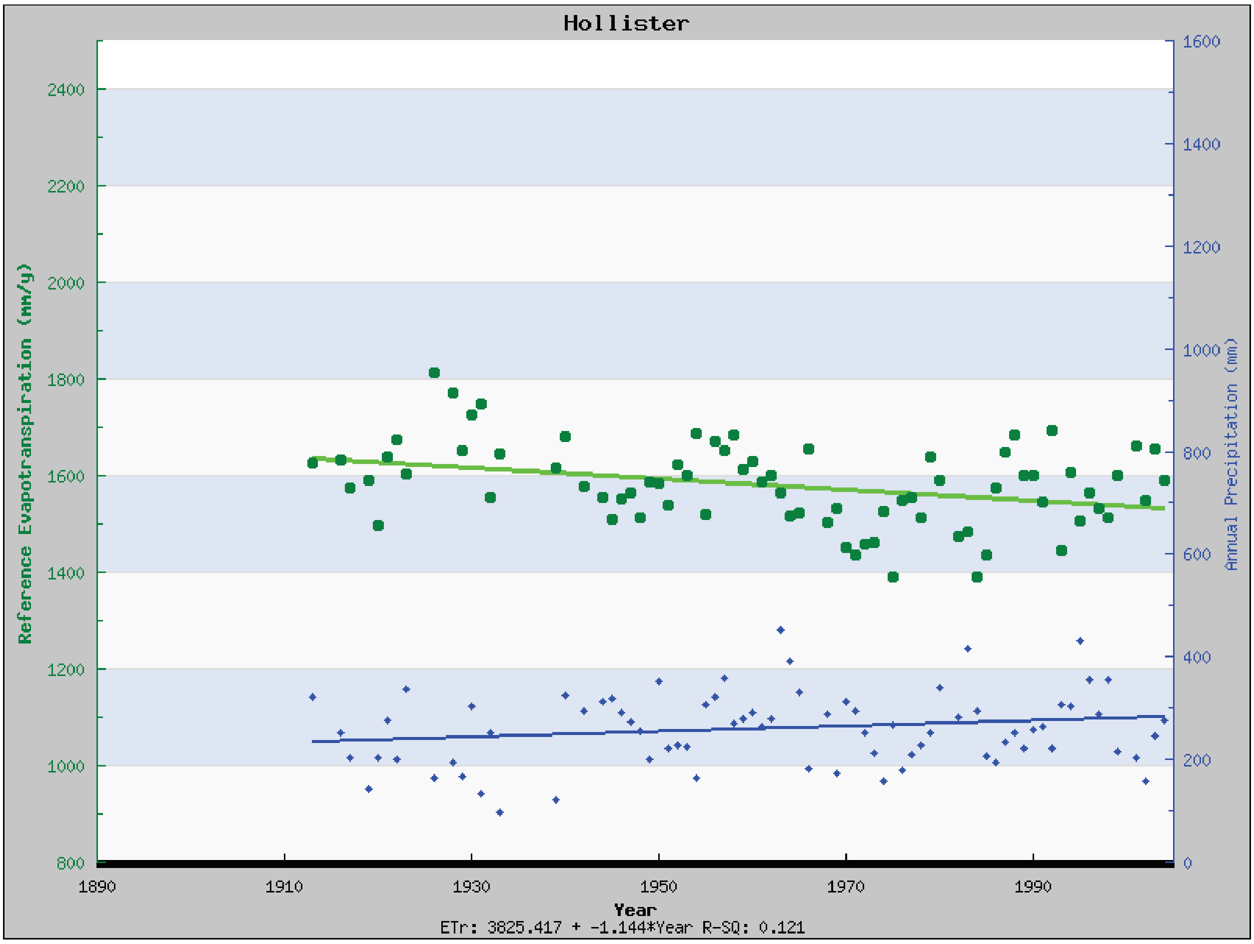

Figure 15.5. Plot of series of annual reference evapotranspiration (for full calendar years) and reported annual precipitation for Hollister, Idaho for the period of record as created by the ETIdaho web site.

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ANNEX 1.

ASCE Journal of Irrigation and Drainage Engineering paper by Allen et al., 2005 describing the approach and application of the dual K_c procedure.

The Allen et al. (2005) paper summarizes the FAO-56 (Allen et al., 1998) procedure for estimating K_c using the 'dual' K_c procedure where evaporation from wet soil is calculated separate from and then added to a basal ET that represents ET from a crop having a dry soil surface.

The following equations replace those in the ASCE paper for application to an alfalfa ET_r reference:

Equation (5) of Allen et al. (2005) is not required when the procedure is applied to the alfalfa reference ET_r due to the aerodynamically rougher nature of the alfalfa reference as compared to the smoother grass reference ET_o.

Equation (7) of Allen et al. (2005) is replaced by the following equation when applied to alfalfa reference ET_r:

$$K_{c\max} = \max\left[1.0, K_{cb} + 0.05\right] \qquad (7)$$

Where K_{cb} is the basal crop coefficient (ET_r basis) on the day of the calculation for $K_{c\ max}$. The 'max' function takes the larger of the two values in the brackets that are separated by the comma.

In addition to the changes to Eq. (5) and (7) of Allen et al., (2005), the linearized form of the K_c or K_{cb} curves shown in figures 1 and 7-9 are replaced by curvilinear K_{cb} curves as shown in Appendix 3.

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FAO-56 Dual Crop Coefficient Method for Estimating Evaporation from Soil and Application Extensions

Richard G. Allen, M.ASCE[1]; Luis S. Pereira, M.ASCE[2]; Martin Smith[3]; Dirk Raes[4]; and James L. Wright, M.ASCE[5]

Abstract: Crop coefficient curves provide simple, reproducible means to estimate crop evapotranspiration (ET) from weather-based reference ET values. The dual crop coefficient (K_c) method of the Food and Agricultural Organization of the United States (FAO) Irrigation and Drainage Paper No. 56 (*FAO-56*) is intended to improve daily simulation of crop ET by considering separately the contribution of evaporation from soil. The dual method utilizes "basal" crop coefficients representing ET from crops having a dry soil surface and separately predicts evaporation from bare soil based on a water balance of the soil surface layer. Three extensions to the evaporation calculation procedure are described here that are intended to improve accuracy when applications warrant the extra complexity. The first extension uses parallel water balances representing the portion of the soil surface wetted by irrigation and precipitation together and the portion wetted by precipitation alone. The second extension uses three "stages" for surface drying and provides for application to deep cracking soils. The third extension predicts the extraction of the transpiration component from the soil surface layer. Sensitivity and analyses and illustrations indicate moderate sensitivity of daily calculated ET to application of the extensions. The dual K_c procedure, although relatively simple computationally and structurally, estimates daily ET as measured by lysimeter relatively well for periods of bare soil and partial and full vegetation cover.

DOI: 10.1061/(ASCE)0733-9437(2005)131:1(2)

CE Database subject headings: Evapotranspiration; Evaporation; Crops; Crop moisture index; Soil water.

Introduction

A commonly used approach for estimating consumptive use of water by irrigated crops is the crop coefficient—reference evapotranspiration (K_c ET$_0$) procedure. Reference evapotranspiration (ET$_0$) is computed for a grass or alfalfa reference crop and is then multiplied by an empirical crop coefficient (K_c) to estimate crop evapotranspiration (ET$_c$) (Jensen et al. 1971; Doorenbos and Pruitt 1977; Wright 1981, 1982). In general, three primary characteristics distinguish ET from a crop from ET from the reference surface: aerodynamic roughness of the crop; general resistance within the crop canopy and soil to the flow of heat and water vapor; and reflectance of the crop and soil surface to short wave radiation. Because ET$_0$ represents nearly all effects of weather, K_c varies predominately with specific crop characteristics and only a small amount with climate. This enables the transfer of standard values and curves for K_c between locations and climates. This transfer has led to the widespread acceptance and usefulness of the K_c approach.

In situations where K_c has not been derived by ET measurement, it can be estimated from fraction of ground cover or leaf area index (Allen et al. 1998). K_c varies during the growing season as plants develop, as the fraction of ground covered by vegetation changes, and as plants age and mature (Fig. 1). K_c varies according to the wetness of the soil surface, especially when there is little vegetation cover. Under bare soil conditions, K_c has a high value when soil is wet and its value steadily decreases as the soil dries.

This paper describes the dual K_c procedure of FAO published as *FAO Irrigation and Drainage Paper No. 56* (Allen et al. 1998) and provides a brief rationale for various components of the procedure along with selected sensitivity analyses. Extensions to the original procedure are introduced that may improve accuracy of applications for special situations.

FAO-56 K_c Procedure

The *FAO-56* crop coefficients are intended for use with grass reference ET$_0$ similar to that predicted by the *FAO-56* Penman–Monteith method (Allen et al. 1998). The *FAO-56* Penman–Monteith equation predicts ET$_0$ from a hypothetical grass reference surface that is 0.12 m in height having a surface resistance of 70 s m^{-1} for 24 h time steps and albedo of 0.23. Standardized equations for computing parameters in the *FAO-56* Penman–Monteith equation are given in Allen et al. (1998, 1994) as well

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Note. Discussion open until July 1, 2005. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on February 27, 2003; approved on June 27, 2003. This paper is part of the ***Journal of Irrigation and Drainage Engineering***, Vol. 131, No. 1, February 1, 2005. ©ASCE, ISSN 0733-9437/2005/1-2–13/$25.00.

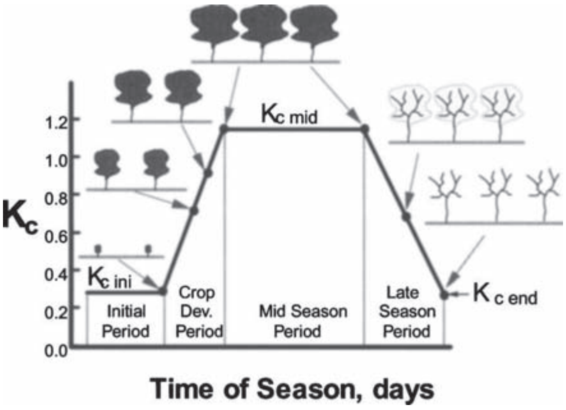

Fig. 1. Schematic showing generalized shape of Food and Agricultural Organization (FAO) K_c curve with four crop stages and three K_c (or K_{cb}) values and relative development of vegetation

as in Smith et al. (1991), Pereira et al. (1998), Pereira and Allen (1999), and ASCE (2002).

Crop Coefficient

Fundamentally, the crop coefficient is defined as the ratio of ET from any specific crop or soil surface to some reference ET as defined by weather data. In *FAO-56* nomenclature

$$K_c = \frac{\mathrm{ET}_c}{\mathrm{ET}_0} \tag{1}$$

In *FAO-56*, values listed for K_c represent ET under growing conditions having a high level of management and with little or no water or other ET reducing stresses and thus represent what are referred to as potential levels for crop ET

$$\mathrm{ET}_c = K_c \mathrm{ET}_0 \tag{2}$$

Actual ET_c can be less than the potential ET_c for a crop under nonideal growing conditions including those having water stress or high soil salinity. In this paper, ET_c representing ET under any condition, ideal or nonideal, is termed "actual ET_c" and is denoted as $\mathrm{ET}_{c\ \mathrm{act}}$. The $\mathrm{ET}_{c\ \mathrm{act}}$ was termed "adjusted ET_c" ($\mathrm{ET}_{c\ \mathrm{adj}}$) in *FAO-56*. The terms are synonymous and

$$\mathrm{ET}_{c\ \mathrm{act}} = K_{c\ \mathrm{act}} \mathrm{ET}_0 \tag{3}$$

where $K_{c\ \mathrm{act}}$ = "actual" crop coefficient that includes any effects of environmental stresses.

A linearized form for mean K_c and basal K_c curves in *FAO-56* was introduced in *FAO-24* (Doorenbos and Pruitt 1977) where the FAO K_c curve is comprised of four straight line segments representing the initial period, the development period, the midseason period, and the late season period (Fig. 1). These segments are defined by three primary K_c values: K_c during the initial period ($K_{c\ \mathrm{ini}}$), K_c during the midseason (full cover) period ($K_{c\ \mathrm{mid}}$), and K_c at harvest (or at the end of the late season) ($K_{c\ \mathrm{end}}$). The $K_{c\ \mathrm{ini}}$ defines the horizontal portion of the K_c curve during the initial period until approximately 10% of the ground is covered by vegetation. The $K_{c\ \mathrm{mid}}$ defines the value for K_c during the peak period for the crop, which is normally when the crop is at "effective full cover." This period is described by a horizontal line extending through $K_{c\ \mathrm{mid}}$. The development period is defined by a sloping line that connects the initial and midseason periods. The late season has a sloping line that connects the end of the midseason period with the harvest (end) date.

In *FAO-56*, two forms for K_c are presented: the "singular" K_c form used in *FAO-24* and the "dual" $K_c = K_{cb} + K_e$ form introduced in *FAO-56*, where K_{cb} is the basal crop coefficient and K_e is the soil evaporation coefficient. In the dual form, K_{cb} represents the ratio of ET_c to ET_0 under conditions when the soil surface layer is dry, but where the average soil water content of the root zone is adequate to sustain full plant transpiration. Under basal conditions, small amounts of evaporation from the surface soil layer occur by diffusion and are included in K_{cb} (and thus $K_{cb\ \mathrm{ini}}$ is usually not set to zero during the growing cycle). The majority of evaporation from soil following wetting by precipitation or irrigation is represented by the separate K_e. The total, actual $K_{c\ \mathrm{act}}$ is the sum of K_{cb} and K_e, reduced by any occurrence of soil water stress

$$K_{c\ \mathrm{act}} = K_s K_{cb} + K_e \tag{4}$$

where K_{cb} and K_e range from [0 to $\sim$1.4]. The stress reduction coefficient K_s [0–1], reduces K_{cb} when the average soil water content or salinity level of the root zone are not conducive to sustain full plant transpiration. K_s for soil water stress is described later and the function for salinity induced stress is described in Allen et al. (1998). The sum of K_{cb} and K_e cannot exceed some maximum value for a crop–soil complex (generally $\sim$1.4 for *FAO-56* based ET_0), based on energy limitations. The form and principle of Eq. (4) was developed by Jensen et al. (1971), Wright and Jensen (1978), and Wright (1981, 1982).

The K_{cb} curve has the same shape as in Fig. 1 and three benchmark values for K_{cb} are used to construct the curve, namely $K_{cb\ \mathrm{ini}}$, $K_{cb\ \mathrm{mid}}$, and $K_{cb\ \mathrm{end}}$. Because K_{cb} can include "diffusive" or residual evaporation from soil for potentially long periods following wetting, $K_{cb\ \mathrm{ini}}$ is generally set to 0.15 in *FAO-56* for annual crops for the period from planting to before 10% ground cover. However, under dry conditions with long periods between wetting events or during the nongrowing season, $K_{cb\ \mathrm{ini}}$ can be set equal to 0. This is illustrated later.

FAO-56 describes the procedure for applying the dual method on a daily basis, with specific estimation of evaporation from wet soil. The dual approach is well suited for predicting the effects of day to day variation in soil water evaporation and the effectiveness of precipitation.

Adjustment for Climate

FAO-24 (Doorenbos and Pruitt 1977) presented, for each crop listing, four values for singular midseason and end-of-season crop coefficients, termed in *FAO-56* as $K_{c\ \mathrm{mid}}$ and $K_{c\ \mathrm{end}}$. The four values represented four climatic cases of wind and humidity that impact the value for K_c. In contrast, *FAO-56* includes only single entries for $K_{c\ \mathrm{mid}}$ and for $K_{c\ \mathrm{end}}$, or, in the case of K_{cb}, for $K_{cb\ \mathrm{mid}}$ and for $K_{cb\ \mathrm{end}}$. The single entries correspond to K_c or K_{cb} values associated with a standard subhumid climate having average daytime minimum relative humidity ($\mathrm{RH}_{\min}$) of about 45% and having calm to moderate wind speeds of $1-3\ \mathrm{m\,s^{-1}}$, averaging $2\ \mathrm{m\,s^{-1}}$. K_c and K_{cb} values are listed for about 80 crops in *FAO-56*. These can be accessed on the FAO web site (FAO 1998).

For climates where mean $\mathrm{RH}_{\min}$ is different from 45% or where wind speed at 2 m (u_2) is different from $2.0\ \mathrm{m\,s^{-1}}$, $K_{cb\ \mathrm{mid}}$ values from *FAO-56* are adjusted as

$$K_{\text{cb mid}} = K_{\text{cb mid (standard climate)}} + [0.04(u_2 - 2) - 0.004(\text{RH}_{\min} - 45)]\left(\frac{h}{3}\right)^{0.3} \quad (5)$$

where $K_{\text{cb mid(standard climate)}}$=value for $K_{\text{cb mid}}$ from Table 17 of *FAO-56*; u_2=mean daily wind speed at 2 m height (m s^{-1}); $\text{RH}_{\min}$=mean daily minimum relative humidity (%) during the midseason period; and h=mean plant height during the midseason period (m). The adjustment in Eq. (5) accounts for impacts of differences in aerodynamic roughness between crops and the grass reference with changing climate and closely replicates the range in K_c values for the four climatic classes of *FAO-24*. Justification for Eq. (5) is given in Allen et al. (1998). Similar adjustment is made to $K_{\text{cb end}}$ when values for $K_{\text{cb end}} > 0.45$. Eq. (5) can be applied daily using daily values for u_2 and $\text{RH}_{\min}$ or can be applied for the midseason in total using averages for u_2 and $\text{RH}_{\min}$ for the period with relatively small loss in accuracy. When only mean daily dewpoint temperature or vapor pressure is known, $\text{RH}_{\min}$ can be approximated as $\text{RH}_{\min} \sim 100 e_a / e^0(T_{\max})$, where e_a is actual vapor pressure and $e^0(T_{\max})$ is saturation vapor at daily maximum air temperature. The crop height adjustment in Eq. (5) is applied to both the wind and the $\text{RH}_{\min}$ terms because both terms appear in the aerodynamic term of the Penman–Monteith equation and both factors influence ET in some proportion to aerodynamic roughness.

Evaporation from Soil

The approach of *FAO-56* is similar to that of Ritchie (1972), Saxton et al. (1974), and Wright (1982) where evaporation from soil beneath a canopy or inbetween plants is predicted by estimating the amount of energy at the soil surface in conjunction with energy consumed by transpiration. When the soil is wet, evaporation is predicted to occur at some maximum rate and the sum $K_c = K_{\text{cb}} + K_e$ is limited by some maximum value $K_{c\,\max}$.

As the surface soil layer dries, a reduction in evaporation occurs, and K_e is simulated as

$$K_e = K_r(K_{c\,\max} - K_{\text{cb}}) \leq f_{\text{ew}} K_{c\,\max} \quad (6)$$

where $K_{c\,\max}$=maximum value of K_c following rain or irrigation; K_r=dimensionless evaporation reduction coefficient and is dependent on the cumulative depth of water depleted (evaporated); and f_{ew}=fraction of the soil that is both exposed to solar radiation and that is wetted. Evaporation is restricted by the energy available at the exposed soil fraction, i.e., K_e cannot exceed $f_{\text{ew}} K_{c\,\max}$. The *FAO-56* dual procedure differs from Ritchie (1972) and Saxton et al. (1974) in that the FAO procedure gives K_e (as limited by $f_{\text{ew}} K_{c\,\max}$) equal priority to transpiration (as represented by K_{cb}) in regard to energy consumption, whereas the Ritchie and Saxton approaches give transpiration priority over evaporation.

$K_{c\,\max}$ represents an upper limit on evaporation and transpiration from the cropped surface and is introduced to reflect the natural constraints on available energy. $K_{c\,\max}$ ranges from about 1.05 to 1.30 when using the grass reference ET_0

$$K_{c\,\max} = \max\left(\left\{1.2 + [0.04(u_2 - 2) - 0.004(\text{RH}_{\min} - 45)]\left(\frac{h}{3}\right)^{0.3}\right\}, \{K_{\text{cb}} + 0.05\}\right) \quad (7)$$

where h=mean plant height during the period of calculation (initial, development, mid-season, or late-season) (m), and the max () function indicates the selection of the maximum of values separated by the comma. Eq. (7) ensures that $K_{c\,\max}$ is always greater than or equal to the sum $K_{\text{cb}}+0.05$, suggesting that wet soil always increases the K_c value above K_{cb} by 0.05 following complete wetting of the soil surface, even during periods of full ground cover. The value 1.2 represents the impact of reduced albedo of wet soil and the contribution of heat stored in dry soil prior to wetting events that are separated by more than 3 or 4 days. The value also considers the effect of increased aerodynamic roughness of surrounding crops during development, midseason, and late season growth stages which can increase the turbulent transfer of vapor from the exposed soil surface. Bonachela et al. (2001) noted $K_{c\,\max}$ of over 1.5 for soil evaporation from a drip-irrigated olive orchard caused by microadvection of heat from dry surface areas to wet surface areas. Under complete surface wetting, $K_{c\,\max}$ would be expected to be lower, for example ranging from 1.0 to 1.2. In addition, if irrigation or precipitation events are more frequent than 3 days each, for example daily or 2 days each, then the soil has less opportunity to absorb heat between wetting events, and the 1.2 value can be reduced to about 1.1.

The surface soil layer is presumed to dry to an air dry water content approximated as halfway between wilting point θ_{WP} and oven dry. The amount of water that can be removed by evaporation during a complete drying cycle is estimated as

$$\text{TEW} = 1000(\theta_{\text{FC}} - 0.5\theta_{\text{WP}})Z_e \quad (8)$$

where (total evaporable water) (TEW)=maximum depth of water that can be evaporated from the surface soil layer when the layer has been initially completely wetted (mm). Field capacity θ_{FC} and θ_{WP} are expressed in ($\text{m}^3\ \text{m}^{-3}$) and Z_e(m)=effective depth of the surface soil subject to drying to 0.5 θ_{WP} by way of evaporation. Typical values for θ_{FC}, θ_{WP}, and TEW are given in Table 1 for various soil types. Z_e is an empirical value based on observation. *FAO-56* recommended values for Z_e of 0.10–0.15 m, with 0.1 m recommended for coarse soils and 0.15 m recommended for fine textured soils. However, the user should select the value for Z_e, or even TEW, that represents evaporation amounts observed over complete drying cycles via gravimetric or other measurement. Some evaporation or soil drying will be observed to occur below the Z_e depth.

Evaporation from exposed soil is presumed to take place in two stages: an energy limiting stage (Stage 1), and a falling rate stage (Stage 2) (Philip 1957 and Ritchie 1972). During Stage 1, the soil surface remains wet and evaporation is predicted to occur at the maximum rate limited only by energy availability at the soil surface and therefore, $K_r=1$. As the soil surface dries, the evaporation rate decreases below the potential evaporation rate (defined as $K_{c\,\max} - K_{\text{cb}}$), and K_r becomes less than one. K_r becomes zero when no water is left for evaporation in the evaporation layer.

Stage 1 holds until the cumulative depth of evaporation D_e is such that the hydraulic properties of the upper soil become limiting and water cannot be transported to near the soil surface at a rate to supply the demand. At the end of Stage 1 drying, D_e is equal to readily evaporable water (REW). Readily evaporable water normally ranges from 5 to 12 mm and is highest for medium and fine textured soils (Ritchie 1972; Ritchie et al. 1989).

The second stage, where K_r is decreasing, begins when D_e exceeds REW. At this point, the soil surface is visibly dry, and evaporation from the exposed soil decreases in proportion to the amount of water remaining in the surface soil layer. Most early Stage 2 models (Philip 1957; Ritchie 1972) proportion the evaporation rate according to the square root of time since the begin-

Table 1. Typical Soil Water Characteristics for Different Soil Types (from *FAO-56*)

				Evaporation parameters		
	Soil water characteristics			Amount of water that can be depleted by evaporation		
Soil type (USDA soiltexture classification)	θ_{FC} $m^3\,m^{-3}$	θ_{WP} $m^3\,m^{-3}$	$(\theta_{FC}\text{-}\theta_{WP})$ $m^3\,m^{-3}$	Stage 1 REW (mm)	Stages 1 and 2 TEW[a] (Z_e=0.10 m) (mm)	Stages 1 and 2 TEW[a] (Z_e=0.15 m) (mm)
Sand	0.07–0.17	0.02–0.07	0.05–0.11	2–7	6–12	9–13
Loamy sand	0.11–0.19	0.03–0.10	0.06–0.12	4–8	9–14	13–21
Sandy loam	0.18–0.28	0.06–0.16	0.11–0.15	6–10	15–20	22–30
Loam	0.20–0.30	0.07–0.17	0.13–0.18	8–10	16–22	24–33
Silt loam	0.22–0.36	0.09–0.21	0.13–0.19	8–11	18–25	27–37
Silt	0.28–0.36	0.12–0.22	0.16–0.20	8–11	22–26	33–39
Silt clay loam	0.30–0.37	0.17–0.24	0.13–0.18	8–11	22–27	33–40
Silty clay	0.30–0.42	0.17–0.29	0.13–0.19	8–12	22–28	33–42
Clay	0.32–0.40	0.20–0.24	0.12–0.20	8–12	22–29	33–43

Note: USDA=United States Department of Agriculture; REW=readily evaporated water; and TEW=totally evaporated water.

[a] $TEW=(\theta_{FC}-0.5\theta_{WP})Z_e$.

ning of Stage 2. This requires manipulation of time terms as new water enters the system. Moreover, the proportionality factor changes with ET_0 demand and therefore requires frequent recalibration (Snyder et al. 2000). In the *FAO-56* model, the reduction in evaporation during Stage 2 is proportional to the cumulative evaporation from the surface soil layer, resulting in a more simple, easily managed computation procedure that is based on a soil–water balance and that does not require recalibration

$$K_r=\frac{\text{TEW}-D_{e,j-1}}{\text{TEW}-\text{REW}} \tag{9}$$

for $D_{e,j-1}>\text{REW}$, where $D_{e,j-1}$=cumulative depletion from the soil surface layer at the end of day $j-1$ (the previous day) (mm); and TEW and REW are in millimeters (REW<TEW). The general form for the K_r function is illustrated in Fig. 2. The prediction by Eq. (9) is similar to that predicted by a square-root-of-time Stage 2 model, and differences are in general smaller than the uncertainties caused by the continuously changing effects of soil hydraulic properties, tillage, soil temperature, wetting characteristics, and root extraction. Saxton et al. (1974) used a nonlinear proportionality based on water content of the surface layer that had similar behavior as Eq. (9). A three-stage drying process can be applied to cracking soils as described in a following section. Mutziger et al. (2001) found good agreement between K_r predicted using the *FAO-56* dual method using REW and TEW from Table 1 (with Z_e=0.1 m) and relative evaporation measurements published by Chanzy and Bruckler (1993) for loam, silty clay loam, and clay soils.

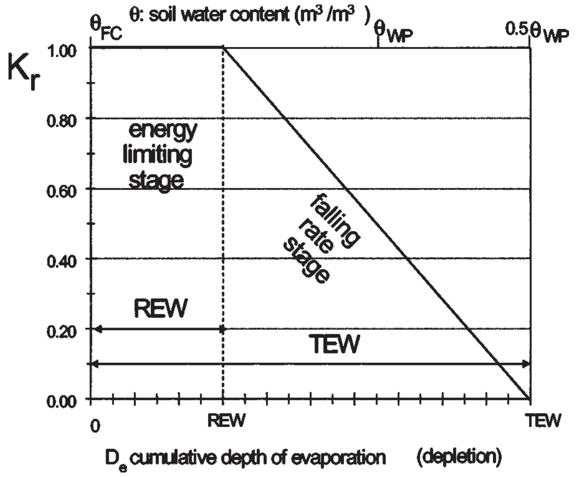

Fig. 2. General function for soil evaporation reduction coefficient K_r for two-stage *FAO-56* model (from *FAO-56*)

In crops having partial ground cover, evaporation from the soil usually occurs nonuniformly over the surface, and is greater between plants having dense canopies near the ground where exposure to sunlight occurs and where more air ventilation is able to transport vapor from the soil surface to above the canopy. This is especially true where only part of the soil surface is wetted by irrigation. While it is recognized that both the locations and the fractions of the soil surface exposed to sunlight and ventilation may change with the time of day and depend on row orientation and near surface canopy density, the procedure of *FAO-56* predicts a general, averaged fraction of soil surface from which the majority of evaporation is expected to occur. Most evaporation from the soil beneath the crop canopy, occurring at a slower rate, is in many situations included in the basal K_{cb} coefficient.

Table 2. Common Values for Fraction of Soil Surface Wetted by Irrigation or Precipitation (after *FAO-56*)

Wetting event	f_w
Precipitation	1.0
Sprinkler irrigation, field crops	1.0
Sprinkler irrigation, orchards	0.7–1.0
Basin irrigation	1.0
Border irrigation	1.0
Furrow irrigation (every furrow), narrow bed	0.6–1.0
Furrow irrigation (every furrow), wide bed	0.4–0.6
Furrow irrigation (alternated furrows)	0.3–0.5
Microspray irrigation, orchards	0.5–0.8
Trickle (drip) irrigation	0.3–0.4

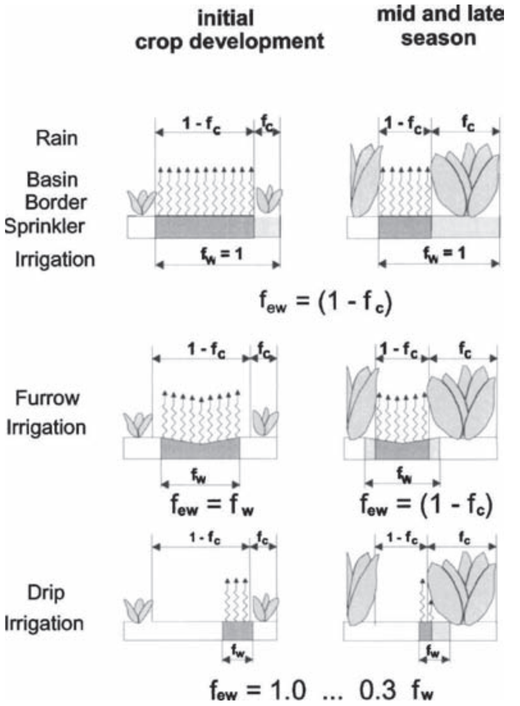

Fig. 3. Determination of f_{ew} (greyed areas) as function of fraction of ground surface coverage (f_c) and fraction of surface wetted (f_w) (from *FAO-56*)

In the *FAO-56* model, the term f_w is defined as the fraction of the surface wetted by irrigation and/or precipitation. This term defines the potential spatial extent of evaporation. Common values for f_w are listed in Table 2. An extension to Eq. (10) is described later.

When the soil surface is completely wetted, as by precipitation or sprinkler, f_{ew} of Eq. (6) is set equal to $(1-f_c)$, where f_c is the fraction of soil surface effectively covered by vegetation and $(1-f_c)$ represents the approximate fraction of soil surface that is effectively exposed to evaporation energy. For irrigation systems where only a fraction of the ground surface (f_w) is wetted, f_{ew} is limited to f_w

$$f_{\text{ew}} = \min(1 - f_c, f_w) \tag{10}$$

Both $1-f_c$ and f_w, for numerical stability, have limits of [0.01–1]. The limitation imposed by Eq. (10) presumes the fraction of soil wetted by irrigation occurs within the primary fraction of soil exposed to sunlight and ventilation. This is generally the case, except with some drip irrigation (Fig. 3). In the case of drip irrigation, Allen et al. (1998) recommended multiplying f_w by $[1-(2/3)f_c]$. Pruitt et al. (1984) and Bonachela et al. (2001) have described evaporation patterns and extent under drip irrigation.

Predicting Fraction of Surface Cover

The difference $(1-f_c)$ represents the fraction of the soil effectively exposed to sunlight and air ventilation and serves as the site where the majority of evaporation is expected to occur. The value for f_c is limited to <0.99 for numerical stability and is generally determined by visual observation. For purposes of estimating f_{ew}, f_c can be estimated from K_{cb} as

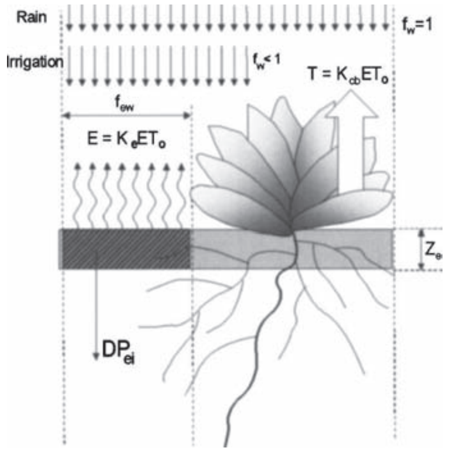

Fig. 4. Water balance of soil surface layer (from *FAO-56*)

$$f_c = \left(\frac{K_{\text{cb}} - K_{c\,\min}}{K_{c\,\max} - K_{c\,\min}}\right)^{(1+0.5h)} \tag{11}$$

where f_c is limited to [0–0.99] and $K_{c\,\min}$=minimum K_c for dry bare soil with no ground cover. Eq. (11) assumes that the value for K_{cb} is largely governed by the fraction of vegetation cover. The $1+0.5h$ exponent in Eq. (11) represents the impact of plant height on shading of the soil surface and in increasing the value for K_{cb} given a specific value for f_c. The difference $K_{\text{cb}}-K_{c\,\min}$ is limited to $\geqslant 0.01$ for numerical stability. The value for f_c will change daily as K_{cb} changes. $K_{c\,\min}$ ordinarily has the same value as $K_{\text{cb ini}}$ used for annual crops under nearly bare soil conditions (i.e., $K_{c\,\min} \sim 0.15$). The value for f_c decreases during the late season period in proportion to K_{cb} to account for local transport of sensible heat from senescing leaves to the soil surface.

Under vegetation having an open canopy near the ground surface, for example some types of orchards, a large proportion, if not all, of the ground surface is effectively exposed to evaporative energy (Bonachela et al. 2001). In these situations, $1-f_c$ does not have large impact on f_{ew}, and $f_{\text{ew}}=f_w$ can be applied. The decision in assigning values for f_c and f_{ew} should be based on field observation of drying patterns.

Water Balance of Soil Surface Layer

Calculation of K_e requires a daily water balance for the f_{ew} fraction of the surface soil layer. The daily soil water balance equation is (Fig. 4)

$$D_{e,j} = D_{e,j-1} - (P_j - \text{RO}_j) - \frac{I_j}{f_w} + \frac{E_j}{f_{\text{ew}}} + T_{\text{ei},j} + \text{DP}_{\text{ei},j} \tag{12}$$

where $D_{e,j-1}$ and $D_{e,j}$=cumulative depletion depth at the ends of days $j-1$ and j (mm); P_j and RO_j=precipitation and precipitation runoff from the soil surface on day j (mm); I_j=irrigation depth on day j that infiltrates the soil (mm); E_j=evaporation on day j (i.e., $E_j=K_e\text{ET}_0$) (mm); $T_{\text{ei},j}$=depth of transpiration from the exposed and wetted fraction of the soil surface layer on day j (mm); and $\text{DP}_{\text{ei},j}$=deep percolation from the soil surface layer on day j if soil water content exceeds field capacity (mm). Assuming that the surface layer is at field capacity following heavy rain or irrigation, the minimum value for $D_{e,j}$ is zero and limits imposed are $0 \leqslant D_{e,j} \leqslant \text{TEW}$. It is recognized that water content of the soil surface layer can exceed TEW for short periods of time while drainage is occurring. However, because the length of time that this occurs varies with soil texture, wetting depth, and tillage, $D_{e,j} \geqslant 0$ is assumed. Additionally, it is recognized that some drainage in soil occurs at very small rates at water contents below field capacity. To some extent, impacts of these simple assumptions can be compensated for, if needed, in setting the value for Z_e or TEW.

RO_j can be computed using the USDA curve number procedure (Hawkins et al. 1985). The irrigation depth I_j is divided by f_w to approximate the infiltration depth to the f_w portion of the soil surface. Similarly, E_j is divided by f_{ew} because it is assumed that all E_j (other than residual evaporation implicit to the K_{cb} coefficient) is taken from the f_{ew} fraction of the surface layer.

Except for shallow rooted crops, where the depth of the maximum rooting is less than 0.5–0.6 m, the amount of transpiration extracted from the f_{ew} portion of the surface soil layer is small and can be ignored (i.e., $T_{\mathrm{ei}}=0$). Where transpiration is known to extract water from the f_{ew} fraction of the surface layer, but is not considered in Eq. (12), *FAO-56* advises that the depth of the surface layer Z_e be decreased to compensate for the quicker drying. Estimation of T from the f_{ew} fraction of the surface layer is described in a following section.

Following heavy rain or irrigation, the soil water content in the surface layer (Z_e layer) might exceed field capacity for short time periods until excess water moves into the root zone and perhaps even deeper. In the simple water balance procedure used in *FAO-56*, however, it is assumed that the soil water content is limited to $\leqslant \theta_{\mathrm{FC}}$ on the day of a complete wetting event. This is a reasonable assumption considering the shallowness of the surface layer. Downward drainage (percolation) of water from the surface layer is calculated as

$$\mathrm{DP}_{e,j} = (P_j - \mathrm{RO}_j) + \frac{I_j}{f_w} - D_{e,j-1} \geqslant 0 \qquad (13)$$

As long as the soil water content in the evaporation layer is below field capacity (i.e., $D_{e,j} > 0$), the surface layer is assumed to not drain, and $\mathrm{DP}_{e,j}=0$.

Initialization of Water Balance

To initiate the water balance for the evaporating layer, the user can assume that the soil surface layer is near θ_{FC} following a heavy rain or irrigation so that $D_{e,j-1}=0$. Where a long period of time has elapsed since the last wetting, the user can assume that all evaporable water has been depleted from the evaporation layer at the beginning of calculations so that $D_{e,j-1}=\mathrm{TEW}=1{,}000(\theta_{\mathrm{FC}} - 0.5\ \theta_{\mathrm{WP}})\ Z_e$.

Order of Calculation

Calculations for the *FAO-56* dual $K_{\mathrm{cb}}+K_e$ procedure, for example when using a spreadsheet, proceed in the following order: K_{cb}, h, $K_{c\ \max}$, f_c, f_w, f_{ew}, K_r, K_e, E, DP_e, D_e, I, K_c, and ET_c.

Extensions to FAO-56 Procedure

The evaporation component of the *FAO-56* dual K_c procedure was intended for routine application under a wide range of conditions. The procedure constitutes a balance between simplicity, understandability, and completeness and is recommended for most applications. The following three extensions to the *FAO-56* procedure may increase accuracy and definition of the total evaporation and drying process under special conditions.

Separate Prediction of Evaporation from Soil Wetted by Precipitation Only

The evaporation component is assumed to be fully concentrated in the exposed and wetted fraction of the surface layer. The slower rate of evaporation occurring from beneath the vegetation canopy is generally included in K_{cb} and is therefore not explicitly quantified. E is computed as $K_e\ \mathrm{ET}_0$. The quotient E/f_{ew} in Eq. (12) describes the concentration of evaporation over the fraction of the soil that is both exposed and wetted.

Parameter $f_w=1$ for precipitation but is often <1 for some types of surface irrigation and micro irrigation. *FAO-56* recommended a procedure for calculating f_w according to the type of last wetting event and its extent. However, this determination can be subjective and uncertain. This section describes an extension to *FAO-56* that incorporates a separate water balance and procedure for K_r for the fraction of soil that is wetted by precipitation only (i.e., not by irrigation). The extension reduces uncertainty in determining the value for f_w and has been applied by Mutziger et al. (2005) in estimating annual evaporation losses from agricultural areas in California.

In the extension to the *FAO-56* procedure, the evaporation calculation is divided into two separate calculations. One calculation is made for the exposed fraction of soil wetted by both irrigation and precipitation and one calculation is made for the exposed fraction of soil wetted by precipitation only. The coefficient K_e is calculated as

$$K_e = K_{\mathrm{ei}} + K_{\mathrm{ep}} \qquad (14)$$

where K_{ei}=evaporation coefficient for the exposed fraction of the soil wetted by both irrigation and by precipitation and K_{ep}=evaporation coefficient for the exposed fraction of the soil wetted by precipitation only.

The modification to Eq. (6) that applies to the fraction wetted by both irrigation and by precipitation is

$$K_{\mathrm{ei}} = K_{\mathrm{ri}} W (K_{c\ \max} - K_{\mathrm{cb}}) \leqslant f_{\mathrm{ewi}} K_{c\ \max} \qquad (15)$$

and the application of Eq. (6) to the fraction of soil that is exposed and wetted by precipitation only is

$$K_{\mathrm{ep}} = K_{\mathrm{rp}} (1 - W)(K_{c\ \max} - K_{\mathrm{cb}}) \leqslant f_{\mathrm{ewp}} K_{c\ \max} \qquad (16)$$

where f_{ewi}=fraction of soil wetted by both irrigation and precpitation and is exposed to rapid drying due to exposure to solar radiation and/or ventilation; f_{ewp}=fraction of soil exposed to rapid drying and is wetted by precipitation only; W=weighting coefficient for partitioning the energy available for evaporation into the f_{ewi} and f_{ewp} soil fractions, depending on water availability; K_{ri} and K_{rp}=evaporation reduction coefficients for the f_{ewi} and f_{ewp} fractions; and f_{ewp} is calculated as

$$f_{\mathrm{ewp}} = 1 - f_c - f_{\mathrm{ewi}} \qquad (17)$$

and f_{ewp} and f_{ewi} are limited to 0.001–1.0. Eq. (10) is reexpressed for f_{ewi} as

$$f_{\mathrm{ewi}} = \min(1 - f_c, f_w) \qquad (18)$$

where $1-f_c$ has limits of [0.01–1] and f_w=average fraction of soil surface wetted by irrigation, only [0.01–1].

The weighting factor W is calculated according to water availability in the two wetted, exposed fractions of the surface layer

$$W=\frac{1}{1+\dfrac{f_{\mathrm{ewp}}}{f_{\mathrm{ewi}}}\dfrac{(\mathrm{TEW}-D_{\mathrm{ep}})}{(\mathrm{TEW}-D_e)}} \tag{19}$$

where D_e=cumulative depletion depth (mm) from the evaporating layer for the f_{ewi} fraction of soil; and D_{ep}=cumulative depletion depth (mm) from the evaporating layer for the f_{ewp} fraction of soil. The limits D_e and $D_{\mathrm{ep}} < \mathrm{TEW}$; D_e and $D_{\mathrm{ep}} \geqslant 0$; and $f_{\mathrm{ewi}}(\mathrm{TEW}-D_e) > 0.001$ are imposed for numerical stability.

An associated water balance is computed for the fraction of the evaporation layer wetted by precipitation, but not by irrigation, and is in the exposed portion of the soil

$$D_{\mathrm{ep},j}=D_{\mathrm{ep},j-1}-(P_j-\mathrm{RO}_j)+\frac{E_{p,j}}{f_{\mathrm{ewp}}}+T_{\mathrm{ep},j}+\mathrm{DP}_{\mathrm{ep},j} \tag{20}$$

where $D_{\mathrm{ep},j-1}$ and $D_{\mathrm{ep},j}$=cumulative depletion depths at the ends of days $j-1$ and j in the f_{ewp} fraction of the surface (mm); $E_{p,j}$ =evaporation from f_{ewp} fraction on day j ($E_{p,j}=K_{\mathrm{ep}}\ \mathrm{ET}_0$) (mm); $T_{\mathrm{ep},j}=T_e$ from f_{ewp} fraction of the evaporation layer on day j (mm); ($T_{\mathrm{ep},j}$ can be set equal to zero for simplification); and $\mathrm{DP}_{\mathrm{ep},j}$=deep percolation from the f_{ewp} fraction of the evaporation layer on day j if soil water content exceeds θ_{FC} (mm). The limits on $D_{\mathrm{ep},j}$ are $0 \leqslant D_{\mathrm{ep},j} \leqslant \mathrm{TEW}$. The $E_{p,j}$ is divided by f_{ewp} because it is assumed that all E_p is taken from the f_{ewp} fraction of the surface layer.

Eq. (12) is expressed for the f_{ewi} fraction as

$$D_{e,j}=D_{e,j-1}-(P_j-\mathrm{RO}_j)-\frac{I_j}{f_w}+\frac{E_j}{f_{\mathrm{ewi}}}+T_{\mathrm{ei},j}+\mathrm{DP}_{\mathrm{ei},j} \tag{21}$$

where f_w=fraction of soil surface wetted by irrigation.

Eq. (9) is expressed for the f_{ewi} and f_{ewp} fractions as

$$K_{\mathrm{ri}}=\frac{\mathrm{TEW}-D_{e,j-1}}{\mathrm{TEW}-\mathrm{REW}} \tag{22}$$

and

$$K_{\mathrm{rp}}=\frac{\mathrm{TEW}-D_{\mathrm{ep},j-1}}{\mathrm{TEW}-\mathrm{REW}} \tag{23}$$

for $D_{e,j-1}$ and $D_{\mathrm{ep},j-1} \geqslant 0$.

The total evaporation rate from the exposed fraction of the surface is $E=K_e\ \mathrm{ET}_0=(K_{\mathrm{ei}}+K_{\mathrm{ep}})\ \mathrm{ET}_0$. K_{ei} and K_{ep} are both constrained so that $K_{\mathrm{ei}} \geqslant 0$ and $K_{\mathrm{ep}} \geqslant 0$

Eq. (13) is expressed for the f_{ewi} fraction of the surface layer as

$$\mathrm{DP}_{\mathrm{ei},j}=(P_j-\mathrm{RO}_j)+\frac{I_j}{f_w}-D_{\mathrm{ei},j-1} \geqslant 0 \tag{24}$$

As long as the soil water content in the evaporation layer is below field capacity (i.e., $D_{\mathrm{ei},j} > 0$), the soil will not drain and $\mathrm{DP}_{\mathrm{ei},j}=0$. For the fraction of exposed soil that is wetted by precipitation but not by irrigation

$$\mathrm{DP}_{\mathrm{ep},j}=(P_j-\mathrm{RO}_j)-D_{\mathrm{ep},j-1} \geqslant 0 \tag{25}$$

Transpiration from Surface Layer

The amount of transpiration extracted from the f_{ew} fraction of the evaporating soil layer is generally small and can be ignored. However, for shallow-rooted annual crops where the depth of the maximum rooting is less than about 0.5 m, T_e may have significant effect on the water balance of the surface layer and therefore on prediction of the evaporation component, especially for the period midway through the development period.

Under conditions of uniform water availability within the soil profile, the ratio of T extracted from the evaporation layer to total T is presumed proportional to $(Z_e/Z_r)^{0.6}$ (Allen et al. 1996), where Z_e is the depth of the surface evaporation layer and Z_r is the effective depth of the root zone ($Z_e \leqslant Z_r$ and Z_e is contained in Z_r). This relationship is based on the commonly used 40–30–20–10% root extraction pattern for quartile rooting depths (top to bottom) of the root zone for moist soils.

In this extension, it is assumed that the previous extension using f_{ewi} and f_{ewp} is applied. If this is not the case, then only T_{ei} is used and all occurrences of f_{ewi} are set to f_{ew}. The equation for T_e from the f_{ewi} fraction of the evaporation layer T_{ei} is

$$T_{\mathrm{ei}}=K_{\mathrm{ti}}K_{\mathrm{cb}}K_s\mathrm{ET}_0 \tag{26}$$

where K_{ti}, [0–1]=proportion of basal ET(=$K_{\mathrm{cb}}\mathrm{ET}_0$) extracted as transpiration from the f_{ewi} fraction of the surface soil layer, and K_s=soil water stress factor computed for the root zone [0–1]. K_{ti} is determined by comparing relative water availability in the Z_e and Z_r layers along with the presumed rooting distribution. For the f_{ewi} fraction

$$K_{\mathrm{ti}}=\left(\frac{1-\dfrac{D_e}{\mathrm{TEW}}}{1-\dfrac{D_r}{\mathrm{TAW}}}\right)\left(\frac{Z_e}{Z_r}\right)^{0.6} \tag{27}$$

where the numerator and denominator of the first expression of Eq. (27) are limited to $\geqslant 0.001$ and TAW is total available water in the root zone [see Eq. (33) introduced later]. In addition, the value for K_{ti} is limited to $\leqslant 1.0$ to limit T_{ei} to $\leqslant \mathrm{ET}_c$. A value of $K_{\mathrm{ti}} \sim 1.0$ would represent conditions where the soil profile is near wilting point, but the shallow surface layer is partially or fully rehydrated by a light precipitation or irrigation event, or where the root zone is very shallow.

Transpiration from the f_{ewp} fraction of the soil T_{ep} is calculated as

$$T_{\mathrm{ep}}=K_{\mathrm{tp}}K_{\mathrm{cb}}K_s\mathrm{ET}_0 \tag{28}$$

where

$$K_{\mathrm{tp}}=\left(\frac{1-\dfrac{D_{\mathrm{ep}}}{\mathrm{TEW}}}{1-\dfrac{D_r}{\mathrm{TAW}}}\right)\left(\frac{Z_e}{Z_r}\right)^{0.6} \tag{29}$$

where K_{tp}, [0–1]=proportion of basal ET(=$K_{\mathrm{cb}}\mathrm{ET}_0$) extracted as transpiration from the f_{ewp} fraction of the surface soil layer. The same limitations apply as for Eq. (27).

When there is Stage 3 evaporation, as defined in the next section, TEW in Eqs. (27) and (29) is set equal to TEW_3, the upper limit for evaporable water.

Stage Three Evaporation

The third extension to the *FAO-56* procedure applies to soils that crack substantially upon drying, thereby exposing progressively deeper depths of soil to drying by evaporation. This progressive drying continues at a low rate for an extended period of time. Drying to depths as deep as 0.5 m is possible for severely cracking soils containing large amounts of montmorillinite clay where cracks can extend as deep as 1 m (Pettry and Switzer 1996).

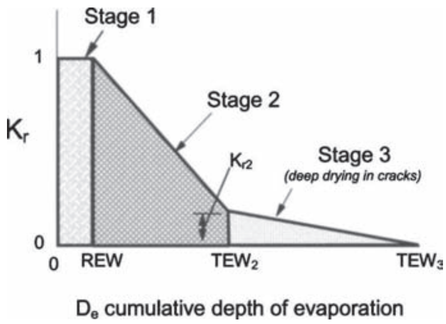

Fig. 5. General schematic showing evaporation reduction coefficient K_r as function of depth of water evaporated (depleted) from surface soil layer for cracking soil having three-stage evaporation.

In the extension for cracking soils, the evaporation process is expanded from two to three stages. The three stages are illustrated in Fig. 5. For normal agricultural soils that do not crack or only mildly crack, only Stage 1 and Stage 2 drying is applied. For cracking soils that have Stage 3 drying, Stage 3 is presumed to begin when K_r reduces to a threshold value labeled K_{r2}.

For three-stage drying, K_r is calculated for the second stage as

$$K_r = K_{r2} + (1 - K_{r2})\frac{\mathrm{TEW}_2 - D_{e,j-1}}{\mathrm{TEW}_2 - \mathrm{REW}}$$

$$\text{for REW} < D_{e,j-1} < \mathrm{TEW}_2 \qquad (30)$$

where TEW_2=maximum cumulative depth of evaporation (depletion) from the soil surface layer when K_r=K_{r2} (point at which evaporation transitions into stage three drying) (mm), and K_{r2} =value for K_r at the junction of Stage 2 and Stage 3 drying. Generally, the value for K_{r2} should be some relatively low value between about 0.1 and 0.4, depending on the nature and degree of cracking as the soil dries. Allen et al. (1998) recommended K_{r2} $\sim$0.2. Mutziger et al. (2001) found best fit values for K_{r2} for two cracking soils in Texas to be 0.3 and 0.2 when comparing against lysimeter measurements of evaporation for a black clay and clay loam.

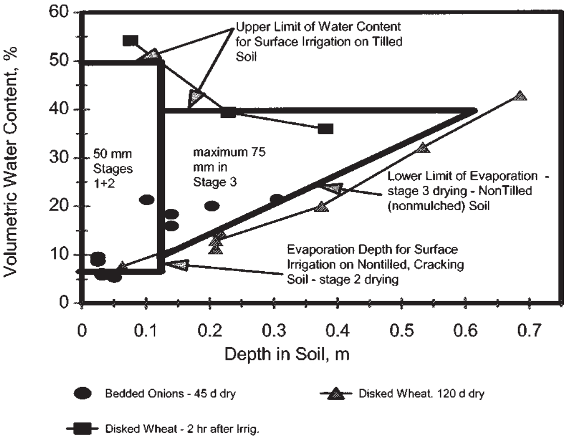

Fig. 6. Field measurements of volumetric water content for cracking soils in Imperial Irrigation District when wet (square symbols) and after 45 and 120 days of drying (circles and triangles). Superimposed on data are abstracted water content profiles associated with Stages 1 and 2 and with Stage 3 evaporation components

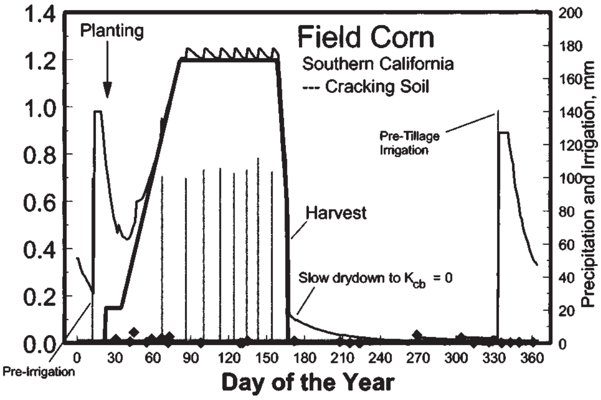

Fig. 7. Simulated K_{cb} (heavy line) and $K_{cb}+K_e$ (light line) curves for crop of field corn planted in late January in southern California on cracking soil having REW=8 mm, TEW_2=50 mm, TEW_3=100 mm, K_{r2}=0.2, and f_w=0.7 for growing period irrigations and f_w=1.0 for preirrigations. Bars denote predicted timing and depths of irrigation and diamonds denote rainfall

K_r is calculated for the third stage as

$$K_r = K_{r2}\frac{\mathrm{TEW}_3 - D_{e,j-1}}{\mathrm{TEW}_3 - \mathrm{TEW}_2}$$

$$\text{for } \mathrm{TEW}_2 \leqslant D_{e,j-1} \qquad (31)$$

where TEW_3=maximum cumulative depth of evaporation (depletion) from the soil surface layer when the soil is dry and no further evaporation occurs (K_r=0) (mm). The value TEW_3 includes REW and TEW_2. For application of the three-stage drying extension with the first extension, Eqs. (22) and (23) are expanded using Eqs. (30) and (31), with each application (I+P) and (P) having its own water balance.

The three stage drying extension has been applied to cracking heavy clay soils in the Imperial Irrigation District of California (Allen et al. 2005) and to two cracking or partially cracking soils in Texas (Mutziger et al. 2001). Values used for the Imperial soils were REW=8 mm, TEW_2=50 mm, TEW_3=100 mm, and K_{r2}

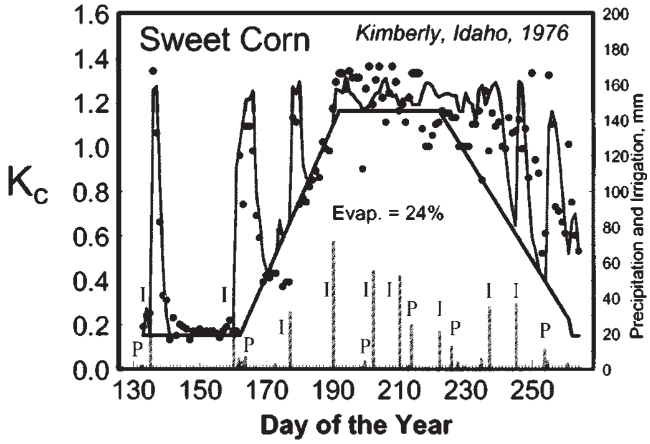

Fig. 8. Daily crop coefficients based on measured evapotranspiration and simulated using *FAO-56* dual K_c approach at Kimberly, Id. for a crop of sweet corn (lysimeter data from Wright 1982, personal communication 1990).

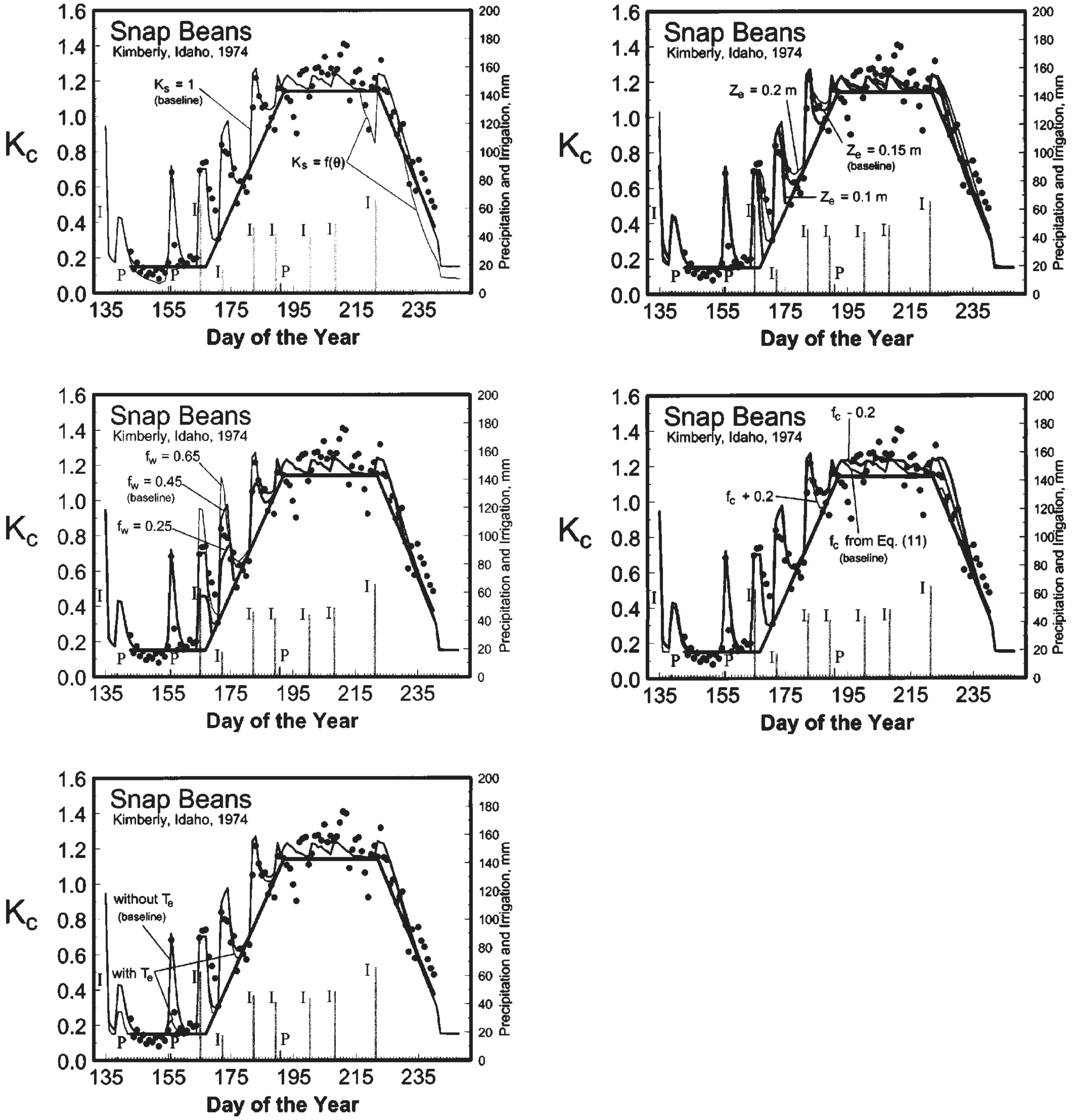

Fig. 9. Sensitivity of daily $K_{c\ \mathrm{act}}$ estimation for snap bean crop near Kimberly, Id. (lysimeter data from J. L. Wright, unpublished) to: (a) application of water stress function [Eq. (32)] (thin line) with comparison to K_c predicted using $K_s=1$ (medium line), K_{cb} (thick line), and measured K_c (symbols); (b) value for f_w; (c) application of T_e in Eq. (12); (d) value for Z_e; and (e) value for f_c

=0.2. Best fit values (to lysimeter evaporation measurements) for the Houston black clay and Pullman clay loam soils evaluated by Mutziger were REW=7 mm; TEW_2=30 and 22 mm; and TEW_3 =50 and 45 mm.

TEW_2 and TEW_3 for the Imperial Valley soils were estimated from sampled soil water contents at the beginning and end of drying cycles in fallow fields as shown in Fig. 6. The sampling sites were in an area of mixed Imperial silty clay and Imperial-Glenbar silty clay loam soil. Cracks penetrated to about 1 m on drying on an approximately 0.5 to 2 m grid and average crack width was 10 mm. Moisture was gravimetrically determined from cored samples. In the case of sampling the dry profile where the soil was deeply cracked, samples were taken approximately 0.3 m in from the face of cracks. The areas between the upper horizontal and the lower horizontal or diagonal lines in the figure suggest the equivalent depth of water evaporated during Stages 1 and 2 and during Stage 3 from the cracking soil. The sampling indicated drying to a depth of more than 0.5 m due to cracking. Even though the apparent depletable depth from 0.12 to 0.6 m shown in Fig. 6 was about 75 mm, a value of 50 mm for Stage 3 drying

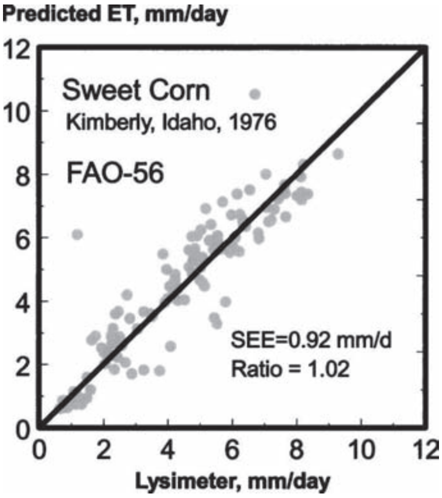

Fig. 10. Daily measured and estimated evapotranspiration for sweet corn near Kimberly, Id. using *FAO-56* dual K_c procedure (data from Wright 1982, personal communication 1990).

(so that $TEW_3=50+50=100$ mm) was selected for routine application in the Imperial Valley to account for dampening effects of disking and other tillage on creating a surface soil mulch and any effects of water extraction by roots (Allen et al. 2005).

The net impact of Stage 3 drying is to prolong the time for K_r to decrease to zero, thereby creating a prolonged "base-line" evaporation rate. As shown in Fig. 7, where the *FAO-56* $K_{cb}+K_e$ method was applied with Stage 3 drying, base-line evaporation was prolonged following harvest for more than 60 days, even when time between wetting events was large. Without the Stage 3 drying, $K_{c\ \mathrm{act}}$ reduced to zero within 5–10 days following harvest. The K_{cb} prior to planting and following harvest was set to zero to allow evaporation (and total ET) to approach zero during extended dry periods.

Impacts of Water Stress

The final component in Eq. (4) is the water stress coefficient K_s used to reduce K_{cb} under conditions of water stress or salinity stress. Allen et al. (1998) describes the salinity stress function and computation. The water stress function is described here and is illustrated later. Mean water content of the root zone in the *FAO-56* procedure is expressed by root zone depletion, D_r, i.e., water shortage relative to field capacity. At field capacity, $D_r=0$. Stress is presumed to initiate when D_r exceeds RAW, the depth of readily available water in the root zone. For $D_r>\mathrm{RAW}$, K_s is

$$K_s=\frac{\mathrm{TAW}-D_r}{\mathrm{TAW}-\mathrm{RAW}}=\frac{\mathrm{TAW}-D_r}{(1-p)\mathrm{TAW}} \qquad (32)$$

where TAW=total available soil water in the root zone (mm), and p=fraction of TAW that a crop can extract from the root zone without suffering water stress. When $D_r\leq\mathrm{RAW}$, $K_s=1$. The total available water in the root zone is estimated as the difference between the water content at field capacity and wilting point

$$\mathrm{TAW}=1000(\theta_{\mathrm{FC}}-\theta_{\mathrm{WP}})Z_r \qquad (33)$$

where Z_r=effective rooting depth (m) and Z_r contains Z_e. RAW is estimated as

$$\mathrm{RAW}=p\mathrm{TAW} \qquad (34)$$

where RAW has units of TAW (mm). *FAO-56* contains recommended values for p for 60 crops and describes several means to model the development (increase) in Z_r with time for annual crops including in proportion to development of K_{cb} and in proportion to time. Other methods for Z_r development include a sine function of time (Borg and Grimes 1986), an exponential function of time dampened by soil temperature and soil moisture (Danuso et al. 1995), and a full root growth simulation model by Jones et al. (1991).

Example Applications and Sensitivity Analyses

Illustrative applications of the *FAO-56* procedure are given in Fig. 8 for a sweet corn crop and in Fig. 9 for a snap bean crop grown near Kimberly, Id. during 1976 and 1974 by Wright (1982). Daily ET was measured using a precision weighing lysimeter planted to and immediately surrounded by a specific crop. Fetch of the lysimeter was at least 50 m in all directions for the specific crop and resolution of the lysimeter system was about 0.05 mm (Wright 1982). The daily measured K_c values in the figures were calculated by dividing daily lysimeter measurements by ET_0 as computed by Eq. (1). Weather data were assembled from a grassed weather station located about 1 km north of the lysimeter site. Dates for planting and harvest and for precipitation and irrigation were based on field notes (Wright, personal communication 1990; Vanderkimpen 1991). Values for K_{cb} were taken from *FAO-56*. Dates for beginning of development, midseason and late season periods for the *FAO-56* procedure were selected to fit the lysimeter data.

The application used the original *FAO-56* procedure with extension for T_e. The Portneuf silt loam soil at Kimberly was modeled using two-stage drying with Z_e set to 0.15 m and REW =8 mm and TEW=34 mm. The value for f_w was 0.6 for the furrow-irrigated sweet corn and 0.45 for alternate furrow-irrigated beans.

For the application to beans, ranges in values for parameters K_s, f_w, T_e, Z_e, and f_c were applied to illustrate the sensitivity of the *FAO-56* model predictions to these parameters. In the case of K_s and T_e, the sensitivity was with and without the inclusion of functions for these parameters.

Results

Simulated daily K_{cb} and $K_{c\ \mathrm{act}}$ and measured $K_{c\ \mathrm{act}}$ for the growing period for the sweet corn crop shown in Fig. 8 indicate relatively

Table 3. Standard Error of Estimate (SEE) and Ratio of Estimated to Measured Daily Evapotranspiration for Full Season of Snap Beans in 1974 near Kimberly, Id. (n=98 days), where Baseline Conditions were f_w=0.45, T_e=0, K_s=1, Z_e=0.15 m, and f_c from Eq. (11)

	Baseline	f_w=0.25	f_w=0.65	with T_e	with K_s	Z_e=0.10 m	Z_e=0.20 m	f_c−0.2	f_c+0.2
SEE (mm day^{-1})	0.63	0.74	0.68	0.67	0.78	0.76	0.61	0.66	0.68
Ratio to measured	1.00	0.96	1.03	0.98	0.96	0.96	1.04	1.03	0.95

good agreement between simulated and measured values. The peak spikes in $K_{c\ \mathrm{act}}$ following wetting agreed well with measurements as did the rate of decay of the K_e curve. There was some underestimation of $K_{c\ \mathrm{act}}$ during the midseason period which may have been caused by underestimation of ET_0 by Eq. (1) or underestimation of the midseason K_{cb} for corn by *FAO-56*. The $K_{c\ \mathrm{act}}$ predicted during the late season overestimated measured $K_{c\ \mathrm{act}}$ for some days and underestimated over two 5 day periods. Much of the under- and overestimation during the senescence period was probably caused by uncertainty in the estimation of f_c during that period and the impact of ground shading on the wetted portion of the soil surface.

The unadjusted standard error of estimate (SEE) between the estimated and lysimeter-measured daily ET (Fig. 10) was $0.92\ \mathrm{mm\ day^{-1}}$ and the seasonal ratio of predicted ET to measured ET was 1.02. Total seasonal evaporation for the sweet corn crop was estimated to be 24% of the total seasonal ET. Because the lysimeter measurements provide only integrated values of ET, the separate estimation of evaporation cannot be evaluated for accuracy. Estimates of soil evaporation do not include the evaporation from soil that occurs as a diffusive component of K_{cb} over time.

Sensitivity of the $K_{\mathrm{cb}}+K_e$ procedure of *FAO-56* to invocation of a K_s soil moisture stress function under conditions where mild stress may have occurred is shown in Fig. 9(a) for the 1974 snap bean crop. Without the K_s function (thus $K_s=1.0$), the $K_{c\ \mathrm{act}}$ curve (medium gage line) "bottomed" against the K_{cb} curve (heavy line). With the K_s function [Eq. (32)], drying below the p level of the root zone was predicted during the development period, late midseason, and latter part of the late season. These predictions were based on actual irrigation dates and values for soil water holding properties from Table 1 ($\mathrm{AW}=160\ \mathrm{mm\ m^{-1}}$), and $p=70\%$ during the initial period and $p=55\%$ for the other three periods, and maximum rooting depth of 1.6 m, based on measurements by Wright (unpublished data, 2000). The application of the K_s function improved estimation of $K_{c,\mathrm{act}}$ for some dates and caused underestimation for others. No visual or measured stress by the lysimeter crop in 1974 was noted by Wright (1982).

Figure 9(b) illustrates the impact that f_w, the fraction of soil surface wetted by irrigation, has on the $K_{c\ \mathrm{act}}$ estimate. Higher values for f_w extended the magnitudes and time lengths of drydown for K_e "spikes" during the development period when the value $1-f_c$ in Eq. (10) was large. During midseason period, $1-f_c$ in Eq. (10) limited the value for f_{ew} regardless of range in f_w. Thus, sensitivity to f_w is generally prominent only during the initial and development periods.

The inclusion of the T_e function for extraction for transpiration from the Z_e layer impacted the estimation for K_c during the initial and development periods and had no impact during the mid and late season periods when the evaporation layer was largely shaded. The T_e function reduced the prediction of K_e for the precipitation event on Day 156 [Fig. 9(b)] because T_e extraction during prior days increased D_e so that the 6 mm precipitation depth was absorbed into the Stage 2 depletion reservoir, rather than adding to Stage 1 drying. This illustrates a weakness of the *FAO-56* model in that any light precipitation event is subtracted from the total D_e for the Z_e depth, rather than left on the soil skin for immediate evaporation. D_e was increased during the initial period with the application of the T_e function because all of the K_{cb} value [0.15 in Fig. 9(b)] is assigned to basal transpiration in the dual procedure, even though the 0.15 value may contain significant amounts of diffusive evaporation. There is danger in assigning too large a value for K_{cb} in the dual method, including the method of Wright (1982), since no limit is placed on K_{cb} extraction from a shallow, initial root depth unless the K_s function is invoked. The fact that inclusion of the T_e function did not improve predictions for the snap beans may reflect the tillage practices for beans, where open spaces between rows are cultivated two to three times during the growing season, thus reducing root activity there and thus extraction by transpiration. The $1-f_c$ parameter in Eq. (10) represents these open spaces.

The impact of the value assigned to Z_e, the effective depth of the evaporating layer, is illustrated in Fig. 9(d). With all other parameters fixed, the impact of greater Z_e is to extend the lengths of drydown periods and to increase the estimated evaporation component of ET. The impact of Z_e was pronounced during all periods.

Sensitivity to the estimation of fraction of surface covered by vegetation is illustrated in Fig. 9(e), where 0.2 was added and subtracted from the value for f_c predicted by Eq. (11). The impact of value for f_c was negligible for the initial and most of the development period when $1-f_c$ exceeded the value assigned to f_w. In this case, f_w controlled the estimate of evaporation. As f_c increased, its value began to control f_{ew} from Eq. (10) and impact on K_e and K_c increased. The smaller value for f_c (i.e., $f_c-0.2$) during late development and mid season tended to improve estimates during those periods.

Table 3 lists summary statistics for the five sensitivity tests. The smallest SEE ($0.61\ \mathrm{mm\ day^{-1}}$) occurred when Z_e was increased from 0.15 to 0.20 m, however, the reduction in SEE over the baseline was very small. The impact by the individual ranges in the parameters on the ratio of estimated seasonal ET to measured ET ranged from −5 to +4%.

Summary and Conclusions

The *FAO-56* dual K_c procedure was established to provide daily estimates of evaporation from wet soil in conjunction with crop transpiration. The procedure uses a daily water balance of the soil surface layer and accounts for the fraction of soil surface wetted by irrigation or by precipitation and exposed to radiation and ventilation. Three optional extensions to the original method are described. The first is the establishment of a separate water balance for the fraction of the surface wetted by precipitation, only, and for the fraction wetted by both irrigation and precipitation. The second extension is a procedure to approximate the drying of the surface layer by transpiration in addition to evaporation. The third extension provides for the application to deep cracking soils. The dual K_c procedure is useful when short term estimates of evapotranspiration are needed, for example in research and in irrigation scheduling for individual fields as well as in estimation of total consumption of water where impacts of wetting frequency are important.

The sensitivity analysis indicates that inclusion of a function to estimate transpiration from the evaporating layer may not substantially impact or improve estimates, especially for crops having periodic cultivation. Calculations are moderately sensitive to values specified for the depth of the evaporation layer and fraction of surface wetted by irrigation, and to the estimation of fraction of ground cover.

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ANNEX 2.

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Evaporation from American Falls Reservoir in Idaho via a Combination of Bowen Ratio and Eddy Covariance

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Abstract

Evaporation and energy balance components were measured and estimated for the American Falls reservoir of SE Idaho during 2004. The energy balance for this reservoir that stores snow-melt is dominated by water heat storage that consumes more than one-half of net radiation during the growing season. Evaporation fluxes from the reservoir average less than 40% of alfalfa reference ET, which indicates relatively efficient water storage. Some general relationships between albedo as sensed by satellite and water turbidity and among air and water temperature are presented that may be useful in satellite-based simulation of the energy balance and evaporation processes from the reservoir.

Introduction

Evaporation from deep, relatively clear lakes in temperate climates can be substantially lower than pan evaporation and reference evapotranspiration due to the large amount of heat storage during spring and summer. This occurs due to the penetration of solar radiation beneath the water surface. Because evaporation is a surface phenomenon, any solar radiation stored as heat is not readily available for immediate consumption by evaporation. Heat storage is only available to the surface energy balance when transferred there by conduction or convection. Significant amounts of stored heat are transferred to the surface during fall and winter when water temperature may be relatively warmer than air temperature so that a significant amount of stored energy may be partitioned into sensible heat to air or long-wave emission rather than to evaporation. In reservoir systems, significant amounts of stored heat can be advected via stream discharge.

Our ability to model evaporation from temperate lakes requires either measurement of skin temperature of the water surface coincident with air

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temperature and vapor pressure and wind measurements (to apply an aerodynamic approach) or to apply some method to predict change in heat storage of the lake (via water temperature profile or some empirical method) and then apply an energy balance on a daily or monthly timestep. The heat storage term for deep, open water is difficult to parameterize due to the influence of turbidity, depth, circulation and water advection. During 2004, a Bowen ratio system was operated along the shore of the American Falls (AMF) Reservoir in southern Idaho to measure the ratio of sensible heat flux to evaporative flux. The system was collocated with a 3-D sonic anemometer system for measurement of sensible heat flux. An estimate for evaporative flux can be made via the combined systems. When combined with net radiation, the heat storage to the lake can be estimated as a residual of the energy balance. This paper reports preliminary findings from 2004.

Study Area and Methods

Evaporation from the AMF reservoir was estimated from May through November 2004 using Eddy Covariance (EC) and Bowen ratio systems installed along the southern shoreline.

American Falls Reservoir

American Falls (AMF) Reservoir is the largest reservoir in the state of Idaho and is located near 42.8°N and 112.7°W. The reservoir is formed by American Falls Dam on the Snake River. The reservoir is supplied by mostly snow melt from the Yellowstone and Teton Mountain areas and ground-water inflows and provides storage for irrigation, flood control, power generation, recreation and supports a variety of fish and wildlife resources. At the full level of the reservoir, the reservoir has mean depth of 9 m (30 ft) including shallow backwater areas, a surface area of 227 million m^2 (56,000 acres) and storage volume of 2060 million m^3 (1,671,300 acre-ft). During the 2004 study, the average water depth along the fetch transect for the micrometeorological instrumentation is estimated to have ranged from about 12 m at the beginning of the study to about 3 m in October. The reservoir water storage level is managed by the U.S. Bureau of Reclamation. In general years, the reservoir reaches a nearly full level in early spring following mountain snow melt before local irrigation demands begin, and is nearly empty in fall during dry years following the completion of the irrigation season. Figure 1 shows the storage and the inflow/outflow of the AMF reservoir during 2004.

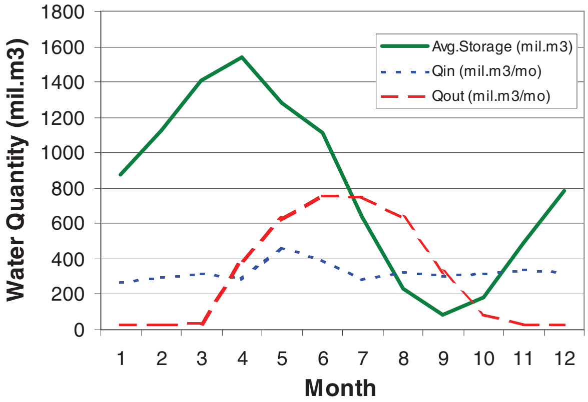

Figure 1. Reservoir storage and monthly inflow/outflow of AMF reservoir during 2004 (BOR 2005a).

Instrumentation and Measurements

During the study period, an eddy covariance (EC) system (Campbell Sci. CSAT3) and a Bowen Ratio system (Radiation and Energy Balance Systems, Inc. EBSTD1) were installed near the shoreline at the general location shown in Figure 2. Coordinates of the measurement site were 42°51'N, 112°48'W. Photographs of the instruments are shown in Figure 3. The instruments were installed near the waterfront and were periodically relocated as the waterfront of the reservoir receded (or acceded) so that the instruments were near enough to the waterfront to sample the near surface boundary layer developed over the water body. On average, instruments were relocated every three weeks. Predominant wind direction was from the west and southwest directions and fetch length over water upwind of the instruments averaged 5 to 10 km. Table 1 summarizes parameters measured. The EC measurements were conducted at 10Hz frequency with 15 minutes blocking interval. Temperature and vapor pressure were measured by the Bowen ratio energy balance (BREB) system with 1 m vertical separation at 2 to 4 m (lower arm) and 3 to 5 m (upper arm) above the water surface, depending on the distance from the shoreline.

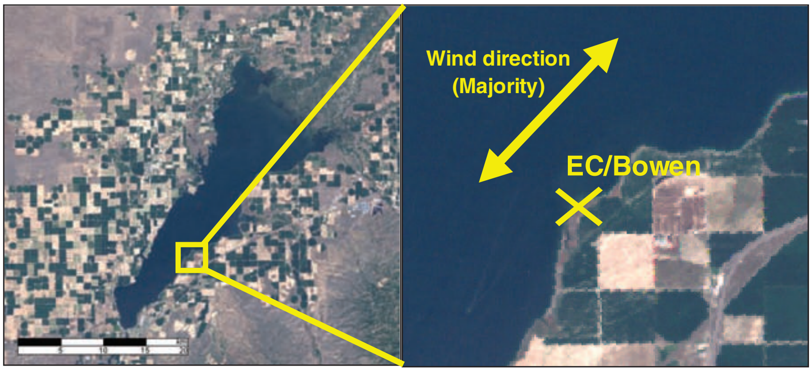

Figure 2. American Falls Reservoir and the location of measurements.

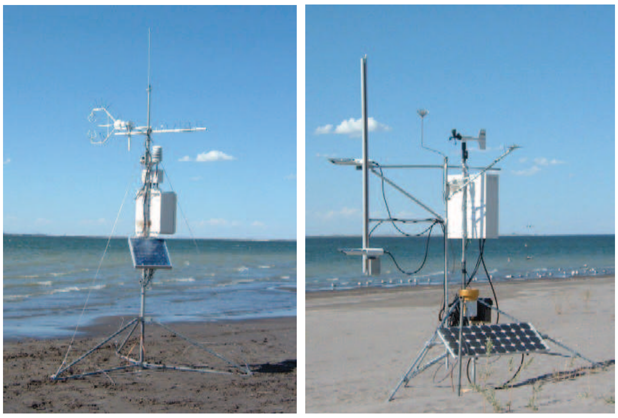

Figure 3. (left) Campbell Sci. CSAT3 3D sonic system, and (right) REBS Bowen ratio system.

Table 1. Summary of measurement items

Items	Instrument	Remarks
WindSpeed and direction	Campbell Sci. CSAT3	
Sonic temperature	Campbell Sci. CSAT3	
Fine Wire temperature	Campbell Sci. CSAT3	Only for limited periods in spring
Sensible heat (H) by sonic	Campbell Sci. CSAT3	
Sensible heat (H) by finewire	Campbell Sci. CSAT3	Only for limited periods in spring
Air temperature	Campbell Sci. HMP45C	
Vapor pressure	Campbell Sci. HMP45C	
Solar Radiation	LI-COR LI-200SZ	
Incoming Longwave Radiation	REBS THR	Only for limited periods in late summer
Water surface temperature	Apogee IRTS-P	
Atmospheric temperature	Apogee IRTS-P	
Air temperature (2 heights)	REBS EBSTD1	
Vapor pressure (2 heights)	REBS EBSTD1	
Bowen Ratio (by Tair & ea)	REBS EBSTD1	
Horizontal WS and WD	RMYoung 05103-5	
Precipitation	Rain gauge	

Data Quality Control and Calculations

In this study, lake evaporation was estimated using sensible heat flux (H) measured by the EC system and the Bowen ratio measured by BREB as:

$$\mathrm{LE} = \frac{\mathrm{H}}{\beta} \tag{1}$$

where LE is latent heat flux, H is sensible heat flux from EC, and β is the Bowen ratio measured by the BREB system. The Bowen ratio is defined as:

$$\beta = \frac{\mathrm{H}}{\mathrm{LE}} = \frac{c_p P (T_2 - T_1)}{\lambda \varepsilon (e_2 - e_1)} = \gamma \frac{T_2 - T_1}{e_2 - e_1} = \gamma \frac{\Delta T}{\Delta e} \tag{2}$$

where c_p is specific heat of moist air at constant pressure, P is atmospheric pressure, λ is latent heat of vaporization, ε is the ratio of molecular weights of water to air, T is air temperature at one of two heights above the surface and e is vapor pressure at one of two heights above the surface. The symbol Δ indicates a finite difference in T and e. The REBS BREB system utilized Vaisalla HMP electronic sensors to measure relative humidity at the 1.5 and 2.5 m heights and platinum resistors for air temperature. The two pairs of sensors were housed in triple-wall radiation shields with forced ventilation and were interchanged each 15 minutes to reduce sensor bias. Near surface pressure was measured by electronic barometer.

The following corrections were applied to the EC derived sensible heat: coordinate rotation of the 3D sonic wind speed vectors as described by Tanner and Thurtell (1969), sonic temperature correction to actual temperature as described by Munger and Loescher (2004), and air moisture correction as described by Sun et al. (1995). In equation 1, estimates of LE become unstable due to high relative measurement error when $|\beta| \sim 0$. Thus, data were disgarded when $|\beta|$ was less than 0.05. Data that were missing or that occurred during low quality periods, such as caused by malfunction of BREB ventilating fans (in summer by sand and flies) or by low system battery (in late fall during long periods of clouds and/or snow), were identified and rejected. All data that did not have sufficient proximity to the water surface or sufficient upwind fetch of water surface were rejected. The acceptable fetch condition was identified using wind direction as the indicator, and included wind direction within ±70 deg of the perpendicular line to the nearest shoreline. The accuracy of the sensible heat measurement by EC, after corrections noted above, is expected to be < +/- 40 W m^{-2} (Twine et al., 2000, Wilson et al., 2002) and accuracy of the LE from Eq. (1) is expected to be < +/- 80 W m^{-2} or about double that for H.

<u>Water Surface Energy Balance</u>

The general equation for the <u>land</u> surface energy balance is:

$$R_n = H + LE + G \tag{3}$$

where R_n is net radiation and G is soil heat flux. In the case of energy balance over a water surface, the counterpart to G is Q_t, or “water heat flux”, which is the energy transferred to the water body, where the transfer is not only by conduction and convection but also by penetration of shortwave radiation below the surface. Because of the significant dissimilarity between G for land and heat storage for water, Eq. (3) is rewritten for water as:

$$R_n = H + LE + Q_t - Q_v + Q_w \tag{4}$$

where Q_t is the change in water heat storage (equivalent to G for land), Q_v is net energy advected into the water body by streamflow or groundwater (less that discharged), and Q_w is the energy advected by the evaporated water (prior to evaporation) and relative to mean reservoir surface temperature. Q_w is generally less than 1% of LE and can be ignored. Q_v can be substantial for reservoirs having large releases. The principal difference between G and Q_t is the impact of transparency of the water surface where there can be large penetration by solar energy, depending on turbidity and water depth.

Figure 4 shows penetration depth as a function of wavelength of solar radiation for three levels of absorption (i.e., extinction) based on coefficients from List (1966). Figure 5 shows percent absorption of total solar radiation incident to the water surface. These figures illustrate that even pure water is nearly opaque to near infrared wavelengths longer than about 0.8 micrometers, but is relatively transparent to light wavelengths between 0.45 and 0.6 micrometers, which represent the blue and green colors of the solar spectrum and a large fraction of total incoming solar radiation. About 40% of total solar radiation penetrates below 2 m in pure water and 20% penetrates below 20 m in pure water when the solar zenith angle is at 30 degrees (typical of near noon conditions in much of the USA) at 1100 m elevation representing southern Idaho. Penetration depths decrease with increasing turbidity.

R_n and Q_t were not measured in this study due to the distance from the micrometeorological equipment to far enough into the reservoir to be away from shallow water having higher than average surface temperature. Instead, R_n was calculated using measured solar radiation and temperature of the water surface and effective temperature of the atmosphere using infrared temperature sensors (IRTs). During the R_n calculation, water surface albedo was assumed to be 0.05, and the water surface emissivity was assumed to be 0.99. Q_t was calculated as the residual of the energy balance using Eq. (2). The sum of measured solar radiation (R_s) and estimated incoming long wave radiation (R_{Li}) was compared with total incoming hemispherical radiation measured by a REBS THR radiometer. The THR measurements, which represent global (hemispherical) incoming radiation typically ranged from 10 to 100 W m^{-2} above $R_{Li} + R_s$ calculated using the IRT, which measured temperature mostly overhead. However, trends were very similar. The R_{Li} measurements and calculations are still under investigation.

As an independent assessment of accuracy of H from the EC system and LE via Eq. (1), H and LE were also calculated from measured data using two essentially independent fully aerodynamic approaches. To summarize all three approaches for H and LE:

Approach 1 (EC and BREB) (preferred). H was estimated directly by the eddy covariance system using the 3D sonic anemometer, with sonically measured air temperature corrected for humidity effects. LE was derived using Eq. (1) using H from the EC system and β from the BREB system.

Approach 2 (Kondo). H and LE were calculated aerodynamically using the bulk aerodynamic equations as presented by Kondo (1975, 1994 and 1997) and summarized by Tasumi (2005). The method estimates H and LE using observed windspeed, air temperature and humidity at one height above surface along with water surface temperature. Sensible and latent heat fluxes were expressed as:

$$\begin{aligned} H &= C_p\, \rho_{air}\, C_H\, u(T_s - T_a) \\ LE &= \lambda\, \rho_{air}\, C_E\, u\left(q_{satTs} - q_a\right) \end{aligned} \qquad (4)$$

where ρ_{air} is density of moist air, u is wind speed, T_s is surface temperature, T_a is air temperature, q_{satTs} is the saturated specific humidity at surface temperature, q_a is the specific humidity at observation height z, and C_H and C_E are bulk transfer coefficients for sensible heat and water vapor respectively. C_H is essentially equivalent to the aerodynamic expression:

$$C_H = \frac{k^2}{\ln(z/z_{om})\ln(z/z_{oh})} = \frac{1}{u \cdot r_{ah}} \qquad (5)$$

where z_{om} and z_{oh} are roughness lengths for momentum and sensible heat transfer, k is the von Karman constant (0.41) and r_{ah} is aerodynamic resistance for heat transfer between the surface and z. C_H was recommended by Kondo for neutral conditions as 0.0012 and literature reviews indicate that C_H=C_E=0.0012 for most applications to water. In approach 2, T_s and q_{satTs} were derived from IRT measurements of the water surface and T_a and q_a were primarily from the upper arm of the BREB system. Wind speed was measured at about 3 m.

Approach 3 (Aerodynamic from BREB gradients). Approach 3 estimated LE and H using q and T_{air} measured at two heights (z_1 and z_2) by the BREB. This method is expected to have less instrumentation bias than approach 2, since the exchange arms of the BREB system eliminated sensor bias. In this approach, the exchange coefficients are applied between the two measurement heights (1.47 and 2.47 m) and u_* was estimated using a constant z_{om} = 0.0005 m, so as to be independent of the sonic anemometer:

$$C_{H(z1-z2)} = C_{E(z1-z2)} = \frac{k^2}{\ln\left(\frac{3}{0.0005}\right)\ln\left(\frac{2.47}{1.47}\right)} = 0.0372 \qquad (6)$$

where u was wind speed measured by a RM Young anemometer at 3 m height. H and LE were then calculated as:

$$\begin{aligned} H &= \rho_{air} \cdot c_p \frac{T_1 - T_2}{r_{ah(z1-z2)}} = \rho \cdot c_p \cdot u \cdot C_{H(z1-z2)} \cdot (T_1 - T_2) \\ LE &= \lambda\, \rho_{air}\, C_{E(z1-z2)}\, u\left(q_1 - q_2\right) \end{aligned} \qquad (7)$$

In approach 3, C_H and C_E were about 30 times larger than for approach 2, since the the ΔT and Δq gradients were significantly smaller.

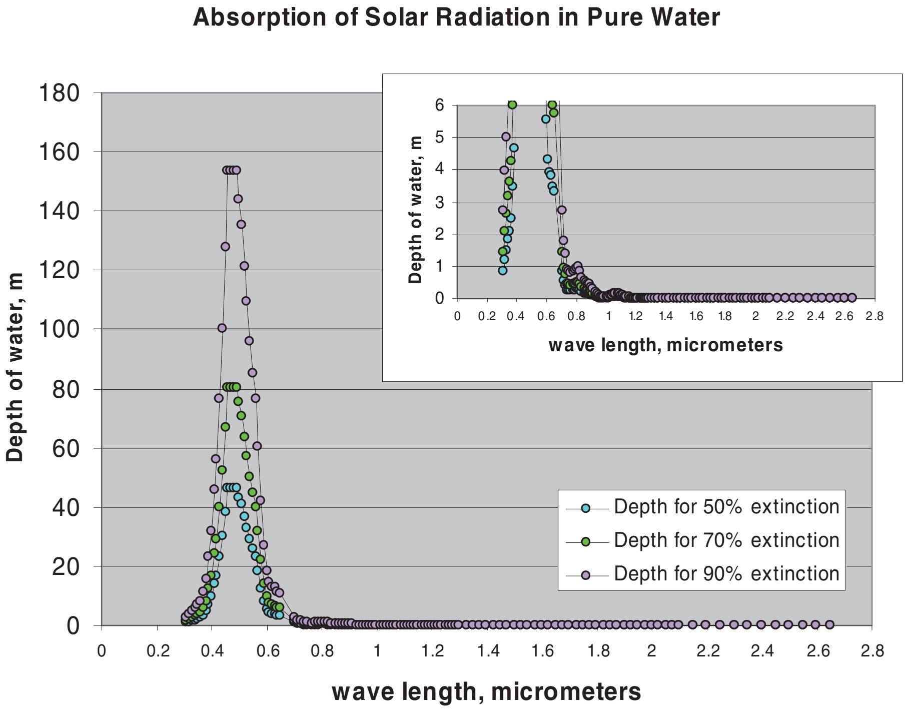

Figure 4. Penetration depths as a function of solar wave length for pure water.

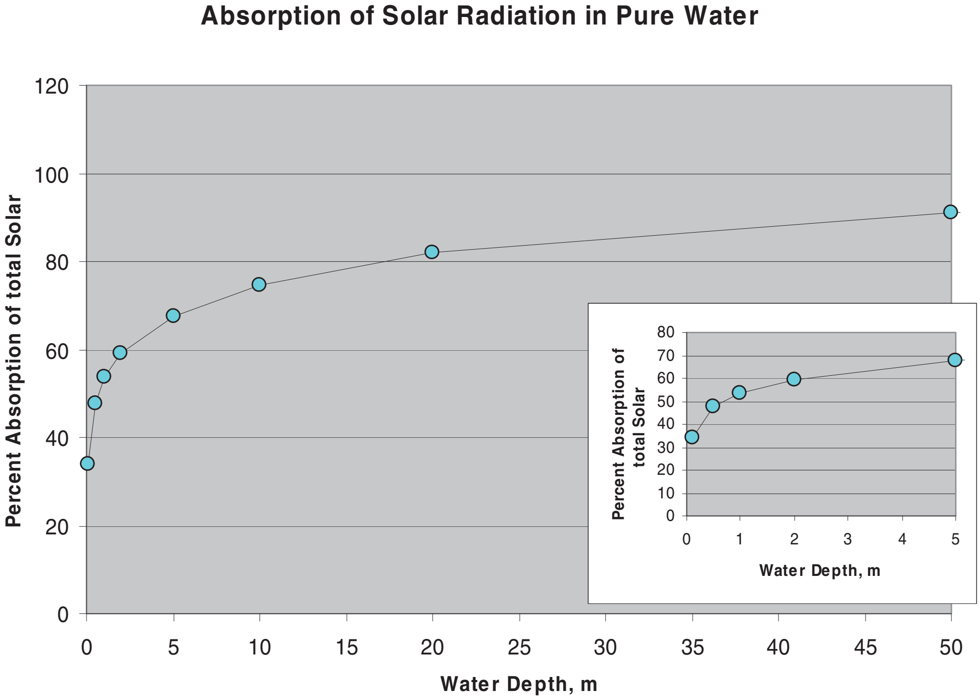

Figure 5. Percent absorption of solar radiation as a function of water depth for pure water.

Results

The energy budget analysis was conducted using 15 minute data and summarized on a monthly basis. The results of the reservoir surface energy balance are summarized in Table 2 for "midday" periods (10 am to 2 pm) and in Table 3 for 24-hour averages using H and LE from approach 1. Midday Q_t and other energy balance components are of interest for use in energy balance calculated using satellite imagery where satellite overpass times are typically between 10:30 am and 1:30 pm. Figure 6 illustrates average hourly energy balance during months of May through November for the three estimation approaches.

Table 2. Observed monthly reservoir energy balance for midday (10:00~14:00) based on the EC / BREB combination

Month	R_n (W/m2)	H (W/m2)	LE (W/m2)	Q_t (W/m2)[1]	β	Q_t/R_n	ET_rF
5	646	28	64	555	0.44	0.86	0.18
6	697	20	85	592	0.23	0.85	0.19
7	693	31	152	510	0.21	0.74	0.34
8	674	54	124	497	0.43	0.74	0.27
9	498	29	113	357	0.26	0.72	0.37
10	410	28	62	320	0.46	0.78	0.30
11	279	23	27	229	0.82	0.82	0.24

[1] Q_t (water heat storage) was calculated as a residual of the energy balance.

Table 3. Observed monthly reservoir energy balance, 24-hour average based on the EC / BREB combination

Month	R_n (W/m2)	H (W/m2)	LE (W/m2)	Q_t (W/m2)[1]	β	Q_t/R_n	ET_rF
5	204	25	71	108	0.35	0.53	0.45
6	197	8	53	136	0.15	0.69	0.26
7	202	23	121	59	0.19	0.29	0.59[a]
8	187	24	74	89	0.32	0.48	0.35
9	120	11	40	69	0.27	0.57	0.30
10	77	18	43	16	0.42	0.21	0.60
11	39	18	26	-5	0.69	-0.14	0.76

[1] Q_t (water heat storage) was calculated as a residual of the energy balance.

[a] The LE calculated by the EC / BREB combination for July exceeded that by the two aerodynamic methods and is considered to be impacted by unknown error or bias. ET_rF for July (24-hour) probably averaged nearer to 0.35.

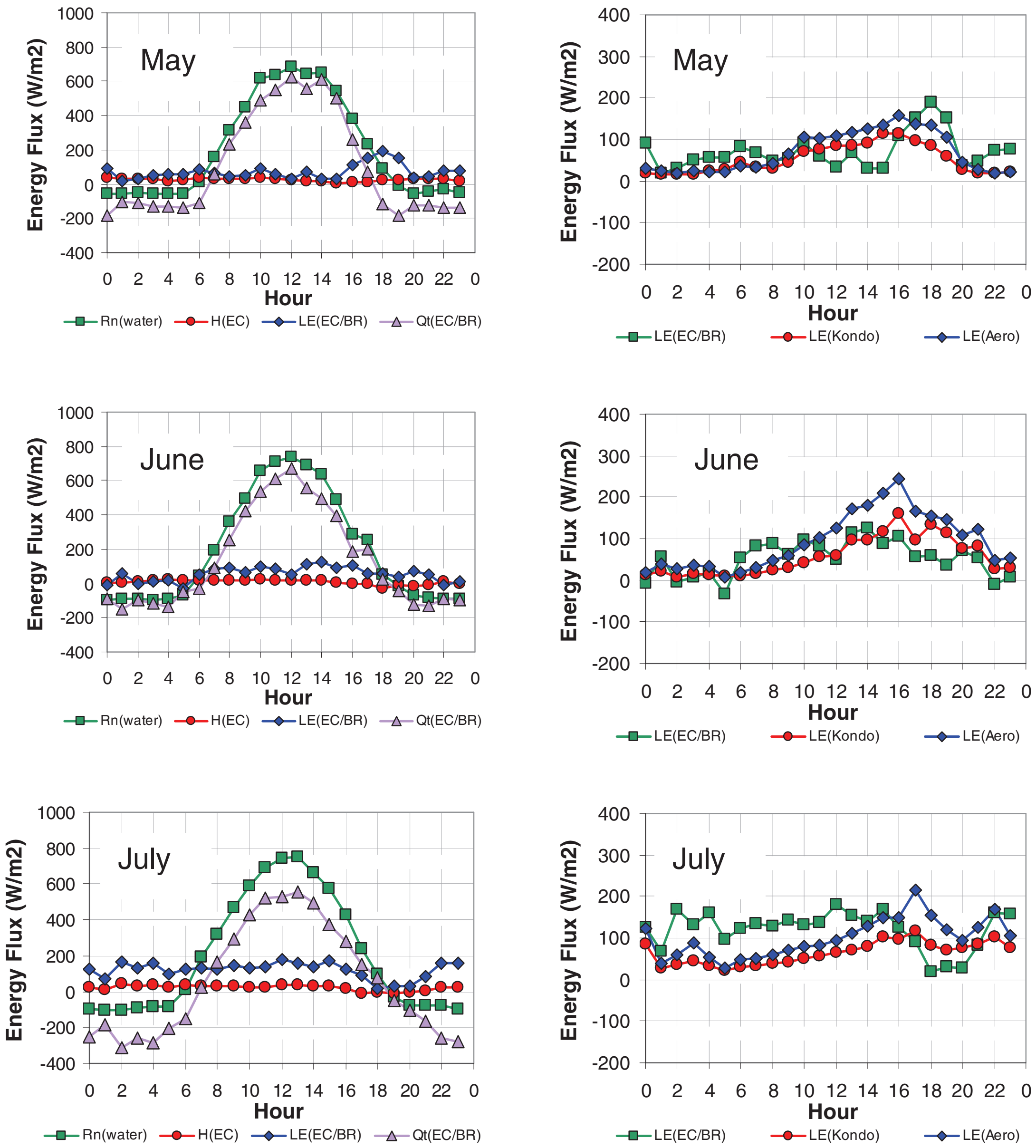

Figure 6. Monthly average energy balance (left) at AMF reservoir in 2004 where H is measured by eddy covariance and LE by H/β and water heat storage, and Q_t is calculated as a residual based on the EC / BREB combination (Approach 1), and LE from all three independent methods (right).

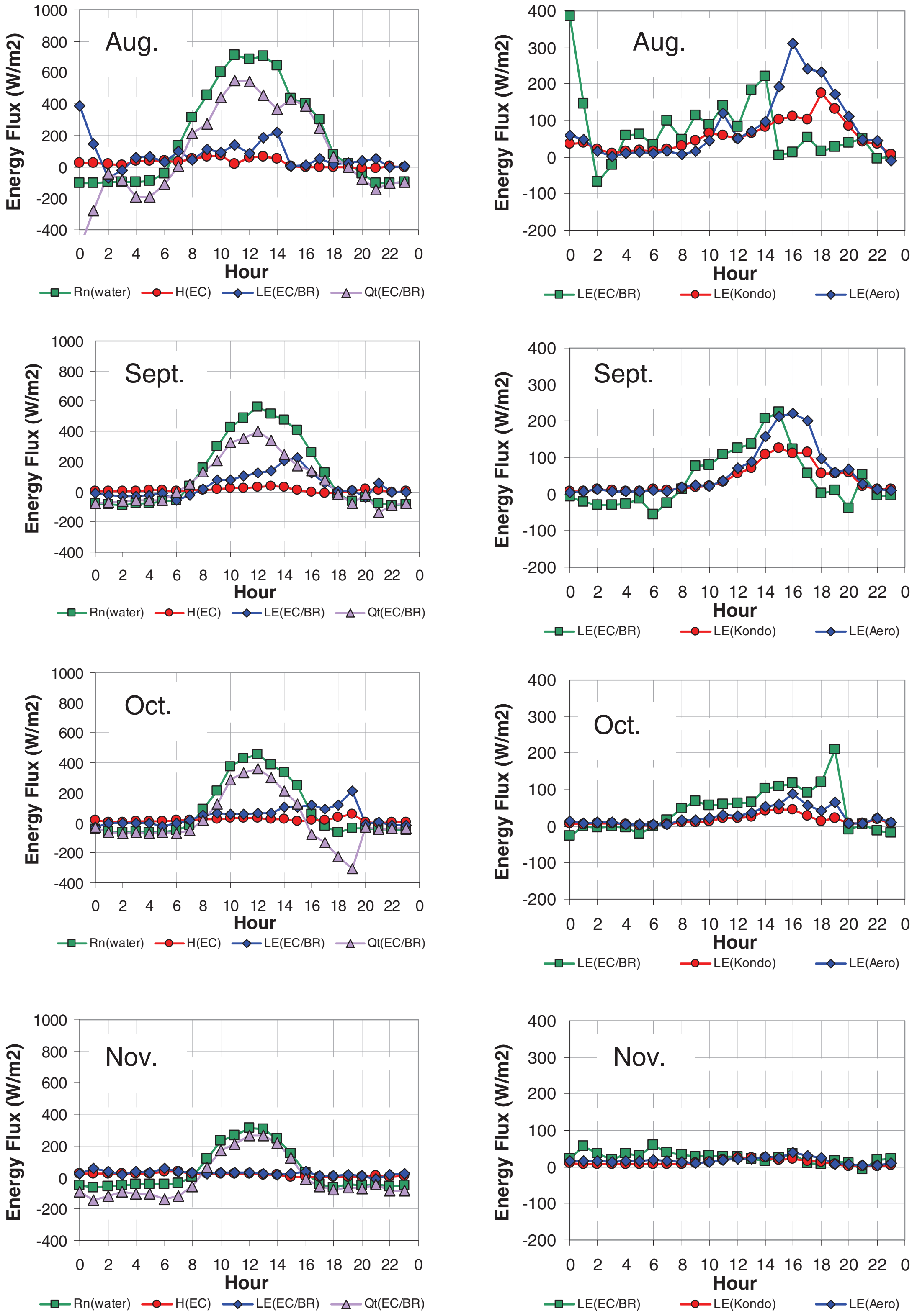

Figure 6, continued.

Results from aerodynamic Approaches 2 and 3 agreed well with results from the EC/BREB approach (1) as shown in the right hand column of figures in Figure 6. All three largely independent estimates of LE were of the same order of magnitude, with relatively low values and similar trends during the day for most months. LE was often estimated about 100 W m^{-2} higher with the aerodynamic approaches during late afternoon and early evening than with the EC/BREB approach. However, all cases, which are largely independent, indicate the large Q_t for the AMF water body and relatively small LE and H. Approach 2 estimated slightly negative H during most months due to lower T_s as sensed by IRT relative to air temperature. H from approach 3 was very slightly positive, on average, indicating a very slight warming of air by the water body. Heat energy to the water surface was supplied by absorbed near-infrared radiation absorbed near the surface.

The typical close proximity of water surface temperature and air temperature for AMF reservoir is illustrated in Figure 7a where trends in air temperature, water temperature and atmospheric temperature are shown for 7/3/2004. The atmospheric temperature is scaled by the second y-axis. Figure 7b shows the calculated clear-sky solar radiation (R_{so}) and the actual solar radiation (R_s) for the same day. The day had a clear sky until 15:30 when deep cloud cover occurred. As shown in Figure 7a, air temperature, water surface temperature and atmospheric temperature behaved similarly under clear-sky conditions. Under clouds, atmospheric temperature significantly increased while air and water surface temperatures decreased, but retaining good correspondence. The close correspondence between atmospheric and surface temperature is due to the domination of both temperatures by incoming and outgoing thermal radiation, which are closely coupled and feedback to one another. Correspondence between air and surface temperature is due to the large fetch of open water (5 to 10 km) and surrounding irrigated agriculture.

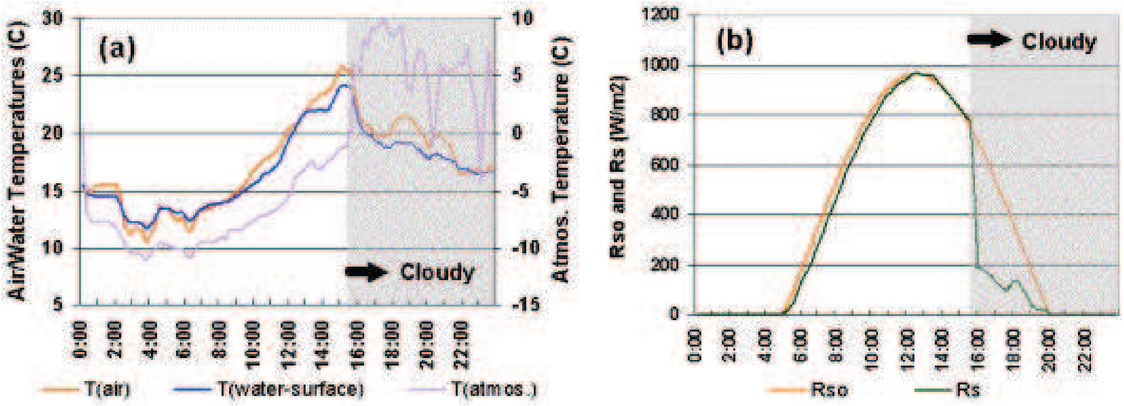

Figure 7. (a) Air temperature, water surface temperature and atmospheric temperature measured at the AMF site at 7/3/2004 (DOY=185), and (b) solar radiation for the corresponding date.

According to the results shown in Tables 2 and 3 and in Figure 6, most net radiation is partitioned as water heat storage flux, which is the term equivalent to “soil heat flux” in land surface energy balances. Estimated Q_t for the AMF reservoir (based on the EC/BREB method) ranged from 72 to 86% of net radiation during midday during the May – November study period. Visual observation of hourly Q_t in Figure 6 shows that Q_t from AMF reservoir during nighttime was conducted/convected to the surface at about 50 to 100 W m^{-2} during all months. This is expected to be a function of water temperature profile, turbidity and surface – air temperature differences. In November, when daylength was short, the integration of negative Q_t at night exceeded the integrated positive Q_t during day. Coupled with less penetration of solar radiation due to lower sun angle, 24-hour Q_t was substantially lower in November. The 24-hour Q_t peaked in summer (at about 50 to 60% of R_n) and reached a minimum in November at negative 15% of R_n. The actual minimum value for Q_t/R_n may have occurred after the end of the study period, such as during January to March, depending on presence of ice formation. If the Q_t/R_n pattern is extrapolated into winter, evaporation, sensible heat, and emission of longwave radiation from the AMF are expected to be significantly larger than from the general land surface during winter, as was shown for the Great Lakes region by Croley et al., 1996 (Figure 8). Croley’s ratios of Q_t/R_n for Lake Superior are quite similar to those observed for the American Falls reservoir.

The large Q_t for the AMF reservoir surface is in contrast with G expected for general land surfaces. The midday values for G from land surfaces average about 5% of R_n for full-cover, tall vegetation and about 15 to 40% of R_n for bare soil. G averages approximately zero over 24 hour periods. This is quite different from Q_t of water bodies. The primary reason for the large Q_t for the AMF reservoir is the penetration of solar radiation beneath the water surface which does not occur for opaque vegetation and soil. In addition, irrigation reservoirs like AMF reservoir tend to have larger Q_t than do natural lakes. Reservoirs collect solar energy during spring-summer. However, substantial releases for irrigation during summer and fall advect stored energy out of the reservoir (see, Figure 1) either to irrigated fields or further downstream. This horizontal transfer of energy causes an imbalance in the reservoir energy balance that must be accounted for in the Q_v term of Eq. (3). In the case of irrigation reservoirs, annual Q_t tends to be positive. As an illustrative reference value, the annual imbalance of energy in the Pacific Ocean caused by advection by regional currents is ± 80 W/m^2 (Kondo, 1994).

ET_rF is the ratio of evaporation to alfalfa reference ET as calculated using the ASCE-EWRI standardized Penman-Monteith equation. The ET_rF for the AMF reservoir averaged about 0.2 to 0.4 during midday and about 0.3 to 0.7 for 24-hour periods over the season. This indicates that evaporation from the reservoir water surface was only 20 to 70% of the ET from a full-cover alfalfa field. The monthly pattern of ET_rF was directly correlated to the Q_t/R_n ratio since Q_t dominates the process. The 24-hour ET_rF rapidly increased during late fall, because extra energy was provided from the reservoir water body in the form of negative Q_t.

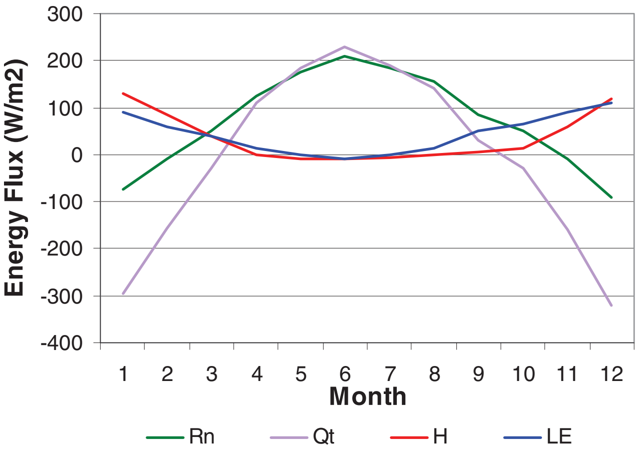

Figure 8. Simulated energy balance at Lake Superior for an assumed climate scenario (Data by Croley et al.,1996).

Application to Satellite-based Remote Sensing of Energy Balance

This section describes additional findings by our UI-Kimberly research group that might prove useful in future applications for lake evaporation modeling using satellite imagery. The analyses for this section are based on eleven Landsat satellite images acquired during year 2000 and associated hydrological and metrological data.

During 2000, a strong correlation was noted between satellite derived reservoir albedo and the water turbidity for the AMF reservoir (measured in the reservoir discharge) (Figure 9). The correlation suggests the potential to estimate effective thermal depth of water using satellite imagery, because water transparency, water depth and the effective thermal depth are generally interrelated (Tasumi, 2005). The thermal depth affects seasonal evaporation patterns of water bodies. Figure 10a shows satellite based water surface temperature and the water temperature of releases from the AMF reservoir. Even though measurement dates for the two temperatures were different, and reservoir discharges represented some mixture of water from various depths, the two temperatures were well correlated, with differences usually less than a few degrees. The similarity is primarily due to the tendency for water temperature in lakes to be relatively constant for depths of 10 to 30 m, which are associated with solar penetration. AMF reservoir has a mean depth of 10 to 20 m when full. Therefore water surface temperature is approximated by average water temperature of the reservoir releases. Figure 11 shows an example of the vertical temperature profile for a Japanese lake.

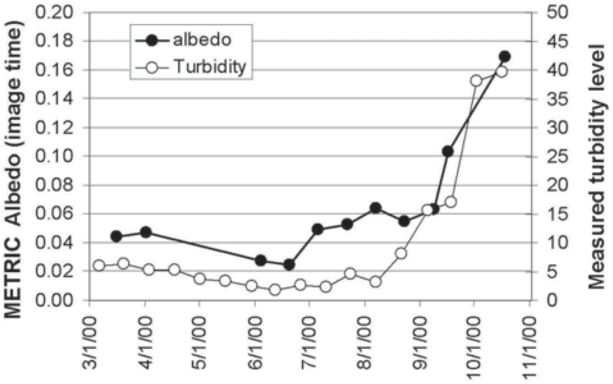

Figure 9. Relationship between albedo and turbidity for the AMF reservoir during 2000 – albedo values were derived by Landsat imagery and the METRIC (Allen et al. 2005) energy balance procedure, and turbidity was from BOR (2005a) measured directly downstream of the AMF dam.

Figure 10b is a plot of water temperature (same data as Figure 10a) and air temperature measured at the nearby Aberdeen agricultural (Agrimet) weather station. Water discharge and air temperature were nearly identical from mid March to the end of June. From August through October, water discharge temperature exceeded air temperature by a few degrees. These differences in Fall provide a hint for energy balance partitioning and estimation of Q_t.

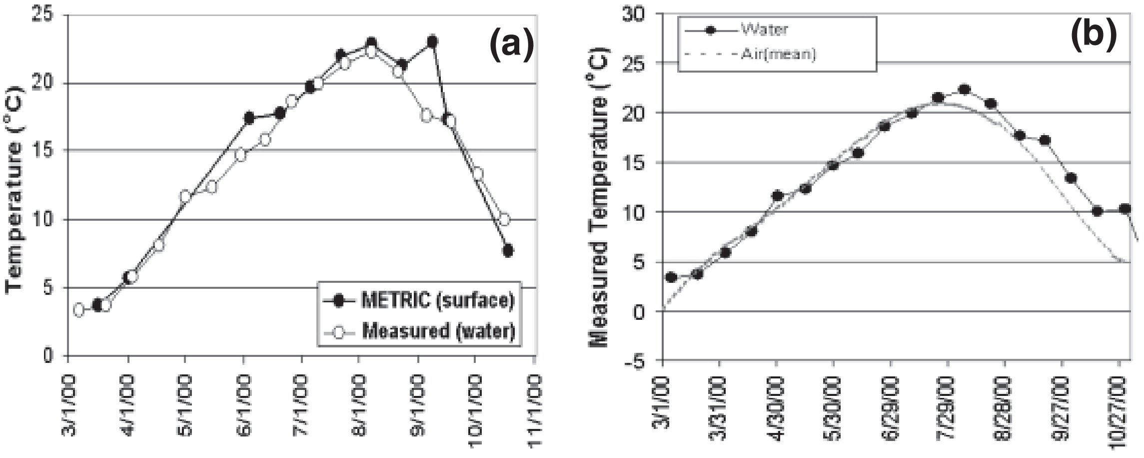

Figure 10. (a) Satellite measured reservoir surface temperature and water temperature at downstream of the AMF dam (from Hydromet (BOR, 2005a)); (b) the same water temperature by BOR, 2005a and air temperature by Aberdeen station of AgriMet (BOR, 2005b).

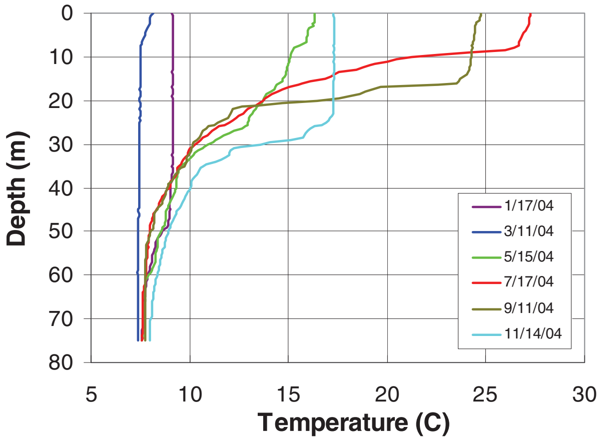

Figure 11. Annual change in vertical temperature profile at Lake Biwa, Japan, during 2004 (Data by S. Endoh, 2005)

Summary and Conclusions

The combination of eddy covariance and Bowen ratio systems enabled the estimation of heat storage in American Falls reservoir without the need for thermal profiling. The combination also eliminated the need for a collocated fast-response hygrometer in the EC system. Accuracy of the H and LE estimates was confirmed by largely independent aerodynamic calculations. The heat storage was found to dominate the energy balance for the reservoir, consuming more than one-half of net radiation during the growing season. Evaporation fluxes from the reservoir average less than 40% of alfalfa reference ET, which indicates relatively efficient water storage.

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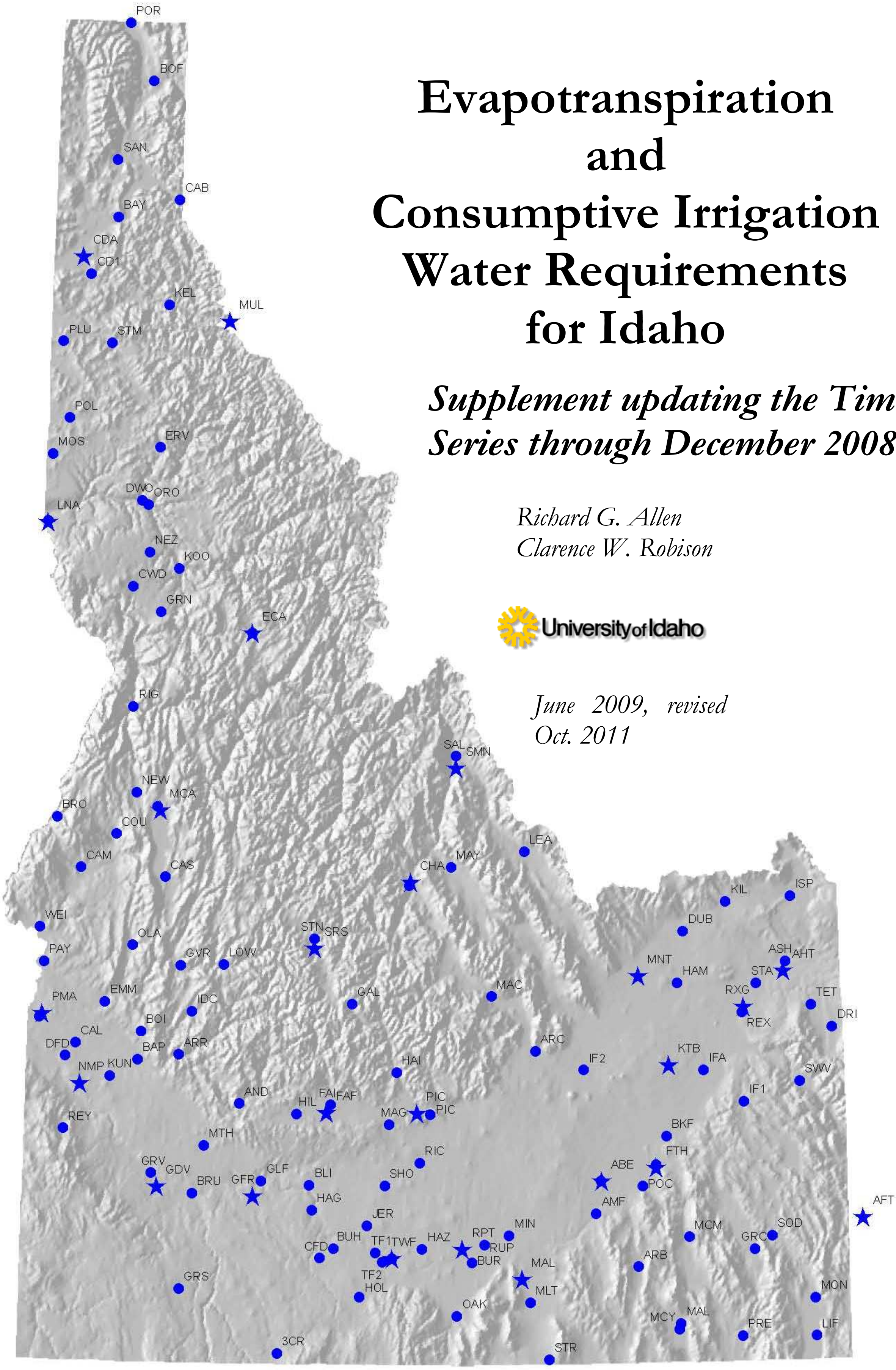

Evapotranspiration and Consumptive Irrigation Water Requirements for Idaho

Supplement updating the Time Series through December 2008

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Clarence W. Robison

University of Idaho

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All compiled evapotranspiration data files are available via internet download from the following University of Idaho website:

http://www.kimberly.uidaho.edu/ETIdaho/

SUMMARY

Updated evapotranspiration and net irrigation water requirement estimates were produced by the University of Idaho in 2007 for agricultural areas in Idaho through December 2004. These estimates have been recomputed and updated through December 2008 in this supplement to the 2007 report. ET has been calculated for daily, monthly and annual timesteps for 125 weather station locations across Idaho for complete, available periods of record. This number includes two stations added to the 2009 calculations: Craters of the Moon (Coop station 102260, 1959-2008) and Howe (Coop station 104384, ~1958-2008). Thirty year normals have been updated to end in 2008 (if 2008 were an active year of data collection). During this revision, the complete National Weather Service Cooperative station database for Idaho stations was re-downloaded from the National Climate Data Center (NCDC) site so that some previous 'holes' in daily time series were filled in for some stations.

The ET calculation procedures employ the ASCE standardized Penman-Monteith method for calculating reference crop ET and use an FAO-56 style procedure to calculate crop coefficients with consideration of the impact of surface wetting by irrigation and precipitation on total evapotranspiration. The ET estimates represent 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 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 109 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. Calculations have been made through December 31, 2008 for the NWS and AgriMet stations.

The ASCE standardized Penman-Monteith reference evapotranspiration equation is a nationally standardized method (ASCE-EWRI 2005), is well regarded, and serves as a reproducible index approximating the climatic demand for water vapor. Reference ET is the ET rate from an extensive surface of reference vegetation having a standardized uniform height and that is actively growing, completely shading the ground, has a dry but healthy and dense leaf surface, and is not short of water. The ASCE Penman-Monteith (PM) equation was recently standardized by ASCE-EWRI (2005) for application to a full-cover alfalfa reference and to a clipped cool season grass reference.

Because only maximum and minimum air temperature are observed at the National Weather Service 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. 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.

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 according to growing degree days following the start of season. Growing seasons were terminated by predicted maturation of the crop or by a killing frost. The base K_{cb} curves were expressed on relative time scales or relative thermal unit scales to allow K_{cb} curves to be 'stretched' differently each year, according to weather conditions. Four different methods were used to express the base K_{cb} curves, depending on the crop or land-use type: 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 FAO-56 method for estimating evaporation from bare, wet soil, was utilized where a daily water balance was computed for the top 10 cm of soil as a means for reducing evaporation losses as the soil surface dries. In irrigated regions of the state, irrigations were simulated for typically irrigated crops for purposes of estimating evaporation from wet soil surfaces. Scheduling of irrigations was made using a root-zone water balance assuming a nonresistricted root zone and depletion of soil water to an allowable depletion level. Simulated irrigation schedules were typically like those practiced with surface irrigation and with hand-move or wheel-line sprinkler systems (i.e., 'low frequency'). Available water holding capacity and texture of soil for each station was determined using information from the National StatsGo soils information data base using a GIS analysis of the data base for the area assigned to each station. Precipitation runoff was estimated using the NRCS Curve Number method where antecedent moisture was computed from the daily surface soil water balance. The curve number was determined from soil texture based on the StatsGo soils data base.

Snow cover data as observed at many of the NWS stations were used to modify winter time estimates of evaporation caused by high albedo of snow and energy required for heat of fusion and was also used during adjustment of cumulative growing degree days for winter wheat during winter.

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 115 years at Oakley (1893-2008). 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.

Enhancements to the Statistical Processing of ET in ETIdaho

Changes in Terminology from 2007:

We now refer to the former variable Prz as **Przel** (Precipitation stored in the root zone and evaporation layer) so as to better communicate that this Precipitation is the precipitation that is subject to evaporation (and perhaps transpiration).

We continue to refer to **PrzT** as it was currently stated (PrzT is Precipitation stored in root zone that is used for transpiration (and does not include that precipitation that is lost to evaporation)).

Background and Logic regarding computation of the Precipitation Deficit (i.e., the irrigation water requirement):

Prior to 2009 (i.e., 2006-08), the precipitation deficit (also known as the consumptive irrigation water requirement, IWR), was computed as Pdef = ETpot - Przel, where ETpot is potential ET (for no stress and including evaporation from wet soil). Both of the terms ETpot and Przel include evaporation from soil, Es. ETpot sometimes exceeds the calculation of actual ET, ETact, especially during the offseason (NGS), when ETact may be reduced due to drying soil. In that case, the computation of the Pdef (i.e., IWR) should not include potential ET, but only actual ET. Accordingly, the Pdef was changed to Pdef = ETact - Przel in 2009.

Pdef during the Nongrowing Season (NGS)

Some methods assume that Pdef = 0 during the NGS, but this precludes credit for stored PrzT (manifested as a negative Pdef calculation) during the NGS.

One considered approach was to calculate Pdef = max(ETact – Przel, 0). However, this makes Pdef zero or positive if the evaporation slab is wet at the termination of the prior GS so that there is ETact from a prior wetting event not counted in Przel. The same may occur for a P event a day or two before planting, however this would occur more rarely. This approach precludes a negative Pdef calculation which represents a gain in soil moisture from precipitation. This gain may be important for some months.

The best approach for estimating Pdef during the NGS is to calculate Pdef as **Pdef = ETact – Przel** and allow it to go both positive (see above) and negative (when PrzT is stored). Pdef should be able to be positive and negative day to day. One could limit Pdef to <= 0 when integrated over the entire NGS period, since evaporation during the NGS is generally not replaced using irrigation, except for rehydrating the evaporation slab prior to planting. This was not done in this study.

Przel is used in the calculation of Pdef because ETact is used (ETact is the actual ET that is calculated from a daily soil water balance, and ETact includes evaporation from precipitation (Pevap). Because ETact includes Pevap, then Przel must be subtracted from ETact since Przel includes Pevap as well.

Pdef during the Growing SEason (GS):

IF the crop is irrigated, then **Pdef = ETact – Przel** .

As described for the NGS, Przel is used because ETact is used and ETact includes evaporation from precipitation (Pevap). Because ETact includes Pevap, then Przel must be subtracted from ETact since Przel includes Pevap as well.

For irrigated crops, ETact during the GS, as calculated in ETIdaho, will be nearly the same as ETpot, since a full water supply is assumed. ETact may be 5 to 20 mm less than ETpot for some crops due to the exercise of some stress during crop development stages when crop root depths are small and frequent irrigations would be called for if a normal MAD were used. (no irrigations are initiated in ETIdaho unless Kcb > 0.22).

Less frequent irrigation during crop development (especially the first few weeks after planting) is a cultural practice.

Where rainfed crops are grown, ETact may be well below ETpot during the GS due to stress to the crop, and is therefore not useful for computing Pdef. However, knowledge of Pdef (i.e., IWR) may still be of interest for these rainfed crops. Therefore, for rainfed (nonirrigated) crops, Pdef is computed using ETpot as:

Pdef = ETpot – Przel when the crop is rainfed.

Expansion of statistical analyses and output in 2009

Annual Time Series. Prior to 2009, the statistics program created monthly and annual time series for all crops for the following parameters:

Actual ET (mm)
Potential ET (mm)
Precipitation Deficit (mm) (i.e., consumptive irrigation water requirement)
Precipitation residing in root zone (mm)
Effective precipitation for transpiration (mm)
Estimated growing season period (days)

The first five parameters were computed for the entire calendar year.

In 2009, three additional sets (files) of annual times series were established to describe ET and effective precipitation for both growing season and nongrowing season segments. Generally, all parameters are in units of millimeters. The three additional sets of annual time series contain the following information:

Annual ET series file (name = xxxxAnnual_ET.dat where xxxx is a station number)

ETpG -- potential ET (with no stress) during the growing season. A more full acronym is $ET_{pot\ GS}$.

ETpN -- potential ET (with no stress) during the nongrowing season. A more full acronym is $ET_{pot\ NGS}$.

ETaG -- actual ET (no stress) during the growing season. A more full acronym is $ET_{act\ GS}$.

ETaN -- actual ET (no stress) during the nongrowing season. A more full acronym is $ET_{act\ NGS}$.

ETac -- annual actual ET (no stress) (ETac = ETaG + ETaN) and includes evaporation of P and I. A more full acronym is $ET_{act\ Ann}$.

P_df -- the precipitation deficit, which is the same as the irrigation water requirement

Annual Precipitation time series (name = xxx_Annual_Precip.dat)

PzTG -- the precipitation effective in supporting transpiration during the growing season (PzTG = PzeG - surface evaporation losses). A more full acronym is $P_{rz\ T\ GS} = P_{eff\ mo} – E_{s\ precip}$ calculated during the growing season for the crop. This parameter is computed in the stats program on a monthly basis, where $P_{eff\ mo}$ is monthly $P_{rz\ el}$ = P - RO – DP and $E_{s\ precip}$ is the evaporation (monthly) from precipitation (see definition at end)

PzTN -- the precipitation effective in supporting or stored for transpiration during the nongrowing season. A more full acronym is $P_{rz\ T\ NGS}$. This computation includes "T" during the NGS as represented by the K_{cb} for the winter cover condition.

PzTA -- the annual precipitation effective in supporting or stored for transpiration (for the full calendar year). PzTA = PzTG + PzTN. A more full acronym is $P_{rz\ T\ Ann}$.

PzeG -- the precipitation entering and residing in the rootzone during the growing season (PzeG = P - SRO - DP and includes surface evaporation losses). A more full acronym is $P_{rz\ el\ GS} = (P – RO – DP)_{GS}$ calculated during the growing season of the crop.

PzeN -- the precipitation entering and residing in the rootzone during the nongrowing season. A more full acronym is $P_{rz\ el\ NGS} = (P – RO – DP)_{NGS}$

Annual Effective Precipitation time series (name = xxx_Annual_Eff_Prec.dat)

PrzT -- annual precipitation effective in supporting transpiration generally occurring during the growing season (PrzT = PzeG + PzeN - surface evaporation losses) *(same as PzTA above)*

PzTG -- the precipitation effective in supporting transpiration during the growing season (PzTG = PzeG - surface evaporation losses)

PzTN -- the precipitation effective in supporting or stored for transpiration during the nongrowing season. A fuller acronym is: $P_{eff\ NGS} = P_{rz\ T\ NGS} = P_{rz\ el\ NGS} – ET_{act\ NGS} = P_{NGS} – RO – DP – ET_{act\ NGS}$.

PzFA -- annual fraction of gross P that is effective in supporting transpiration. PzFA = PrzT/P on an annual basis.

PzFN -- annual fraction of Nongrowing season precipitation effective in supporting transpiration. $PzFN = PzTN/P_{NGS}$

DSn is the number of days in the estimated growing period.

P_GS is precipitation during the growing season

Przac = Precipitation to root zone that is accumulated and transferred to the GS.

Normals

Prior to 2009, the normals output included separate files containing statistics on 30 year (or shorter) normals:

ETcact_stats.dat *(actual ET)*
ETcbas_stats.dat *(basal ET)*
ETcpot_stats.dat *(potential ET)*
Prec_def_stats.dat *(precipitation deficit = consumptive irrigation requirement)*

These normals are computed from the most recent 30 years having "complete"[1] data. Statistics (mean, std. dev., skew, kurtosis, and 20% and 80% exceedence values) were computed for 30, 15, 7 and 3 day series. In 2009 the statistics output was expanded to include the following additional files for statistics on 30-yr normals:

PrzT_stats.dat -- precipitation that resides in the soil that is used at some point for transpiration
Przel_stats.dat -- precipitation that resides in the root zone and/or evaporation layer that is used for both transpiration and evaporation

Partitioning of evaporation into the precipitation and irrigation sources

Prior to the 2009 ETIdaho edition, in the stats program, evaporation from both P and I was partitioned into the P source and the I source on a monthly basis as:

Es_precip = Es * (P / (P + TEW * NIRRMO))

where TEW is total evaporable water (mm) and NIRRMO(i) is the number of irrigations per month. P is the monthly Precipitation and Es is the monthly Evaporation. Es is computed by differencing ETpot and ETbas. In the 2009 edition, the evaporation stemming from precipitation was computed on a daily basis as:

1. If it had been more than 10 days since irrigation, evaporation from a specific crop was assumed to be all from precipitation.

2. If less than 10 days since irrigation, evaporation from a specific crop due to precipitation was computed using a previous ratio to evaporation from bare soil: $E_{s\ from\ P} = (ET_{pot}(Baresoil) - ET_{bas}(Baresoil)) * E_{sratio}(i)$ where $E_{sratio}(i)$ was computed from a previous time period prior to an irrigation event as $E_{sratio}(i) = E_s / E_{sbare}$ where i was the number of a specific crop and Baresoil is the internal number assigned to bare soil. $E_{sbare} = ET_{pot}(Baresoil) - ET_{bas}(Baresoil)$. E_s was total evaporation.

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[1] A year is consider to be complete when more than 350 days are present in the annual period and fewer than 6 days are missing from the 'growing period'. At least 26 days are required in any month when calculating running averages in the normals file.

3. Precipitation stored in the rootzone and used for transpiration was then computed as: $P_{rz\ T}(i) = P - \text{Runoff}(i) - DP(i) – E_{s\ from\ P}$

4. Evaporation from the irrigation event was computed as $E_{s\ i} = E_s - E_{s\ from\ P}$.

The above procedure was required to separate evaporation of P from that of I when events occurred during the same period. The labeling of evaporation from P and I was not preserved in the daily time series generated by the ETIdaho program. This partitioning procedure assumes that evaporation from P takes precedence over evaporation from irrigation. In other words, irrigation is not penalized for evaporation that would have occurred anyway due to a concurrent rain event.

Corrections to the Statistics.bas code in 2009:
A correction was made to the Statistics program to preclude calculations of deep percolation from irrigation from going negative.
Also, a line that kept Peff from being negative on any day was deleted (Peff needs to be negative to account for delayed deep percolation of precipitation).

Corrections to the KcETref.bas code in 2009:

Oversights in the in "crop startup" routine were corrected that prevented the correct estimated date of greenup or planting from being recognized.

Some reseting of variables between crops was done.

A error in estimating deep percolation from very shallow rooting depths in course soils was corrected (this did not occur often).

Download of NCDC data and computation of reference and crop ET

The procedure for downloading NCDC data in the 2009 revision was modified from that used for the original 2007 report. For the 2007 report, data were obtained from *Inside* Idaho due to a more complete data record for historical periods dating to the late 1800's. In the 2009 revision, data were obtained directly from the NOAA NCDC web portal.

Data from NCDC were downloaded in large segments of data files containing data for all COOP stations in each of the 10 regions of Idaho and in some cases in 20 year blocks due to NCDC file size constraints. The NCDC files were downloaded in 'simple' format.

The procedure in 2009 followed the following computation steps. Text in bold after each bulleted number are the 'name' of a Visual Basic 'form' (.frm) file containing code for implementing the process:

1. **Shift_and_strip_NCDC_and_parse.frm** March 2009. Read comma delimited (standard) daily weather files from NCDC for all Idaho Coop stations (from multiple joined files) and strip out the monthly sums and blank lines. NCDC files were fragmented by the 10 regions and in some cases in 20 year blocks due to NCDC file size constraints. The NCDC files were downloaded in 'simple' format.

This program reads 'file_names.txt' for names of weather data files and creates NCDC_order_of_years.txt and creates individual files with the names "------".txt, where "------" is the WBN station number assigned by the NWS. NOTE THIS PROGRAM DOES NOT YET SHIFT P and Tmax back one day.

2. Order_and_shift_NCDC.frm Read individual txt files from the NCDC created by the parse program check for correct order. March 2009

3. Shift_NCDC.frm 'Read each station file and shift Tmax and P one day back in time. This is necessary because Tmax reported on Day "x" is the Tmax that occurred on the prior day ("x-1"). The precipitation reported on Day "x", at 0700 represents precipitation from 0700 – 2400 on day "x-1" and from 0001 to 0700 on day "x". It was assumed that all P occurred on day "x-1" and therefore both Tmax and P data were shifted. It was assumed that reported Tmin occurred on the morning it was reported (i.e., after midnight).
input file names are "------".txt and output file neames are "------s".txt.

4. Order4b_for_wbn_d4_files.frm (run by Order4b_weather_d4_files.vbp) 'This program, in 2005 went through the ET files and ordered the data 'chronologically. The Inside Idaho database download had sections 'out of order. In 2009, this program was modified to to insure chronological order of the 'old' NCDC files from 2007 (the xxxxxxd4.dat files). These are ordered so that they could be properly merged with the NCDC files downloaded in 2009 that are in order.
Reads: ------d4.dat
Writes: ------d5.dat

5. Add_missing_and_2005_2008b.frm. Reads "D5" files from 2007 work and writes "D7" files.
This form/code was originally morphed in 2007 from the ETrcalc code to simply add the missing Aug 2000 Temp 'data to all weather files. Aug 2000 was missing from Inside Idaho dbase.
In 2008, the program was modified to add 2004-May or June 2008 to the data files. 2004 is already in the files, but it is added (replaced) here as a check.
In March 2009, the program was modified to scan through new NCDC files (all NCDC data were downloaded for all of Idaho region by region for the entire period of record) for all periods of record and fill in missing data anywhere in the record as well as append data through Dec. 2008. New NCDC files were fragmented by the 10 Idaho regions and in some cases, in 20 year blocks due to NCDC file size constraints. The NCDC files were downloaded in 'simple' format. These block files were broken down and Tmax, P shifted via a series of three other programs run prior to this one.

Reads individual "----D5.dat" files from the 2007 ETIdaho process and new ------s.txt files from the 2009 download of NCDC data and build new daily weather files that have minimized missing data and run through Dec. 2008
Writes: -------D7.dat files

The StationF2.txt file has been updated to include 2 more stations on the ESPA (Craters, Howe) the following two WBN's are not in the NCDC record and therefore there are no new files for them.
If WBN = 104457 Then GoTo atfileend 'station is not in NCDC record (IF AP)
If WBN = 104908 Then GoTo atfileend (Kilgore)

6. combine_Agrimet_all_2.frm For Agrimet in 2009, combine 2006-2008 data with previous Agrimet files and add snowdepth and precipitation data from nearby Coop stations.

7. ***ETr_calc5c.frm*** –ETr_calc5c2.frm in 2009, run by ETr_Calc_5project3c.vbp
Visual Basic language – Reads the -----da.dat NWS data files, estimates solar radiation and dewpoint temperature from air temperature data (on a daily basis), assigns a long-term monthly wind speed, and **calculates alfalfa reference evapotranspiration (ETr)**. VisualBasic files are: ETr_calc5c.frm for the primary code and ETr_Calc_5project3.vbp for the Visual Basic project.
Reads:Stationf.txt (Stationf2.txt in 2009)
Reads:Windmon.txt
Reads:Txnmon.txt (longterm monthly Tmax and Tmin)
Reads:------da.dat (d4.dat in May 2007 rerun) (d7.dat in 2009)

Writes:Txnmon2.txt (creates new Txnmon.txt file each run (file does not change))
Writes: TxTnLog3.txt – log file showing days when Tmax < Tmin
Writes: ------ET.dat – daily reference ET by station where '------' is the WBN.
(------E4.dat in May 2007 rerun) (-----E5.dat in 2009)

8. ***Order4.frm*** -- (Order4d.frm in 2009, run by Order4d.vdp) Visual Basic language – (see comments in file for full description) – Orders the computed ETr data chronologically (the data as received from Inside Idaho were sometimes out of order or had missing data at the beginning). VisualBasic files are: Order4.frm for the primary code and Order4.vbp for the Visual Basic project.
Reads: stationf.txt
Reads: ------ET.dat (------E4.dat in May 2007 rerun) (E5.dat in 2009)
Writes: ------E2.dat (------E5.dat or ------ETr.dat in May 2007 rerun) (ETr.dat in 2009)

Crop ET and Irrigation Water Requirements

9. The following describes the computer program file used to calculate crop ET and irrigation water requirements in support of the 2007 report "Evapotranspiration and Consumptive Irrigation Water Requirements for Idaho" by Allen and Robison. The program, ***UI_NVKcETr48.frm*** operated by UI_NV_KcETref29b.vbp was coded in Visual basic, version 6. This code was enhanced in 2008 and 2009, in collaboration with Justin Huntington of the State of Nevada State Engineers Office, to work with both alfalfa (ETr) and grass (ETo) references. The code contains a reference type 'toggle' that can be switched between ETr and ETo (of course, the Kc file that is read by the program must be congruent with the reference type). The code also contains a "StateToggle" switch that points to which state (Idaho or Nevada) to operate in regarding reference type and folder/file names and structure. For the Idaho application:

Reads: *Final_Kcs_for_IDWR_17.csv* for crop curve information. File extracted from xls spreadsheet having the same name.
Reads: *Idaho_Crop_parameters28.csv* for parameters associated with each crop type. File extracted from xls spreadsheet having the same name.
Reads: *Idaho_Stations_Crops_2009.csv* for list of crops associated with each weather station. File extracted from QuattroPro spreadsheet *Final_stations_Data_file_setup_v.qpw or derivative*
Reads: *Final_stations_Properties_d.csv* for weather station parameters. File extracted from QuattroPro spreadsheet *Final_stations_Data_file_setup_q.qpw or derivative*
Reads: *ETrfilename$* containing daily ETr, Precipitation, snow depth, air temperature.
For station numbers < 108 (NWS), *ETrfilename$* = ETrfilespath$ & station_IDno(ns) & "E2.dat" (------ETr.dat in May 2007 and 2009 runs)
For station numbers > 109 (Agrimet), *ETrfilename$* = Agrimetpath$ & "Aberdeen" & "_final_ETr_precip_thru_2008.dat" (where "Aberdeen" is name of Agrimet station). The "------" is the WBN station number assigned by the NWS. The Agrimet stations were created with Excel spreadsheets, based on *REF-ET* output.

Writes and Reads: *tempETc.dat* -- temporary file that contains daily ETc (row by row), with one set of seven columns per crop (*ETactual, ETpotential, ETbasal, net irrigation, growing season flag, runoff, deep percolation*). These files have columns added for each successive crop that is processed for a particular station.

Writes: *ETcfilename$* and *ETcfilename2$* -- Final files for daily ETc and NIR for all crops at a station. *ETcfilename$* contains results for the first 34 crops (to keep no. columns < 256) and *ETcfilename2$* contains the second half of crops for the station.
*ETcfilename$* = ETcfilespath$ & station_IDno(ns) & "ETc.dat" *ETcfilename2$* = ETcfilespath$ & station_IDno(ns) & "ETcb.dat" (second half of ETc file if more than 34 crops).

10. ***Filter_missing_daily7b.frm*** (not used (nor needed) in 2009 runs) is run by project Filter_daily_project4b.vbp and is used to clean up the start of the 'ETc.dat' and 'ETcb.dat' daily ETc data files so that the files begin on Jan. 1 of the first full year of data. *Filter_missing_daily7c.frm* also rearranges crops in the two files to start with crop no. 1 and to run sequentially. (run by Filter_daily_project4c.vbp)

Reads: *ETrfilename$* containing daily ETr, Precipitation, snow depth, air temperature.
For station numbers < 110 (NWS), *ETrfilename$* = ETrfilespath$ & station_IDno(ns) & "E2.dat"
For station numbers > 109 (Agrimet), *ETrfilename$* = Agrimetpath$ & "Aberdeen" & "_final_ETr_precip.dat" (where "Aberdeen" is name of Agrimet station). The Agrimet stations were created with Excel spreadsheets, based on *REF-ET* output.
Reads: *ETcfilename$* = ETcfilespath$ & station_IDno(ns) & "ETc.dat" *ETcfilename2$* = ETcfilespath$ & station_IDno(ns) & "ETcb.dat" (second half of ETc file if more than 30 crops).

Writes: *ETcfinished$* and *ETcfinished2$* -- Final files for daily ETc and NIR for all crops at a station. *ETcfinished$* contains results for the first 34 crops (to keep no. columns < 256) and *ETcfinished2$* contains the second half of crops for the station.
*ETcfinished$* = ETcfilespath$ & station_IDno(ns) & "ETca.dat" *ETcfinished2$* = ETcfilespath$ & station_IDno(ns) & "ETcb.dat" (second half of ETc file if more than 34 crops).

Statistics Calculation Program

11. ***UI_NV_ETc_Stats26cfrm.frm*** in project Stats_project5x.vbp calculates monthly and annual time series from daily time series for the periods of record and statistics describing the most current 30 year normal period. Computations are done for each crop and land cover type as well as for reference ET, 30 day mean air temperature and precipitation. This statistics program is also toggled for use in Idaho or Nevada in regard to the folder/file pathways, which are hard-wired in.

Reads: "*Idaho_Stations_Crops_2009.csv*" file for the number of crops per station and other station data (irrigationflag, etc.).
Reads: "*Final_stations_Properties_d.csv*" for waterholding capacity information (used in calculating P_efT where P_efT is the component of precipitation effective in supplying transpiration).
Reads: "*xxxxxxETca.dat*" ("*xxxxxxETcb.dat*" if no. crops > 30) for the daily ETc time series, where xxxxxx is the station no.
Writes: "*xxxxxxETc_monthly.dat*" and "*xxxxxxETc_annual.dat*" files that contain monthly and annual time series for the entire periods of record and for each crop (in parallel columns). In 2009, the annual series files were expanded to describe:
annual_ET.dat – actual and potential ET
<u>Original ET Annual Time Series:</u>
Actual ET (mm)
Potential ET (mm)
Precipitation Deficit (mm) (i.e., consumptive irrigation water requirement)
Precipitation residing in root zone (mm)
Effective precipitation for transpiration (mm)
Estimated growing season period (days)

<u>Annual ET series file:</u>
(name = xxxxAnnual_ET.dat where xxxx is a station number)
ETpG -- potential ET (with no stress) during the growing season. A more full acronym is $ET_{pot\ GS}$.

ETpN -- potential ET (with no stress) during the nongrowing season. A more full acronym is $ET_{pot\ NGS}$.
ETaG -- actual ET during the growing season. A more full acronym is $ET_{act\ GS}$.
ETaN -- actual ET during the nongrowing season. A more full acronym is $ET_{act\ NGS}$.
ETac -- annual actual ET (ETac = ETaG + ETaN) and includes evaporation of P and I. A more full acronym is $ET_{act\ Ann}$.
P_df -- the precipitation deficit, which is the same as the irrigation water requirement

<u>Annual Precipitation time series</u> (name = xxx_Annual_Precip.dat)
PzTG -- the precipitation effective in supporting transpiration during the growing season (PzTG = PzeG - surface evaporation losses). A more full acronym is $P_{rz\ T\ GS} = P_{eff\ mo} - E_{s\ precip}$ calculated during the growing season for the crop. This parameter is computed in the stats program on a monthly basis, where $P_{eff\ mo}$ is monthly $P_{rz\ el}$ = P - RO – DP and $E_{s\ precip}$ is the evaporation (monthly) from precipitation (see definition at end)
PzTN -- the precipitation effective in supporting or stored for transpiration during the nongrowing season. A more full acronym is $P_{rz\ T\ NGS}$. This computation includes "T" during the NGS as represented by the K_{cb} for the winter cover condition.
PzTA -- the annual precipitation effective in supporting or stored for transpiration (for the full calendar year). PzTA = PzTG + PzTN. A more full acronym is $P_{rz\ T\ Ann}$.
PzeG -- the precipitation entering and residing in the rootzone during the growing season
(PzeG = P - SRO - DP and includes surface evaporation losses). A more full acronym is $P_{rz\ el\ GS} = (P – RO – DP)_{GS}$ calculated during the growing season of the crop.
PzeN -- the precipitation entering and residing in the rootzone during the nongrowing season. A more full acronym is $P_{rz\ el\ NGS} = (P – RO – DP)_{NGS}$

<u>Annual Effective Precipitation time series</u> (name = xxx_Annual_Eff_Prec.dat)
PrzT -- annual precipitation effective in supporting transpiration generally occurring during the growing season (PrzT = PzeG + PzeN - surface evaporation losses) *(same as PzTA above)*
PzTG -- the precipitation effective in supporting transpiration during the growing season
(PzTG = PzeG - surface evaporation losses)
PzTN -- the precipitation effective in supporting or stored for transpiration during the nongrowing season. A fuller acronym is: $P_{eff\ NGS} = P_{rz\ T\ NGS} = P_{rz\ el\ NGS} – ET_{act\ NGS} = P_{NGS} – RO – DP – ET_{act\ NGS}$.
PzFA -- annual fraction of gross P that is effective in supporting transpiration. PzFA = PrzT/P on an annual basis.
PzFN -- annual fraction of Nongrowing season precipitation effective in supporting transpiration. PzFN = $PzTN/P_{NGS}$
DSn is the number of days in the estimated growing period.

P_GS is precipitation during the growing season
Przac = Precipitation to root zone that is accumulated and transferred to the GS.

The Stats program also Writes:
"*xxxxxxETcact_stats.dat*",
"*xxxxxxETcpot_stats.dat*",

"*xxxxxxETcbas_stats.dat*",
"*xxxxxxPrec_def_stats.dat*"
and in 2009:
PrzT_stats.dat -- precipitation that resides in the soil that is used at some point for transpiration
Przel_stats.dat -- precipitation that resides in the root zone and/or evaporation layer that is used for both transpiration and evaporation

These files describe statistics (mean, standard deviation, skew, kurtosis and 20 and 80% exceedance values) for 30, 15, 7 and 3 day periods in each month as well as annual and seasonal statistics. Statistics are computed for only the last 30 years of data (30 year normals). The six files contain information on 'actual ETc', 'potential ETc', 'basal ETc' and 'precipitation deficit (i.e., net irrigation water requirement)'. These parameters are described in Appendix 11 of the final report.

12. ***UI_ETc_Monthly_Parse2.frm*** in project Monthly_Parse2.vbp is used to split the monthly and annual time series files created by the statistics program into two sets of files (a and b) so that the number of data columns in each file are less than 256. This allows the files to be imported into spreadsheets. **Note that this program was not run in the 2009 update since Excel can now import more than 256 columns.**

Reads: the "*xxxxxxETc_monthly.dat*" and "*xxxxxxETc_annual.dat*"files created by the statistics program where xxxxxx is the station number.
Reads: "*xxxxxxETca.dat*" which is the daily time series file to confirm the number of crops per station
Reads: "*Idaho_Stations_Crops_i.csv*" file for the number of crops per station
Writes: "*xxxxxxETc_monthlya.dat*" and "*xxxxxxETc_monthlyb.dat*" (if needed) and "*xxxxxxETc_annuala.dat*" and "*xxxxxxETc_annualb.dat*" (if needed (if there are more than 41)).

Filling in of missing NCDC data

Annual Time Series and Statistics:

Any years that had less than 350 days of valid data for the year or more than 5 days of missing data during the growing season (defined as the growing period for grass hay) were reported as "missing" and were not included in the 30 year normal calculations or in the annual time series. Years having one to fifteen missing days during the year (and fewer than 6 missing days during the growing season) had annual values for ET and precipitation deficit adjusted by multiplying by 365 or 366 divided by the number of valid days. Any years that had more than 5 days of missing data during the growing season for a crop were reported as –999 for the seasonal ET totals. Years having one to five missing days had growing values for ET and precipitation deficit adjusted by multiplying by the length of the growing season divided by the number of valid days in the season.

Monthly Time Series and Statistics:

Statistics for 1 (daily), 3-day, 7-day, 15-day and 30-day (monthly) time lengths were computed for each month. The following rules were applied in considering whether a period was considered to be 'valid' (i.e., having a minimum of missing data):

Daily: no missing data were allowed

3-Day: No missing days were allowed in the 3-day series (for its inclusion in statistical summaries for the month)

7-Day: No missing days were allowed in the 7-day series (for its inclusion in statistical summaries for the month)

15-Day: Two missing days were allowed in the 15-day series (for its inclusion in statistical summaries for the month)

30-Day: Five missing days were allowed in the 30-day series (for its inclusion in statistical summaries for the month)

The 30 year normals were created, monthly, by progressing backward, in time, until 30 'valid' years of data were collected for that month. Therefore, statistics for individual months can have different years included. The most current, valid 30 years were considered for each month.