DISSERTATION

MODIFICATIONS TO TEMPERATURE-BASED ESTIMATES OF CONSUMPTIVE WATER USE BY MOUNTAIN MEADOWS

Submitted by

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY DARCY G. TEMPLE ENTITLED MODIFICATIONS TO TEMPERATURE-BASED ESTIMATES OF CONSUMPTIVE WATER USE BY COLORADO MOUNTAIN MEADOWS BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

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ABSTRACT OF DISSERTATION

MODIFICATIONS TO TEMPERATURE-BASED ESTIMATES OF CONSUMPTIVE WATER USE BY MOUNTAIN MEADOWS

Legal and engineering water communities in Colorado utilize the original Blaney-Criddle method to manage competing demands for water in mountain meadows, yet Blaney-Criddle underestimates in semi-arid, high-elevation environments. Blaney-Criddle consists of a consumptive use (CU) term, *f*, that is the product of mean monthly temperature, *t*, and percentage of daylight hours; and a crop coefficient, *k,* which accounts for crop variation and additional meteorologic effects. Low night temperatures at high elevations incorrectly weight *f*, and year-to-year variability among *k* values often results in significant variation between computed consumptive use and lysimeter measurements. Three modifications of the Blaney-Criddle temperature expression were tested against two existing temperature methods (Blaney-Criddle with conventional mean *t*, and Hargreaves) using lysimeter measurements from nine irrigated grass meadow sites in the upper Gunnison River basin (1999-2003). Use of two modified temperature expressions resulted in improved correlation of estimated Blaney-Criddle *f* with lysimeter CU. These improvements were similar to those observed when estimating with Hargreaves, which incorporates an additional term, T_{diff}, the difference between maximum and minimum daily temperature. Climatological sources of variability in the crop coefficient, *k*, were also examined. The May - September crop coefficients *k* were

better correlated with T_{diff} (r = 0.28 to 0.54) than with mean t (r = 0.01 to 0.43). Specific regression equations based on T_{diff} were used to develop crop coefficients from a dataset comprising the current study and three previous calibration studies in Colorado mountain meadows. Based on the standard error of estimate (SEE), estimates using the modeled coefficients more closely predicted CU than did estimates based on averages of locally calibrated k's (SEE difference of up to 5 mm mo^{-1}). Correlations of solar radiation (R_s, the primary energy input to evapotranspiration) with alternative temperature expressions and T_{diff} were improved over correlations of R_s with mean t, supporting the improved prediction performance of alternative temperature expressions and of the modeled k based on T_{diff}. Those modifications can be applied successfully throughout Colorado mountain basins, and it is hoped that the same technique can be applied to other areas of the western U.S.

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CHAPTER 1

INTRODUCTION

Throughout the western USA, the demand for water is increasing and the perception of proper allocation of water is changing. Population growth and an increasing focus on environmental goals compete with traditional western water uses of irrigated agriculture and power generation. The means used to allocate water among these competing needs include water rights adjudication, water transfers between uses, interstate water compacts, and international water agreements. An important presumption underlying the administration of water rights in the west is that water should be used judiciously, or 'without waste', as stated in law. Thus, managing limited water supplies for optimal use requires an accurate assessment of the water budget for any existing water use.

Crop consumptive water use is an important element of the water budget. The term 'consumptive water use' is often used synonymously with evapotranspiration (ET), the combined water losses from crop transpiration and evaporation from soil and crop surfaces. Consumptive use also includes water that is retained in plant tissues, but this is a minor amount relative to ET, so it is often ignored. Crop ET varies with plant species, cropping conditions, and atmospheric evaporative demand, and may be limited by the availability of soil water.

Because water resources are limited, values of ET that are both accurate and affordable to obtain are essential for legal, engineering, and management purposes. ET measurements based on lysimeters, soil moisture, or hydrologic budgets are inherently the most accurate, but such methods are generally restricted to research situations. In practice, ET is estimated by a variety of methods that relate consumptive use to climatic data. These methods may be loosely grouped as combination models, which are physically based multivariable equations, and empirical methods, which are based on observations of the correlation between ET and one or two climate variables. The preferred method in any given setting is determined by expense, data availability, and the utility of a given method.

Although combination models provide the most accurate estimates of ET, their use may be limited by the cost and effort required to obtain the necessary input data. Empirical estimates requiring fewer inputs are more affordable and may be used with success, particularly when locally calibrated. Because energy available to drive evaporation is the factor that accounts for variation in ET, the simpler equations are typically based on radiation, temperature, or some combination of these variables.

One temperature-based equation commonly used for legal and engineering purposes was proposed in its original form by Blaney and Criddle (1962). The so-called Blaney-Criddle method estimates ET based on a consumptive use factor, which is calculated from mean monthly temperature (often readily available from the network of weather stations) and the percentage of annual daylight hours for the period of interest, and a crop-specific consumptive use coefficient (k) that adjusts the consumptive use factor to account for variation in cropping conditions as plants mature. It was intended to estimate ET for periods of 15 days or greater. The original publication suggested monthly k values for a range of crops and locations.

In an attempt to improve short-period estimation accuracy, the SCS-modified Blaney-Criddle equation (USDA, 1970) separated the crop consumptive use coefficient (k) into a temperature coefficient (k_t) and a crop growth stage coefficient (k_c). The k_t coefficient is related to mean air temperature, and k_c is obtained from curves determined empirically and provided in the publication.

Neither of these equations works equally well in all environments. In particular, attempts to estimate ET using Blaney-Criddle methods in high altitude mountain meadows has resulted in underestimation or inconsistent results. These inaccuracies were attributed to the effects of altitude, and to the use of published crop consumptive use coefficients, among other causes. Both the Blaney-Criddle k and the SCS-modified Blaney-Criddle k_c have been shown to be affected by meteorological as well as crop factors. The Blaney-Criddle k and the SCS-modified Blaney-Criddle k_t are affected by elevation. Attempts to resolve problems using an elevation correction (Pochop, 1984) or by local calibration of crop consumptive use coefficients have had mixed results and poor year-to-year reproducibility.

In light of these problems, our overall objective was to develop an improved temperature-based model for ET estimates under mountain meadow conditions. Methods were evaluated by comparing calculated estimates of ET with lysimeter measurements obtained at nine irrigated high-altitude mountain meadow sites in the upper Gunnison river basin (Fig. 1.1). In general, our approach was to determine the effect of using alternative temperature functions and alternative monthly crop coefficients within the conventional Blaney-Criddle formula on the overall accuracy of ET estimates. We also explored the potential of using the Hargreaves method (Hargreaves and Samani, 1985) for estimating monthly ET.

Most variables are herein expressed in metric or SI units. However, it is desirable to express some variables in their conventional dimensions. Water volume and elevation will be reported in English units in text, tables, and figures. In the text, comparable metric or SI unit values will be reported in parentheses immediately following the English units.

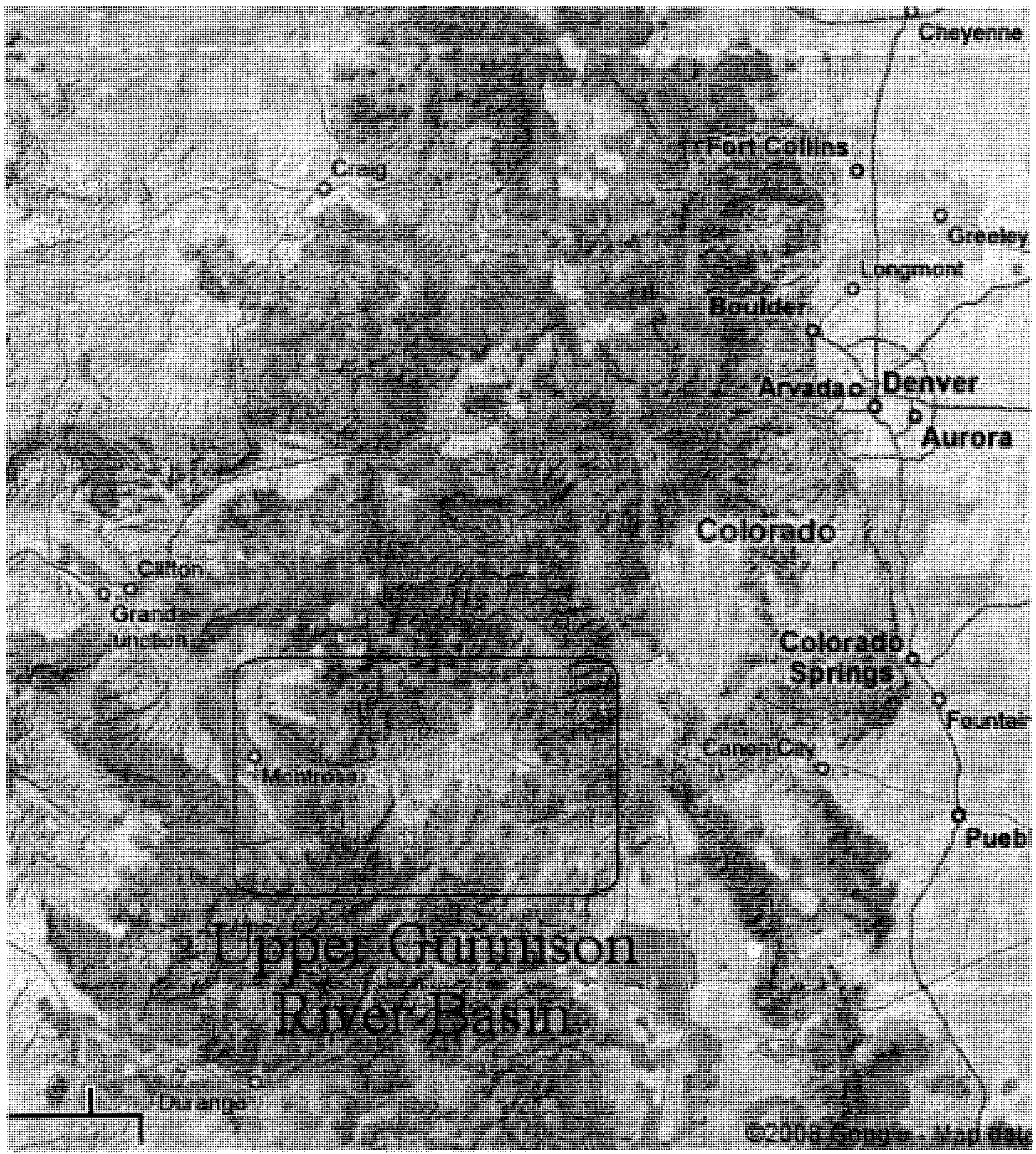

Fig. 1.1. Location of upper Gunnison River basin, Colorado.

CHAPTER 2

LITERATURE REVIEW

The upper Gunnison River basin, an area of high-altitude mountain meadows in central Colorado, is experiencing water use pressures common to many areas of Colorado. The 3,000 square mile upper Gunnison River basin includes the river mainstem and five tributaries. The microclimates of the meadows adjacent to streams vary widely within the basin. Population increase, reservoir operation, and instream flow concerns compete with the traditional water use of irrigating grass meadows to feed cattle. The majority of irrigation water rights in the upper basin are junior to water rights in the lower basin. Consequently, upper-basin irrigators are susceptible to economic losses that could result from decreased forage production if water supplies were diminished by calls on the upper Gunnison River. To protect its users from drought-related water shortages, the Upper Gunnison River Water Conservancy District plans to increase its water supply by using some combination of alternative supply strategies including constructing new storage, purchasing additional water rights, and formalizing existing verbal water agreements. Knowledge of crop consumptive water use is necessary to design storage, perform economic analyses of proposed construction and purchases, inventory irrigation depletions for water administration, and perform water accounting for interstate compacts.

Estimating Evapotranspiration

Consumptive crop water use or evapotranspiration (ET) is the amount of water evaporated and transpired. Both evaporation and transpiration involve the phase change of liquid water to vapor at an interface. This phase change requires available water, an energy source, a vapor pressure gradient, and a mechanism to maintain that gradient, commonly the wind. Thus, solar radiation, air temperature, humidity, and wind are the major climate factors that affect ET. Evapotranspiration is further affected by soil and plant properties that determine the ease of movement of water through the system. Since long-term lysimeter measurement of ET is not practical or cost-effective, most management decisions are based on ET estimates from climatic data.

The usual approach to estimating ET of irrigated crops is to determine reference ET based on climatic data from some local source and then adjust this reference ET value to the specific irrigated crop of interest by applying a crop coefficient. Reference ET is calculated for a grass or alfalfa reference crop of a defined reference height, under conditions of sufficient water. This reference ET represents the meteorological demand under a defined set of cropping conditions. It is then multiplied by an experimentally derived crop coefficient (K_c), which represents the characteristics of the specific crop of interest and its growth stage, to obtain actual crop ET (Jensen et al., 1990).

Reference ET is calculated by a variety of techniques, including energy balance, mass transfer, combination, and empirical equations. Energy balance methods require determination of measurable inputs and sinks of energy available for phase change to compute the residual energy used for evapotranspiration. Mass transfer methods evaluate turbulent transport of water vapor away from the leaf surface as a function of wind speed.

Penman combination methods partition energy between that used in phase change (the radiation component) and that used in turbulent transfer of water vapor away from the plant canopy (the aerodynamic component). The Penman equation includes all variables that affect energy exchange and the corresponding latent heat flux from vegetation (Allen, 1986). Measurements of temperature, radiation, wind speed, and in later equations, humidity are required. Penman was initially developed for evaporation from an open water surface, and was subsequently modified for plant canopies, estimating potential evaporation from a grass reference surface (Allen, 1986). Refinements of the procedure include the FAO-24 Penman grass reference (Doorenbos and Pruitt, 1984), Kimberly-Penman alfalfa reference (Wright, 1982; Wright, 1996), and Penman-Monteith grass reference (Allen, 1986). A further modification, the ASCE Penman–Monteith equation for grass and alfalfa references (Allen et al., 1989), was found to predict reference ET more accurately and consistently at both humid and arid sites on a daily or monthly basis than seven other combination equations (Jensen et al., 1990). The FAO-56 Penman-Monteith grass reference (Allen et al., 1998) and Standardized ASCE Penman-Monteith for grass and alfalfa references (Walter et al., 2000) provide simplified alternative equations using a standardized hypothetical reference crop.

The ASCE Penman-Monteith combination equation and its later modifications are accepted as the standard for estimating crop water use when reliable data are available (George et al., 2002; Allen et al., 1998). However, Penman methods require specific meteorological inputs that may be of poor quality, lacking, or too costly or time consuming to acquire. Allen (1996) and Allen et al. (1998) discussed methods to assess weather data integrity. Missing wind, humidity, or radiation data needed for Penman calculations can be estimated by substituting data from nearby areas or by producing estimates with locally validated algorithms. Alternatively, empirical equations that require fewer variables can be used.

The comparative reliability of using data estimates within the framework of a combination approach versus using simpler empirical methods with limited data inputs has been evaluated in a variety of environments. For 10-day or monthly ET estimates, Allen et al. (1998) recommend applying the FAO-56 Penman-Monteith equation regardless of data availability (the minimum data requirement for the FAO-56 Penman-Monteith is measured maximum and minimum temperature). They suggest estimating or importing missing weather data from nearby locations after evaluating the validity of nearby data. They caution that imported radiation, wind, and humidity data must be from a nearby weather station that is affected by the same air mass and has negligible differences in relief, elevation, and exposure. Imported radiation data must be adjusted for differences in latitude and should only be used for estimating monthly reference ET. Daily reference estimates should only be used from data averaged over periods of a week or longer. Allen (1995) found that direct substitution of solar radiation (R_S) from the nearest station within 300 km resulted in better estimates of R_S than were obtained using the Hargreaves temperature-difference algorithm for estimating R_S.

Algorithms for replacing missing inputs by estimating radiation, wind, and humidity are provided in the FAO-56 publication (Allen et al., 1998). Allen et al. (1996) found that for 5 to 30-day time steps, the FAO-56 Penman-Monteith with estimated radiation, humidity, and wind values provided relatively good estimates of reference ET. At ten sites across the USA and Canada, Campbell Scientific (Christiansen & Worlton,

1998) compared FAO-56 Penman-Monteith reference values from estimated wind and relative humidity to those with all variables measured. Over an entire growing season, values with estimated data were within 5% of values from measured data for well watered sites.

Empirical methods requiring fewer meteorological variables are a common alternative approach to calculate reference ET. These methods are typically based on the observed relationship between ET and actual values for either radiation or air temperature. Radiation methods include Jensen-Haise (Jensen and Haise, 1963), FAO-24 Radiation (Doorenbos and Pruitt, 1984), and Priestly-Taylor (Jensen et al., 1990). Latent heat flux is predicted with equations that ignore aerodynamic and advection effects, and employ net radiation (R_n) or R_s and air temperature as the sole input variables.

Radiation methods have been found to be effective in humid climates where radiation supplies most of the energy for evaporation. In arid climates, where advection of sensible heat from dry to irrigated areas is an important energy source, radiation methods underestimate evapotranspiration by as much as 40% (Smith et al., 1996; Jensen et al, 1990). In high-altitude wet meadows, Grable et al. (1965) noted that ratios of R_n and global radiation (R_s measured at the earth's surface) to lysimeter evapotranspiration were not constant and provided inconsistent estimates of ET. Radiation instruments are relatively expensive to purchase and maintain. Measurements may be subject to calibration problems and should be validated by calculation methods (Allen, 1996).

Temperature methods include Thornthwaite (Jensen et al., 1990), original Blaney-Criddle (Blaney and Criddle, 1962), SCS-modified Blaney-Criddle (USDA, 1970), FAO-24 Blaney-Criddle (Doorenbos and Pruitt, 1984), and Hargreaves (Hargreaves and

Samani, 1985). Evapotranspiration is predicted from air temperature observations alone, based on the presumption that both ET and temperature are well correlated with radiation.

Temperature methods use mean daily temperature (usually defined as the average of maximum and minimum daily temperature) as an index to the amount of energy available for ET, through the mutual correlation of both air temperature and ET with radiation (Jensen et al., 1990). R_n is partitioned among air temperature, soil temperature, and latent heat flux. Thus, although both air temperature and ET vary with R_n, air temperature itself is not a measure of the energy available to drive evaporation (Pelton et al., 1960).

Several weaknesses are inherent in temperature methods. Various geographic and meteorological conditions cause temperature and ET to lag radiation on a daily basis, so temperature methods are better suited to monthly, seasonal, and annual estimates. Pelton et al. (1960) and Pruitt (1964) discuss the lag problem as it applies to Thornthwaite and original Blaney-Criddle. The SCS-modified Blaney Criddle was developed to address the problem of lag and allow shorter term estimates to be made; however, ASCE (1990) ascribes lag problems to SCS-modified Blaney-Criddle as well. To address possible errors due to lag, the Hargreaves temperature method (Hargreaves and Samani, 1985) incorporates average daily temperature range (maximum minus minimum temperature) to improve radiation estimation.

At higher altitudes, average daily temperatures are lower than those observed at lower altitudes where the atmospheric radiation window is less transparent. These lower average daily temperatures occur even though daily solar radiation values are relatively high. Because R_s is the primary source of energy for evaporation and transpiration, consumptive water use can occur at relatively high rates even though average daily temperatures are relatively low. This fact may be reflected in the underestimation of ET by temperature at higher elevations. Doorenbos and Pruitt (1984) state that the FAO-24 Blaney-Criddle should be used 'with skepticism' at high altitudes, and suggest the application of a 10% per 1000 m above sea level elevation correction to the estimated value. Pochop et al. (1984) suggest a different elevation correction to apply to SCS-modified Blaney-Criddle (discussed below). The ASCE (1990) comparison of estimation methods also demonstrates underestimation by SCS-modified Blaney-Criddle in arid high-altitude locations and attributes it to poor correlation between mean daily temperature and radiation. It is reasonable to assume that the original Blaney-Criddle underestimates at high altitudes for the same reasons.

FAO-24 (Doorenbos and Pruitt, 1984) suggests using temperature methods with caution under conditions where temperature and radiation are poorly correlated. Examples of this condition include climates where temperatures are constant but other weather variables are subject to significant variation, where temperature variation is associated with factors other than radiation, and at high altitudes where radiation is high but mean temperatures are low. Nonetheless, equations that require only temperature are widely used for estimating evapotranspiration because temperature observations are either readily available from local weather stations or can be easily obtained using inexpensive instrumentation.

Despite the above-noted limitations, many western water managers and decision support systems rely on empirical temperature methods by virtue of their inexpensive data acquisition requirements and ease of calculation. Studies support the use of empirical equations rather than substitution or estimation of variables in certain situations. Jensen et al. (1990) noted that the reliability of a combination equation might decrease if many variables were estimated. An empirical method using fewer variables is recommended over the ASCE Penman-Monteith in situations when weather station reliability is in doubt, missing data must be estimated (Jensen et al. 1997; Droogers and Allen, 2002), or available weather data is not from a large, well-watered site (Hargreaves and Allen, 2003). Hargreaves and Allen (2003) report a study by Allen (1995) using mean annual monthly data from the 3,000-station FAO Climwat worldwide database that compared an empirical equation (Hargreaves); an equation with estimated wind, relative humidity, and R_s ('reduced-set' FAO-56 Penman-Monteith); and FAO-56 Penman-Monteith with measured data ('full' FAO-56 Penman-Monteith). Allen (1995b) found that the Hargreaves equation and the 'reduced set' FAO-56 Penman-Monteith reproduced the 'full' FAO-56 Penman-Monteith reference ET estimates equally well.

In summary, in limited-data situations, Hargreaves and Allen (2003) state that the choice of method should depend on site characteristics, quality of available weather data, cost considerations, and required simplicity of calculation. FAO-56 (Allen et al., 1998) recommends importing or estimating inputs to FAO-56 Penman-Monteith using algorithms presented in that publication. Alternatively, FAO-56 supports using the Hargreaves empirical equation requiring only measured maximum and minimum temperature to estimate ET. Hargreaves and Allen (2003) recommend using either the FAO-56 Penman-Monteith with estimated data or the Hargreaves empirical method in most data-short cases.

Blaney-Criddle Temperature Methods

The Blaney-Criddle equation (Blaney and Criddle, 1950, 1962) is an empirical temperature method that requires only measured maximum and minimum daily temperatures. It is commonly chosen for agricultural water use planning. The original Blaney-Criddle estimates crop consumptive water use over seasons and monthly periods based on mean monthly temperature, monthly percentage of yearly daylight hours, and a crop-specific consumptive use coefficient, *K* (seasonal) or *k* (monthly). Percent daylight hours and generalized seasonal crop coefficients for humid and arid climates are available from published tables (USDA, 1970). Blaney-Criddle differs from reference ET methods in that it calculates crop ET directly, without using a reference ET.

The original Blaney-Criddle seasonal crop coefficients (*K*) were reasonably reproducible by multiple investigators, but monthly or shorter coefficients (*k*) showed more variability among geographic locations. The *k* coefficient was intended to represent crop growth stage only, but later research showed that it is affected by climate factors such as temperature, among others (Doorenbos and Pruitt, 1984; ASCE, 1990). To use Blaney-Criddle for shorter-term estimates, various modifications were proposed. The SCS-modified Blaney-Criddle equation (USDA, 1970) partitioned the original monthly crop coefficient, *k*, into a temperature-based climate coefficient, k_t, and an empirical crop-growth stage coefficient, k_c.

The introduction of k_t (a function of average monthly temperature) proved to be problematic for high-altitude environments. In Blaney-Criddle, the mean temperature for the desired period of estimation is used as an indicator of radiation, the primary energy source for ET. At higher altitudes, low night temperatures cause low mean daily temperatures, resulting in low mean temperature values. If crops respond to high daylight radiation levels in spite of the lower mean temperature, consumptive use will be underestimated at higher elevations. Use of the k_t variable in the SCS-modified Blaney-Criddle introduces a second mean temperature term into the equation, exacerbating the underestimation.

In addition, published SCS–modified Blaney-Criddle k_c values were shown to have both a crop and a meteorological component (Jensen, 1966), so the goal of separating crop and temperature effects was not completely achieved. On-site calibration of k and k_c values is recommended. If on-site calibration by lysimeter is not possible, Pochop et al. (1984) suggest an SCS-modified Blaney-Criddle ET adjustment of 10% per 1000 m of elevation difference between the closest off-site lysimeter and the site where ET estimation will occur. A more drastic adjustment of 10% for each 1000 m above sea level was proposed for the FAO-24 Blaney-Criddle equation (Doorenbos and Pruitt, 1984). Although local calibration of k_c values has been shown to improve accuracy in some studies (Borelli and Burman, 1982; Pochop and Burman, 1987; Hill et al., 1989), the original form of the Blaney-Criddle formula is most often used to estimate consumptive water use in irrigated mountain meadows.

The original Blaney-Criddle equation, when used with locally-calibrated k values, gives ET estimates that compare favorably to other methods and to measured values from high-altitude mountain meadows of the western US (Burman, Rechard, and Munari, 1975). A limited number of investigations used lysimeters to locally calibrate Blaney-Criddle k coefficients in the mountain west. Summarizing lysimeter data from five previous mountain meadow studies in Colorado, Walter et al. (1990) derived monthly

May through September k values for irrigated mountain meadows of 1.18, 1.40, 1.22, 0.81, and 0.75. Those k values were used to compare Blaney-Criddle ET estimates to measured ET values at two locations in South Park, Colorado. Pochop and Burman (1987) measured ET for three years at eight mountain meadow sites in the Upper Green River basin of Wyoming, at an average 7500 ft elevation. Both original (k) and SCS-modified (k_c) Blaney-Criddle coefficients were calibrated. May through September k values were 0.92, 1.17, 1.10, 1.00, and 0.79. At Gunnison, Colorado (8000 ft), and in South Park, Colorado (9000 ft), for three site-years each, Kruse and Haise (1974) measured ET by lysimeter and calibrated the original Blaney-Criddle and two other empirical equations. Average monthly Blaney-Criddle k values for mountain meadows for May through August were determined to be 1.124, 1.129, 0.971, 0.818, and 0.929. Burman, Rechard, and Munari (1975) synthesized results from several previous studies and determined that a calibrated Blaney-Criddle k performed better in mountain meadows than an SCS-modified Blaney-Criddle k_c. They recommended Blaney-Criddle k coefficients for mountain meadows for May through September of 1.22, 1.03, 0.90, 0.75, and 0.72. Pollara (1991) measured ET for four years at two mountain meadow sites in Grand County, Colorado and derived calibrated k values for May through September of 1.05, 1.08, 1.17, 0.83, and 0.98. In the absence of lysimeters, a physically-based equation such as a form of Penman can be used to calibrate Blaney-Criddle coefficients (Hill, 1994). However, this method is problematic, since Blaney Criddle gives a crop ET value, and Penman returns a reference ET value. In each of the studies mentioned, calibrated coefficients were observed to vary both across sites and across years, and so were not applicable to other locations.

While calibration is intended to correct for variation among crops and between basins, smaller-scale variability occurs as well. The topography associated with mountain valleys results in varying microclimates over relatively short distances. Previous studies (Kruse and Haise, 1974; Pochop and Burman, 1987; Hill et al., 1989; Pollara, 1991) indicate significant variability in calibration factors among years at the same site and across sites. To fully characterize the variability of water use in the upper Gunnison River basin, the current study measured evapotranspiration at multiple sites in the main and tributary valleys. These data were used to clarify the applicability of a basin-wide correction factor.

Hargreaves Temperature Method

An alternative temperature-based method of estimating ET called the Hargreaves method has received increased attention in recent literature on ET methodology. The original form of the Hargreaves equation for calculating reference ET was developed based on lysimeter data generated over 8 years in Davis, CA, and required inputs of R_s and average daily temperature (measured as the mean of the minimum and maximum observed temperature). The difficulty in obtaining estimates of R_s on a routine basis prompted further refinements in the method that resulted in its final version, generally referred to as the 1985 Hargreaves equation (Hargreaves and Samani, 1985). This form of the equation used the novel approach of estimating R_s using the difference in average daily maximum and minimum temperatures, which estimates the magnitude of peak R_s for a given period, and calculated extraterrestrial radiation (R_a , based on variation in latitude), which accounts for variation in day length. The final equation is as follows:

$$ET = 0.0023R_a(T_{diff})^{0.5}(T_{mean} + 17.8) \quad [2.1]$$

where: ET = grass reference ET (mm da^{-1})

R_a = extraterrestrial irradiance expressed in evaporative equivalents,

T_{diff} = difference in maximum and minimum daily temperature (°C),

T_{mean} = average of maximum and minimum daily temperature (°C).

This final form of the equation is actually a temperature-based method. However, it is frequently referred to as a radiation method because the original form was developed as a radiation method and subsequent derivations were the result of attempts to find alternative expressions of radiation. The best evidence supporting use of the 1985 Hargreaves method is found in a recently published review of previous findings. Hargreaves and Allen (2003) compared this method with accepted combination methods using extensive lysimeter-based data sets from around the western US. The authors concluded that the 1985 Hargreaves method produced estimates of reference ET for periods of five days or more that compared closely to those from the FAO Penman-Monteith method, which is accepted world-wide as the most accurate method of estimating consumptive water use by irrigated crops.

CHAPTER 3:

USE OF ALTERNATIVE TEMPERATURE EXPRESSIONS WITH BLANEY-CRIDDLE

Introduction

High altitude mountain basins are primary sources of water for agricultural, municipal, and recreational uses. Because irrigation water use accounts for most of the water depletions in these basins, knowledge of consumptive water use by mountain meadows is essential for water resources planning and management. The choice of an ET estimation method is based on the required timeframe, available meteorological data, and the time and resources to acquire meteorological data. Although best estimates would be obtained by daily or hourly measurements of all four critical meteorological variables, that degree of detail may not be needed or financially feasible. High-elevation ET predictions are typically obtained using temperature-based methods such as the original and SCS-modified Blaney-Criddle methods (Blaney and Criddle, 1962; USDA, 1970). The original Blaney-Criddle method (Blaney-Criddle) consists of a consumptive use factor, *f*, which is based on mean monthly temperature and day length, and experimentally derived crop consumptive use coefficients, *k*. Most estimation methods predict reference ET, the ET of a standardized reference crop (clipped grass or alfalfa). That reference ET is then adjusted by means of a crop-specific coefficient to predict ET for a given crop. Blaney-Criddle, however, returns ET of a specific crop without an intermediate reference ET step.

An advantage of Blaney-Criddle estimates is that temperature measurements are inexpensively and reliably obtained with simple instrumentation. Temperature methods predict ET based on the presumption that both ET and temperature are well-correlated with radiation. Surface net radiation (R_n) is partitioned among air temperature, soil temperature, and latent heat flux in proportions that depend upon local meteorological conditions. Thus, although air temperature is not a measure of the energy available to drive ET, temperature may be used as an index to the amount of energy available for ET (Pelton et al., 1960). The accuracy of temperature methods depends on the strength of the correlation of temperature and ET to radiation. Various geographic and meteorological conditions cause temperature and ET to lag radiation on a daily basis. Without correction, temperature methods are better suited to monthly, seasonal, and annual estimates.

To improve short-term estimation accuracy, several modifications of Blaney-Criddle were proposed. The SCS-modified Blaney-Criddle equation (SCS-modified Blaney-Criddle) partitioned the original monthly consumptive use coefficient, k, into a temperature-based climate coefficient, k_t, and an empirical crop-growth stage coefficient, k_c, in an attempt to separate meteorological effects from crop consumptive use effects. However, k_c retained a meteorological component, indicating that day length did not adequately compensate for radiation changes (Jensen et al., 1990).

Local calibration is often necessary to improve prediction accuracy of empirical methods. Several investigators have used lysimeters to obtain measured values from high-altitude mountain meadows of the western US in order to locally calibrate Blaney-Criddle original k and/or SCS-modified Blaney-Criddle k_c coefficients for higher elevations. Examples of studies that calibrated k include Walter et al. (1990), South Park, CO; Kruse and Haise (1974) at Gunnison and South Park, CO; and Carlson et al. (1991), Grand County, CO. Pochop and Burman (1987), upper Green River basin, WY, calibrated both *k* and k_c. Burman, Rechard, and Munari (1975) averaged Blaney-Criddle *k* values from three previous studies in Colorado (Kruse and Haise, 1974); Winnemucca, NV; and Laramie, WY. In each of those studies, the accuracy of estimated ET values was dependent on the range of lysimeter CU from which the averaged *k* or k_c values were calculated. If lysimeter CU measurements vary widely across years or across sites, relatively large errors in may result in extreme years.

For most months of the irrigation season, the Blaney-Criddle *f* factor is lower than actual consumptive use by high-altitude meadows because of low mean daily temperatures (Pochop et al., 1984). The atmospheric window is more transparent at higher altitudes, resulting in colder nighttime temperatures. Consequently, lower average daily temperatures occur even though daily solar radiation (R_S) values are relatively high. Because R_S is the primary source of energy for evaporation and transpiration, consumptive water use can occur at relatively high rates even though average daily temperatures are relatively low. This poor correlation between temperature and radiation at higher elevations may result in the underestimation of ET by temperature.

Altitude adjustment factors were proposed to correct for Blaney-Criddle ET underestimation at high elevations. Doorenbos and Pruitt (1984) suggested the application of a 10% per 1000 m elevation above sea level upward adjustment to the computed value when using the FAO-24 modification of Blaney-Criddle. If on-site calibration by lysimeter were not possible, Pochop et al. (1984) suggested an SCS-modified Blaney-Criddle ET adjustment of 10% per thousand meters of elevation difference between the closest off-site lysimeter and the site where ET estimation was to occur. These corrections have been used with limited success.

Blaney-Criddle uses a form of mean daily temperature as temperature expression, *t*, in the consumptive use factor, *f*. Mean monthly temperature is defined as the monthly average of the daily mean of maximum and minimum temperatures. A Blaney-Criddle temperature expression that avoids the use of night minimum temperature might provide a temperature value more representative of energy available to drive ET, and thus more accurately predict ET. We evaluated three variations of the Blaney-Criddle temperature expression. A different temperature-based approach, Hargreaves (Hargreaves and Samani, 1985), uses both average daily temperature and the difference in maximum and minimum temperature to estimate ET.

The semi-arid environment of Colorado's upper Gunnison River basin provided an opportunity to evaluate temperature-based prediction methods in high altitude irrigated meadows during the growing season. Our objective was to develop and test three modifications of the Blaney-Criddle temperature expression against two existing temperature methods (Blaney-Criddle with original temperature expression, and Hargreaves). We conducted lysimeter studies over five consecutive years, 1999 to 2003, at nine different sites within the upper Gunnison River basin, to verify ET estimates.

Methods and Materials

Study Location

Irrigated hay meadows within the Gunnison River basin occur on level or gently sloping floodplains as well as on terraces above the modern stream level. Unirrigated rolling hills at mid-elevations serve as rangeland. Higher elevations are increasingly forested. The nine sites selected for this study were representative of irrigated meadows throughout the upper Gunnison River basin and included sites on the main stem of the Gunnison and its tributaries, the Slate River, East River, Ohio Creek, Tomichi Creek, and Quartz Creek (Fig. 3.1). Descriptions and designations for the selected lysimeter sites are presented in Table 3.1.

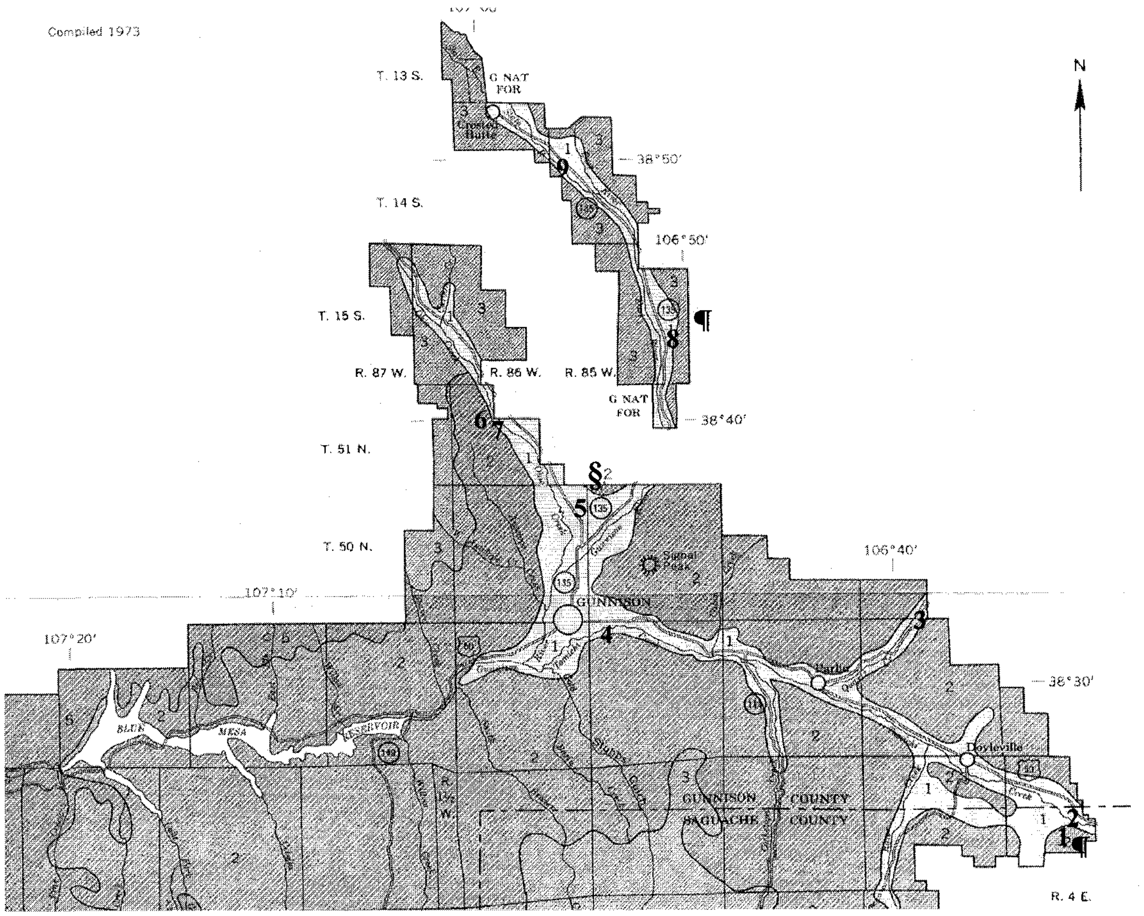

Figure 3.1. Locations of lysimeter sites and weather instrumentation, upper Gunnison River basin, CO. Site numbers correspond to numbering on Table. 3.1. All sites have weather instrumentation included continuously recording temperature logger and rain gauge.

§ Weather instrumentation included fully automated weather station.
¶ Weather instrumentation included Li-Cor pyranometer.

Table 3.1. Descriptions and designations for lysimeter sites.

Site designation #	Site No. †	Elev.	Latitude / Longitude	Soil series/ symbol††	Soil description
		-m (ft)--	--degrees--		org. matter depth / surface texture / subsoil texture / drainage
Upper Tomichi Creek Bottom ‡	1	2472 (8110)	38.436 106.562	Big Blue BbB	10 cm / calcareous loam / clay loam/poorly drained
Upper Tomichi Creek Upland ‡¶	2	2480 (8135)	38.426 106.565	Curecanti CuB	8 cm / loam cobbly sandy cl. loam / cobbly loam / well drained
Quartz Creek Bottom ‡	3	2542 (8340)	38.544 106.646	Irim IrB	10 cm / loam / gravelly loam / poorly drained
Lower Tomichi Creek Bottom ‡	4	2370 (7775)	38.529 106.824	Irim IrA	10 cm / loam / gravelly loam / poorly drained
Gunnison River Upland North and South ‡§	5	2408 (7900)	38.619 (N) 38.618 (S) 106.894 (N,S)	Fola FoB	8 cm / sandy loam / cobbly sandy loam / well drained
Ohio Creek Upland ‡	6	2518 (8260)	38.675 106.997	Evanston EvB	8 cm / clay loam / calcareous loam / well drained
Ohio Creek Bottom ‡	7	2472 (8110)	38.676 106.979	Irim IrA	8 cm / clay loam / cobbly clay loam / well drained
East River Upland ‡¶	8	2539 (8330)	38.740 106.850	Evanston EvB	8-10 cm /loam / sandy cobbly loam / well drained
Slate River Upland ‡	9	2649 (8690)	38.820 106.915	Fola FoB	10 cm / cobbly sandy loam / v. cobbly sandy loam / well drained

† Site numbers correspond to numbering on Fig. 3.1
‡ Weather instrumentation included continuously recording temperature logger and rain gauge
§ Weather instrumentation included automated full weather station
¶ Weather instrumentation included Li-Cor pyranometer
# "Bottom" sites are at river level and have shallow water tables (surface to 1 m) much of the year. "Upland" sites are situated on terraces above river level and have water tables that vary widely.
†† General Soil Map, Gunnison Area, Colorado (USDA, 1975)

Long-term weather measurements were obtained from four weather stations in the basin: Gunnison, 2341 m (7680 ft); Cochetopa Creek, 2438 m (8000 ft); Sargents, 2582 m (8470 ft,) and Crested Butte, 2707 m (8880 ft). Average annual precipitation in the basin increased with elevation, ranging from 254 to 584 mm (10 to 23 in). At Gunnison, mean air temperature for May was 9.9°C (20.2 maximum / -0.3°C minimum); June was 14.4°C (25.6 / 3.2°C); July was 17.6°C (28.2 / 6.9°C); Aug was 16.5°C (27.0 / 6.0°C), and September was 12.4 (23.6 / 1.2°C). Crested Butte mean monthly temperatures were typically 2°C lower than Gunnison temperatures (Western Regional Climate Center, 2005).

Irrigated native and improved meadows occupy about 26,325 ha or 263 km^2 of the valley floor in the upper Gunnison River basin (Kathleen (Klein) Curry, Upper Gunnison River Water Conservancy District, personal communication, 1999), supporting the area's primary agricultural product, cattle. Grass hay and minor amounts of alfalfa hay are the sole crops in this basin, due to the short growing season, rocky soils, and thick organic peat layers present at the soil surface. Meadow soils formed in cobbly alluvium deposited on floodplains, terraces, and alluvial fans, and soil types range from sandy loams and loams to clay loams and clays of the Evanston-Gas Creek–Irim association (USDA, 1975). These soils are deep, with rooting depths below 1.5 m, are often very cobbly or gravelly, and tend to develop 5 to 10 cm thick overlying organic mats. Water available for crops depends on soil type and location relative to the river. Meadows at river level (referred to as "Bottom" sites in Table 3.1) typically have shallow water tables (surface to 1 m) much of the year and are poorly drained. Their soils are Irim loamy skeletal, mixed, frigid Typic Haplaquolls and Big Blue fine, montmorillonitic, calcareous, frigid Typic Haplaquolls. Other meadows situated on terraces above modern river level (referred to as "Upland" sites) are well-drained and have water tables that vary widely with season and require irrigation for summer maintenance. Their soils are Evanston fine-loamy, mixed Aridic Argiborolls, Curecanti loamy-skeletal, mixed Aridic Argiborolls, and Fola loamy-skeletal, mixed Borollic Camborthids.

Lysimeter Installation

One or two compensating lysimeters were installed at each irrigated meadow site with an advection buffer area of established meadow at least 60 m in diameter as recommended (Aboukhaled et al., 1982). A schematic diagram of lysimeter construction is provided in Fig. 3.2. The steel tank, 1 m^2 by 76 cm deep, was placed and leveled in an excavated hole and filled successively with a 10 cm layer of gravel, the excavated soil

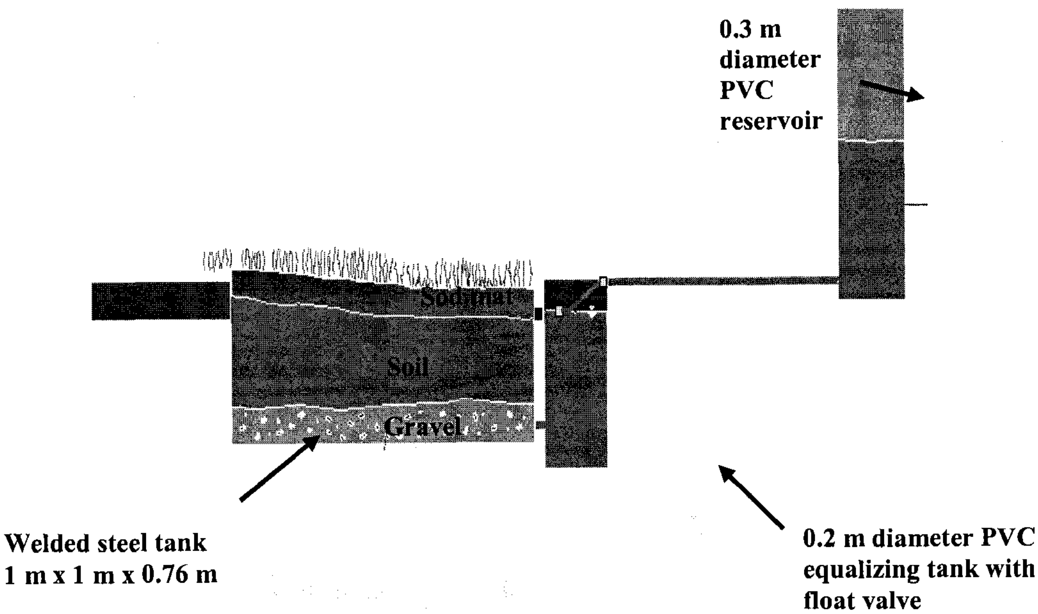

Fig 3.2 Schematic of compensating lysimeters.
After Kruse and Haise, 1974.

layers, and the original 0.15 m sod layer. The lysimeter lip rose approximately 8 cm above the sod surface to prevent encroachment of irrigation water from the surrounding field and to prevent any precipitation runoff. Adjacent to the lysimeter, a 20 cm diameter by 76 cm deep PVC equalizing tank with a float valve was installed to supply water to the base of the lysimeter. The adjustable float height controlled lysimeter water level. The float tank was replenished by gravity feed from a 30 cm diameter, 1.5 m deep PVC reservoir. Water level change in this reservoir corresponded to water removed from lysimeter by evapotranspiration. Prior to replacing soil, a 5 cm diameter PVC access tube was placed in one corner of each lysimeter to allow monitoring of the lysimeter water table. A similar 5 cm diameter observation well was placed in the meadow one meter from each lysimeter to observe the field water table at depths allowed by soil profile characteristics (Table 3.1). Four of the nine sites were riverside locations where water tables often remained above maximum rooting depth when unirrigated, and five were on terrace sites with unirrigated water tables below maximum rooting depth.

Eight sites received lysimeter units at the start of the growing season in 1999; the ninth site and two duplicate units were installed between the 1999 and 2000 field seasons. At one site, a lysimeter was discovered to have been installed in a poorly producing section of a meadow. A second unit was placed 300 m south in a more representative portion of the meadow in September 1999 (Table 3.1, Fig. 3.1). Plants resumed growth rapidly in the lysimeters at most sites, which resulted in a mix of vegetation similar to surrounding fields. In late June, 1999, canopy temperatures within the lysimeters were compared with those of surrounding vegetation using an infrared thermometer to test the lysimeters for any potential plant stress caused by inadequate root development. Based on these measurements, we assumed that root systems within the lysimeters were well established within approximately one month of lysimeter installation.

Weather Data Instrumentation

Instrumentation at each site consisted of a radiation-shielded thermistor temperature sensor and continuously recording temperature logger (HOBO® H8 or H8 Pro, Onset Computer Corporation, Bourne, MA) and a non-recording rain gauge [11.1 cm (4 3/8 in) funnel and 1000-ml graduated cylinder]. Rainfall amounts were manually recorded twice weekly. At two sites the data logger also recorded relative humidity from a resistance device. A fully automated weather station was installed at a centrally located site (Fig. 3.1) to record global irradiance (LI200S photoelectric pyranometer, Li-Cor), wind speed (3001-L Wind Sentry anemometer, RM Young), temperature, and relative humidity (CS500-L platinum resistance temperature detector and INTERCAP capacitive relative humidity sensor, Vaisala) with a Campbell CR10X data logger (Campbell Scientific, Logan, UT). The automated weather station operated for portions of each field season from 1999 – 2003. An additional Li-Cor pyranometer was operated at one northern and one southern site (Fig. 3.1) during June through September, 2001 – 2003.

Irrigation and Lysimeter Operation

At the beginning of each season, water was added to the lysimeters, float tanks, and reservoirs, and the lysimeters were allowed to adjust internally until the water table measured in the lysimeter's access tube equaled the float valve depth. Once the equilibration point for a lysimeter was reached, water-use observations were begun. Our goal was to initiate measurements at each site by the time irrigation in the surrounding meadow began. This was usually on May 1; however, the lysimeters at the eight monitoring sites used in 1999 were installed just prior to the growing season, so recorded observations did not begin until June 1, 1999.

Twice-weekly site visits were made to record data and refill the water supply reservoirs. At each visit, volumetric water loss from the lysimeter was determined by recording the drop in water level in the reservoir. Lysimeter water tables were monitored through the access tube to assess proper functioning of the system. Field water table depth and precipitation were recorded, and temperature data were downloaded. Other measures obtained at each site visit included the magnitude of settling of the lysimeter soil; lysimeter vegetation height; the density, height, and approximate composition of field vegetation; and surface soil wetness of lysimeter and field. These observations were used to make adjustments as needed to maintain desired conditions within the lysimeter.

Monitoring continued until at least September 31 each year from 1999 through 2003. However, the level of the water table in these lysimeters was managed differently among sites and among years. Lysimeter water tables were maintained by adjusting float valve heights to mimic surrounding field water profile and location relative to the river. Float valves in the four lysimeters on river-level locations ("Bottom" sites) were set to maintain the water table between approximately 10 and 15 cm below the soil surface prior to the time when irrigation was terminated in the surrounding meadow in preparation for hay harvest. In the remaining lysimeters ("Upland" sites), the water table was maintained between approximately 20 and 30 cm below the soil surface prior to irrigation termination. To simulate surrounding field water conditions, the water table in the lysimeters was lowered to approximately 50 cm within two weeks of the time when irrigation was terminated on surrounding fields during the growing seasons of 1999, 2001, 2002, and 2003. The timing of the change in water table depth for each lysimeter is given in Table 3.2. In 2000, for the entire growing season, the water table depth within the lysimeters was maintained at the levels used during the irrigation season except at the Gunnison River North site where the water table depth was increased as described for the other years. A second reason for lowering the water table depth in lysimeters for at least part of the growing season was to prevent significant changes in species composition caused by continuous flooding. This problem had been referenced in previous mountain meadow studies conducted over several consecutive years with compensating lysimeters.

Vegetation within lysimeters was maintained in a manner designed to mimic the management of the surrounding hay meadow. Lysimeter harvest coincided approximately with field harvest (Table 3.2). Lysimeter vegetation was clipped to a height of 8 cm at approximately the same time that the surrounding field was harvested to maintain water use comparable to field water use. Clippings were retained to determine yield by weight and species composition.

Lysimeter CU

Crop water use (crop ET) comprises crop evapotranspiration and the water retained in plant tissues. The following water budget equation was used:

$$\mathrm{ET} = R + I + D + S \qquad [3.1]$$

where: R = effective rainfall [mm]; I = irrigation requirement [mm]; D = drainage [mm]; *and* S = change in soil water content [mm]. Lysimeter-measured ET (lysimeter CU) for each of the nine sites was determined for a given observation period, typically 3 to 4 days. Irrigation requirement, consisting of the water depleted from the lysimeter reservoir (replacing water either transpired or evaporated from vegetation or soil surfaces in the lysimeter) during an observation period, was determined by multiplying the measured drop in lysimeter reservoir level [mm] by the ratio of lysimeter area to reservoir area. All

Table 3.2. Date that float adjustment in each lysimeter was changed to lower the depth of the water table within the lysimeter, and date of lysimeter harvest.

	Year									
	1999		2000		2001		2002		2003	
Location	lower water table	harvest lysim.	lower water table	harvest lysim.	lower water table	harvest lysim.	lower water table	harvest lysim.	lower water table	harvest lysim.
	month - day									
Upper Tomichi Cr. Bottom	Jul 26	Aug 19	‡	Jul 29	Aug 17	Aug 20	Jul 16	Jul 31	Jul 25	Aug 6
Upper Tomichi Cr.Upland	Jul 26	Aug 13	‡	Jul 25	Aug 17	Aug 20	§	§	Jul 25	Aug 6
Quartz Cr. Bottom	Jul 26	Aug 19	‡	Aug 17	Aug 21	Aug 22	§	§	Aug 8	Sep 3
Lower Tomichi Cr. Bottom	Jul 26	Aug 19	‡	Jul 21	§	§	§	§	Jul 25	Aug 13
Gunnison R. North Upland	Jul 26	Jul 26	Aug 15	Jul 21	Aug 21	Aug 23	§	§	§	§
Gunnison R. South Upland	†	†	‡	Jul 21	Aug 21	Aug 23	Jul 16	Jul 31	Jul 25	Aug 6
Ohio Cr. Upland	Jul 26	Sep 9	‡	Sep 11	Aug 21	Sep 20	§	Jul 31	Jul 25	Sep 5
Ohio Cr. Bottom	Jul 26	Sep 9	‡	Aug 5	Sep 2	Aug 23	Jul 16	Aug 12	Jul 25	Aug 20
East R. Upland	†	†	‡	Aug 27	Sep 7	Sep 10	Aug 6	Aug 19	Aug 8	Sep 3
Slate R. Upland	Aug 13	Sep 10	‡	Sep 2	Sep 7	Sep 20	Aug 6	Aug 26	Aug 25	Sep 8

† Lysimeter not installed until 2000.

‡ Water table was not lowered during the growing season.

§ Lysimeter observations omitted.

precipitation received was considered part of the consumptive use because we assumed that the 8 cm lip on the lysimeters prevented any runoff from even the most extreme precipitation events. In addition, we assumed that small precipitation events resulting only in the wetting of vegetation and soil surfaces contributed to subsequent evapotranspiration and therefore offset atmospheric demand that would otherwise have been met by water coming from the soil system (through either transpiration or soil surface evaporation). There is no drainage from a compensating lysimeter. Change in soil water content was assumed to be nil since a constant water table was maintained. Monthly values were determined by summing the appropriate observation periods.

Although data collection occurred continuously during the entire seasonal observation period for all installed lysimeters during each year of the study, the measurements from certain lysimeter sites and monitoring periods were not used in summarizing the overall results. Results from the Upper Tomichi Creek Upland, Quartz Creek Upland, and Ohio Creek Upland sites during the entire 2002 season were omitted because drought conditions greatly limited irrigation in the meadows surrounding these sites, and the sites lacked an advection buffer. Results from the Lower Tomichi Creek Bottom site during the entire seasons of 2001 and 2002 were not included because of vegetation damage from rodents. A transition in vegetation composition within the lysimeter at the Gunnison River Upland North site became noticeable at the beginning of the 2002 growing season and persisted throughout that and the subsequent growing season (2003). As a result, the lysimeter vegetation was not representative of the surrounding meadow, so the data from both seasons at this site were eliminated. Finally, the Gunnison River Upland North and Ohio Creek Bottom sites showed evidence of an apparent lysimeter malfunction during the first 15 days of May in 2000. Lysimeter CU was exceptionally high (greater than 150% of ET estimated by the Hargreaves equation, described below) for a period of at least two weeks. The May 2000 data from these two sites were not used in summarizing overall results. Individual observations of lysimeter CU for all combinations of sites, periods of observation, and years are reported in Appendix A.

Data Analysis

Blaney-Criddle. Blaney-Criddle predicts ET based on the product of experimentally derived crop growth stage coefficients (k) and a consumptive use factor, f, which is the product of measured mean air temperature and day length. The equation is of the form:

$$u = k\,f \qquad [3.2]$$

where ET [in] is desired:

u = monthly ET [in],

$f = (t\,p)/100$

t = monthly average of daily maximum and minimum air temperatures (T_{avg} [°F]), and

p = monthly percentage of annual daylight hours [%];

where ET [mm] is desired:

u = monthly ET [mm],

$f = [25.4(1.8t + 32)p/100)]$,

t = monthly average of daily maximum and minimum air temperatures (T_{avg} [°C]), and

p = monthly percentage of annual daylight hours [%].

Blaney-Criddle assumes that water use is never reduced by limited water supply.

As previously discussed, mean daily temperature (and thus mean monthly temperature) may be reduced at high elevations by low night temperatures, despite high daily R_s values that produce correspondingly high ET. Prediction equations such as

Blaney-Criddle that rely upon the correlation of mean daily temperature to R_s values may underestimate ET (Jensen et al., 1990).

SCS-modified Blaney-Criddle has the form of equation [3.2], but the original monthly crop coefficient, k, is modified such that $k = k_c\ k_t$, where k_c is an empirical crop-growth stage coefficient and k_t is a temperature-based climate coefficient. Values of k_t are determined using $k_t = 0.0173(1.8\ t[^{\circ}\mathrm{C}]+32) - 0.314$, where t is monthly average of daily maximum and minimum air temperature, for ET in mm. SCS-modified Blaney-Criddle is more commonly used in English units, with u in inches and t in °F, where $k_t = 0.0173t\ [^{\circ}\mathrm{F}] - 0.314$. This modification was intended to improve short-term estimates by increasing sensitivity to meteorological variation (USDA, 1970). However, the change had unintended consequences for high-elevation estimates. Monthly average temperature appears in both the f and k_t terms of SCS-modified Blaney-Criddle. This usage exacerbates the influence of mean daily temperature and of low nighttime temperatures, and is likely the reason that SCS-modified Blaney-Criddle is less frequently used to estimate ET at high elevations. Of the two Blaney-Criddle methods, the original Blaney-Criddle is preferred for high-elevation estimates. For that reason, this paper attempts to improve estimation by modifying the original Blaney Criddle equation for high-elevation ET estimation.

Modifying the Blaney-Criddle temperature expression, *t*. Our overall objective was to determine whether modified expressions of t would more accurately reflect solar radiation and thus provide better estimates of ET. The units for all temperature expressions are °C.

Conventional t: For purposes of this study, the unmodified temperature term is designated as *conventional t*. Daily maximum and minimum temperatures, $T_{max\ 24\ hr}$ and $T_{min\ 24\ hr}$, were drawn from measurements collected at 10-minute intervals.

Conventional t [°C] = monthly average of mean daily air temperature,

$$\left(T_{max\ 24\ hr} + T_{min\ 24\ hr}\right)/2$$

Daylight mean t: The first modification of the temperature expression was intended to eliminate the effect of low night temperatures on the *t* value. To reduce the error that could be introduced by a momentary change in temperatures that coincided with a recorded reading, three 10-minute readings were averaged to determine 30-minute averages. Maximum and minimum temperatures occurring between sunrise and sunset, $T_{max\ daylight}$ and $T_{min\ daylight}$, were determined from those 30-minute average values. If more than ten minutes of a 30-minute-average period occurred during the sunset-to-sunrise interval, that period was not considered for minimum temperature.

Daylight mean t [°C] = monthly average of mean daylight air temperature,

$$\left(T_{max\ daylight} + T_{min\ daylight}\right)/2$$

Daylight weighted mean t: The second modified temperature term was based on the daily average of all 30-minute averaged daylight temperatures, rather than average of the maximum and minimum temperatures. This expression was expected to represent the daytime radiation more accurately, giving more weight to the rapid morning warming and extended mid-day warm period, and de-emphasizing the cold daybreak temperatures.

Daylight weighted mean t [°C] = monthly average of mean daily sunrise-to-sunset temperatures

Daily maximum t: The third modification was intended to determine an upper bound for the t expression increase needed to remedy underestimation.

Daily maximum t [°C] = monthly average of mean daily $T_{max\ 24\ hr}$

Values of each temperature expression were determined for each site and year, for the months of May, June and July using temperatures recorded at each site. During the months of August and September, irrigation was terminated, lysimeter water tables were lowered, fields were hayed, and lysimeter vegetation was clipped. While lysimeter management thus mimicked surrounding fields, greater variation in consumptive use values occurred in both lysimeters and fields. In order to make consistent comparisons across sites, August and September temperature values were omitted from the computations.

Blaney-Criddle monthly consumptive use factor, *f*. For each of the four temperature expressions, the monthly Blaney-Criddle consumptive use factor ($f = t\,\mathrm{p}$) was determined, for the site-year-month combinations just described. Percentage of daylight hours, p, were calculated for a given period by summing the daylight hours (h) in each day of the period and dividing by the daylight hours in a year:

$$h = [(\arccos(-\tan(latitude)\tan(declination))]\,24/\pi\,. \qquad [3.3]$$

Alternatively, SCS TR21 (USDA, 1970) provides a table (Table 1) for the interpolation of p values from latitude.

The resulting f factors were designated $f(conventional\ t)$, $f(daylight\ mean\ t)$, $f(daylight\ weighted\ mean\ t)$, and $f(daily\ maximum\ t)$.

Hargreaves. The 1985 Hargreaves equation (Hargreaves) (Hargreaves and Samani 1985) employs a different temperature based approach, as follows:

$$\begin{aligned} \text{Hargreaves reference ET} &= 0.0023\ R_a\ (T_{diff})^{1/2}\ (T_{mean} + 17.8) \\ \text{Hargreaves ET} &= (\text{Hargreaves reference ET})\ K_c \end{aligned} \qquad [3.4]$$

where reference ET and R_a are in units of water evaporation [mm d^{-1}]; R_a is extraterrestrial irradiance; T_{diff} = difference in maximum and minimum daily temperature [°C]; and T_{mean} = mean daily air temperature [°C]; note that T_{mean} is equivalent to the temperature expression term of Blaney-Criddle (the *conventional t* value as defined in the previous section). K_c is the crop-specific crop coefficient.

The original form of the Hargreaves equation (Hargreaves, 1975) based ET estimates on a regression of global radiation (R_s measured at the earth's surface), and mean daily air temperature. As in Blaney-Criddle, low night temperatures at high elevations produce mean temperatures that would cause Hargreaves to overestimate ET based on measured R_s. However, because of the difficulty in obtaining measurements of R_s on a routine basis, the 1985 Hargreaves equation estimates R_s based on a regression of R_a and T_{diff}. Low night temperatures at altitude increase the temperature difference, and decrease the estimate of R_s. Hargreaves and Samani (1982) suggest that the use of both average temperature and temperature difference may have approximately equal and offsetting effects at high elevations. In this paper, the performance of Hargreaves containing both a mean temperature term and a temperature difference term is compared to the performance of Blaney-Criddle, whose temperature expression contains mean temperature, and to versions of Blaney Criddle with modified mean temperature expressions. Hargreaves reference ET [3.4] was estimated for all site-year-month combinations, using temperatures measured at each site.

Results and Discussion

Consumptive use and weather variable measurements were conducted during five consecutive growing seasons at nine lysimeter sites in the Gunnison River basin. These measurements provided a database for testing whether modifications of the temperature expression, *t*, can improve the predictive accuracy of Blaney-Criddle at higher elevations.

Comparison of Blaney-Criddle temperature expressions, *t*

In order to expect that modifications of *t* will improve estimations of ET, it is important to establish that a modified temperature expression will produce values of *t* that are different from the original *conventional t* expression. Values obtained by original and modified temperature expressions for each month, site, and year are presented in Appendix B2. Descriptive statistics for monthly *t* values averaged across sites and years are presented in Table 3.3.

For all months, the *daylight mean t* (Table 3.3) produced average temperatures less than 1°C different than average temperatures from the *conventional t* expression, since minimum 24-hour temperatures and minimum daylight temperatures ($T_{\text{min-24 hour}}$ and $T_{\text{min daylight}}$) differed only by tenths of a degree (Table 3.4). Temperature measurements taken at each site showed that the coldest temperatures did not occur until just prior to sunrise, so this modification failed to generate temperatures likely to change ET prediction. *Daylight weighted mean t* and *daily maximum t* monthly averages did differ enough from the *conventional t* results to expect differences in resulting calculated ET. Monthly average temperatures obtained from *daylight weighted mean t* were 3 to 4°C higher than the original temperature expression, while means of *daily maximum t*

Table 3.3. Comparison of temperature expressions, *t*. Values were averaged across sites and years, for three months.

Month	Statistical Parameter	*Conventional t*	*Daylight mean t*	*Daylight weighted mean t*	*Daily maximum t*
		--------------------degrees C--------------------			
May	Mean, n=31	8.1	8.4	11.8	17.2
	Standard Deviation	0.9	0.8	0.8	1.1
	Range	3.5	3.4	3.4	5.0
	Minimum / Maximum	6.0 / 9.5	6.3 / 9.7	9.8 / 13.2	14.3 / 19.4
June	Mean, n=41	11.6	11.8	15.7	21.1
	Standard Deviation	1.0	1.0	1.1	1.3
	Sample Variance	0.9	0.9	1.3	1.6
	Range	4.1	4.2	5.0	5.7
	Minimum / Maximum	9.5 / 13.6	9.6 / 13.8	13.3 / 18.3	18.4 / 24.1
July	Mean, n=41	15.3	15.4	18.6	24.7
	Standard Deviation	0.7	0.7	1.0	1.5
	Range	2.7	2.8	4.3	6.3
	Minimum / Maximum	13.8 / 16.5	13.8 / 16.6	16.3 / 20.6	21.4 / 27.7

Table 3.4. Averaged maximum and minimum temperatures determined by two methods.

	Alternative maximum temperatures		Alternative minimum temperatures	
Month	$T_{max\ 24\ hr}$	$T_{max\ daylight}$	$T_{min\ 24\ hr}$	$T_{min\ daylight}$
	--------------------degrees C--------------------			
May	17.4	17.2	-1.2	-0.3
June	21.4	21.1	1.8	2.4
July	25.0	24.7	5.5	6.1

were up to 10 °C higher than the original temperature expression. A statistical *t*-test of the means assuming equal variances found *daylight weighted mean t* and *daily maximum t* means to be significantly different ($p \leq .05$) from *conventional t* for all months. *Daylight weighted mean t* and *daily maximum t* values show a slightly increased range of temperatures over *conventional t*, which indicates that those modifications might describe more variability in meteorological conditions.

A modification that has the potential to produce different estimated values should correlate poorly with the original temperature expression. Correlation coefficients (r) among the four temperature expressions are presented in Table 3.5. *Conventional t* and *daylight mean t* were strongly correlated for all months (r = .99), while *daylight weighted mean t* and *daily maximum t* were less well correlated with *conventional t*, particularly in the months of May and July (r = .62 to .81).

Table 3.5. Correlation of modified temperature expressions with *conventional t*, the original Blaney-Criddle temperature expression.

		Correlation coefficient, r			
Month	Temperature expression	*Conventional t*	*Daylight mean t*	*Daylight weighted mean t*	*Daily maximum t*
May	*Conventional t*	1			
	Daylight mean t	0.99	1		
	Daylight weighted mean t	0.81	0.85	1	
	Daily maximum t	0.75	0.80	0.97	1
June	*Conventional t*	1			
	Daylight mean t	0.99	1		
	Daylight weighted mean t	0.95	0.95	1	
	Daily maximum t	0.92	0.93	0.98	1
July	*Conventional t*	1			
	Daylight mean t	0.99	1		
	Daylight weighted mean t	0.72	0.73	1	
	Daily maximum t	0.62	0.62	0.98	1

These comparisons are illustrated in Fig. 3.3, where *conventional t* values for each month, site, and year are plotted against corresponding values for each of the three modified temperature expressions. For each of the three months, *daylight mean t* was highly correlated with *conventional t*. *Daylight weighted mean t* and *daily maximum t* were less well correlated with *conventional t*, as indicated by the scatter of points, and produced a larger range of average values in June and July (Table 3.3). The differences in intercepts among methods reflected the relative increase in average temperature effected by each successive modification. Slopes of the trend lines of each comparison were similar among months. In June and July, *daylight weighted mean t* and *daily maximum t* plots had slightly higher slopes than *daylight mean t* plots. Minor differences in slope were the result of the increased range of temperature values generated by those two methods.

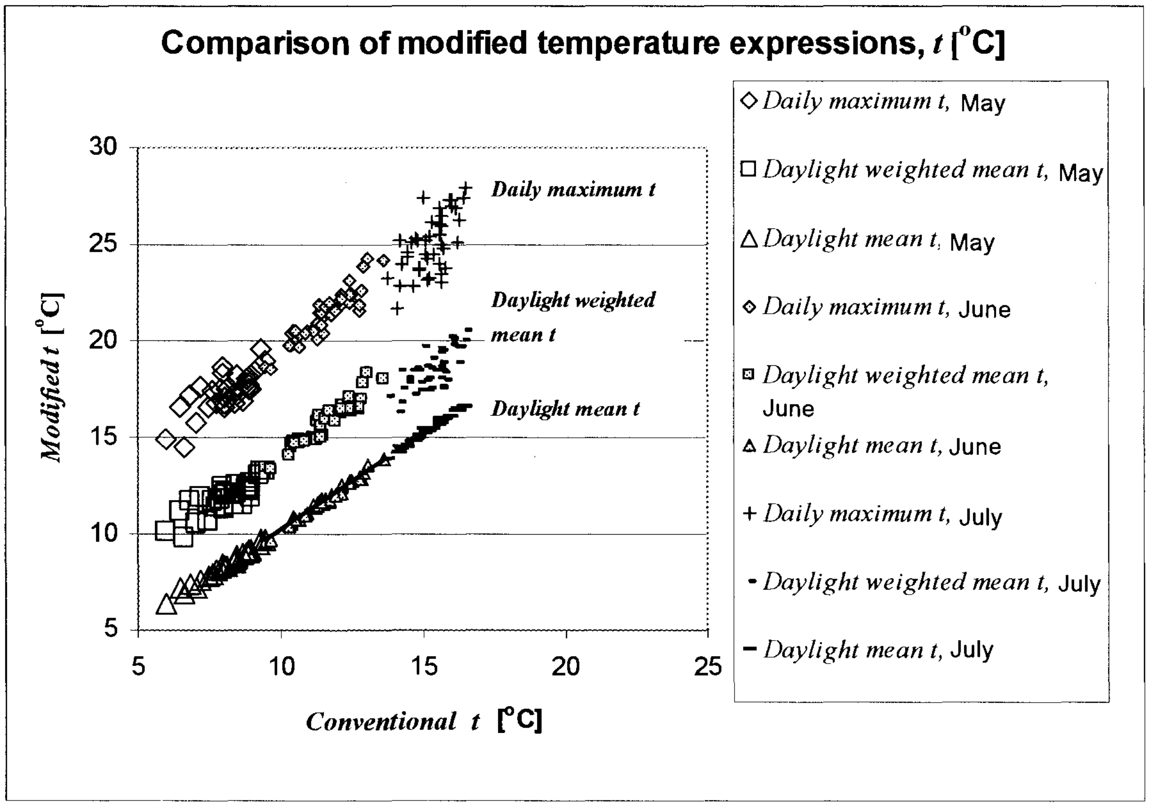

Fig. 3.3. Comparison of modified temperature expressions versus *conventional t*.

Temperature methods predict ET based on the presumption that both ET and temperature are correlated with radiation (R_S). Values of daily R_S from this high-altitude study, measured at three sites for two to five years, are presented in Appendix C. The temperature variable *conventional t* reflects the magnitude of R_S very poorly (Table 3.6). For three sites where radiation was measured over two to five years (Fig 3.1), variation in *conventional t* was not associated with variability in R_S in May and July, and was negatively associated in June. *Daylight mean t* was omitted from this analysis due to its similarity to *conventional t*. *Daylight weighted mean t* and *daily maximum t* correlated with R_S in all three months. This improvement suggests that the use of *daylight weighted mean t* or *daily maximum t* could improve the accuracy of Blaney-Criddle estimates of consumptive water use at altitude.

Table 3.6. Correlation coefficient, *r*, of temperature expressions with daily average R_S measured at three sites from 1999 to 2003.

	Temperature expression		
Month	*Conventional t*	*Daylight weighted mean t*	*Daily maximum t*
May (*n*=29)	0.24	0.50**	0.43*
June (*n*=160)	-0.24**	0.22**	0.18*
July (*n*=314)	0.01	0.52**	0.37**

*, ** significant at the 0.05 and 0.01 probability levels, respectively.

Comparison of Blaney-Criddle monthly consumptive use factors, f, to lysimeter CU

A summary of descriptive statistics for monthly lysimeter CU values averaged across sites and years is presented in Table 3.7. Significant variation in lysimeter CU was observed over sites and years within each month. This variability reflected the diversity of weather conditions in the five years of the study.

Table 3.7. Summary statistics for lysimeter CU. Values were averaged across sites and years.

Statistical parameter	Month May	June	July
	----------mm----------		
Mean	150.6	190.8	174.9
Standard Deviation	28.0	27.7	28.0
Range †	112.7	109.2	124.3
Minimum / Maximum	96.2 / 208.8	135.3 / 244.5	112.6 / 236.9
Number of Observations	31	41	41

† The difference between maximum and minimum observed values.

Blaney-Criddle consumptive use factor values (*f*) were determined using each of the four temperature expressions for each site-year-month combination (Appendix D). The monthly *f* values averaged across sites and years are presented in Table 3.8, along with the averages of the variables from which they were calculated. The differences in temperature expressions created substantial differences among the resulting *f* values, which could affect prediction accuracy. Monthly lysimeter CU averaged across sites and years is shown for comparison. For each of the three months, the small difference between *conventional t* and *daylight mean t* resulted in a small difference between values of *f* from those temperature expressions. The proportion of lysimeter CU estimated by *f* values from *conventional t* and *daylight mean t* was substantially lower than for either of the other temperature expressions in each month as well. The *f* value from *daylight weighted mean t* was larger than that from *conventional t*, and estimated a greater proportion of lysimeter CU than *conventional t* in each month (97% in July). *Daily maximum t* produced the highest values of *f* in each month. In May and July, those high *f* values overestimated lysimeter CU by about 10%, while in June the *daily maximum t* returned the estimate closest to lysimeter CU.

Table 3.8. Monthly calculated variables (f) for estimating ET, based on four temperature expressions and monthly percent of yearly daylight hours, averaged across sites and years for months of May, June and July. Data based on observations from nine lysimeters during 1999 to 2003.

Month	Temperature expression from which f is calculated	t	% of daylight hours, p	f	Lysimeter CU	f as % of lysimeter CU
		[°C]		---------mm---------		
May	*Conventional t*	8.1	9.99	118.2	150.6	78%
	Daylight mean t	8.4	9.99	119.6	150.6	79%
	Daylight weighted mean t	11.8	9.99	135.2	150.6	90%
	Daily maximum t	17.2	9.99	159.7	150.6	106%
June	*Conventional t*	11.6	10.04	134.6	190.8	71%
	Daylight mean t	11.8	10.04	135.6	190.8	71%
	Daylight weighted mean t	15.7	10.04	153.7	190.8	81%
	Daily maximum t	21.1	10.04	178.5	190.8	94%
July	*Conventional t*	15.3	10.19	153.9	174.9	88%
	Daylight mean t	15.4	10.19	154.6	174.9	88%
	Daylight weighted mean t	18.5	10.19	168.9	174.9	97%
	Daily maximum t	24.7	10.19	198.0	174.9	113%

Prediction accuracy is typically evaluated by comparing computed CU to actual CU from lysimeter measurements. In a similar fashion, we compared lysimeter CU to monthly Blaney-Criddle f factors determined using each of the temperature expressions. A typical method-comparison statistical analysis involves descriptive statistics (mean, standard deviation, variance, and ratio of estimated ET to measured CU), as well as standard error of estimate (SEE) and linear regression analysis to evaluate goodness of fit (regression coefficient, b; correlation coefficient, r; and coefficient of determination, r^2). However, in comparing lysimeter CU to Blaney-Criddle f, we omit the unknown crop coefficient k because the crop coefficient is a constant for a given area and month. Therefore, omitting k from computed estimates has no effect on the correlation coefficient, r, or r^2 . However, the omission of k does affect the regression coefficient, b, and it makes the use of SEE incorrect. Thus, when we compared lysimeter CU to the monthly *f*, we assessed not the accuracy of prediction, but the degree of association of lysimeter CU with *f* and thus with the various temperature expressions.

We conducted correlation analyses comparing lysimeter CU with each consumptive use factor to determine the nature of the relationship between each of the different *f* values and lysimeter CU. Correlations were computed separately for each month (May, June, and July) because cropping and management factors vary over the growing season. The summary statistics presented in Table 3.9 include the correlation coefficient (r), coefficient of determination (r^2), and statistical significance of r (p). Graphic illustration of these relationships is provided in Fig. 3.4.

Table 3.9. Summary statistical parameters for determining relationship between monthly lysimeter CU and Blaney-Criddle calculated variable *f* for three months. Data based on observations from nine lysimeters during 1999 to 2003.

		Statistical Parameter		
Month	Consumptive use coefficient	r	r^2	p
May	f(*conventional t*)	0.33	0.11	0.070
(n=31)	f(*daylight mean t*)	0.36*	0.13	0.045
	f(*daylight weighted mean t*)	0.53**	0.28	0.002
	f(*daily maximum t*)	0.54**	0.30	0.001
June	f(*conventional t*)	0.46**	0.21	0.003
(n=41)	f(*daylight mean t*)	0.45**	0.20	0.003
	f(*daylight weighted mean t*)	0.51**	0.26	0.001
	f(*daily maximum t*)	0.45**	0.21	0.003
July	f(*conventional t*)	-0.23	0.05	0.156
(n=41)	f(*daylight mean t*)	-0.23	0.06	0.139
	f(*daylight weighted mean t*)	0.26	0.07	0.107
	f(*daily maximum t*)	0.35*	0.12	0.024

*, ** significant at the 0.05 and 0.01 probability levels, respectively

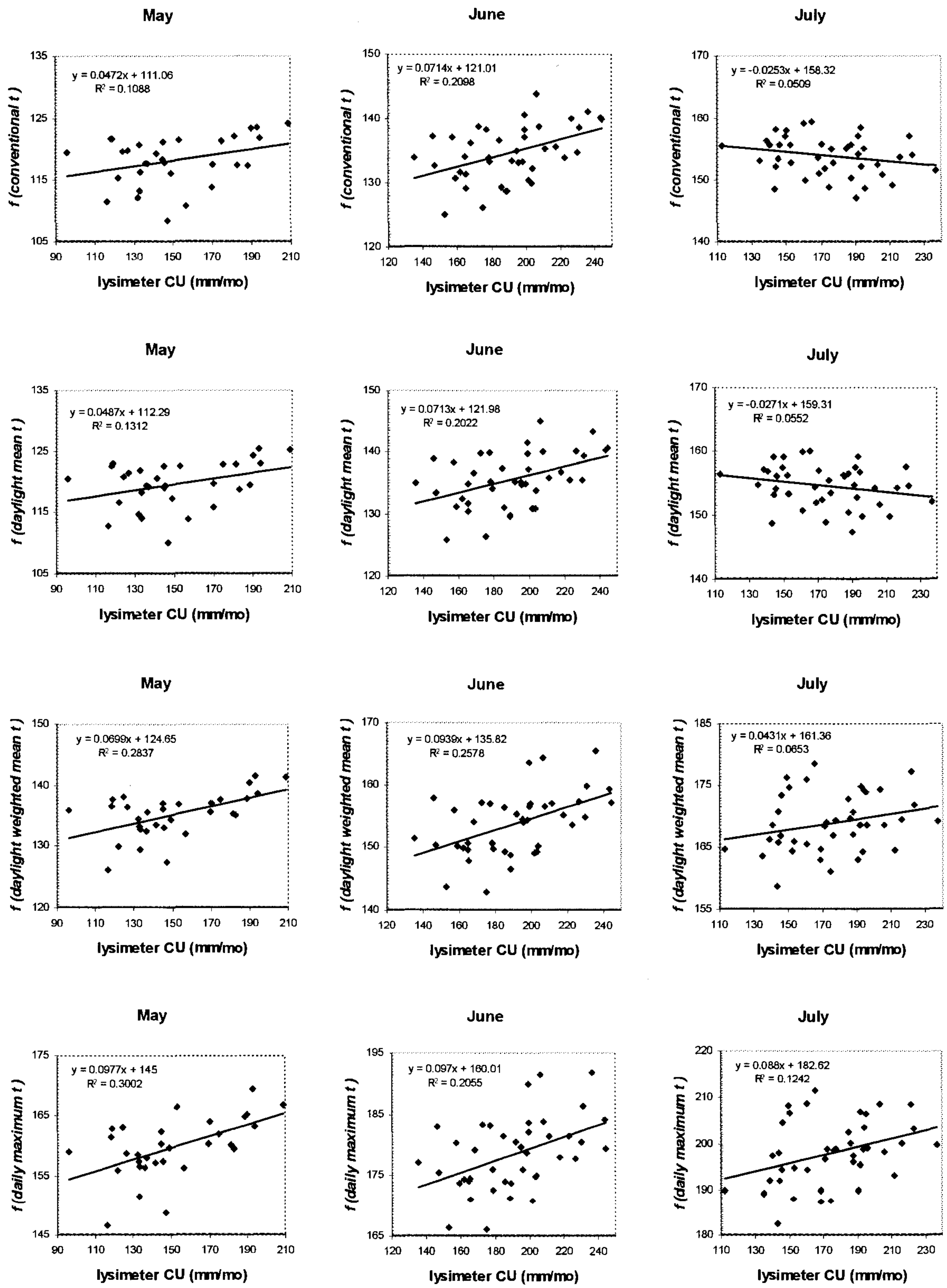

Fig. 3.4. Monthly values of Blaney-Criddle consumptive use factors versus lysimeter consumptive use [mm mo^{-1}].

The *f* values derived from the *conventional t* and *daylight mean t* variables were generally poorly correlated with lysimeter CU in the months of May and July (Table 3.9 and Fig. 3.4). In June, variation in the *f* values from these two variables was more closely associated with variation in actual CU. These results confirm the earlier observations that the *daylight mean t* variable is essentially the same expression of temperature as the *conventional t* variable. In contrast, *f* values from the *daylight weighted mean t* and *daily maximum t* values correlated with actual consumptive use during all three months with one exception. This result was not surprising, since these two alternative temperature variables generally correlated better with R_s than *conventional t* (Table 3.6). The overall significance of these results is that two of the alternative temperature expressions, *daylight weighted mean t* and *daily maximum t*, improve the accuracy of Blaney-Criddle consumptive use estimates under mountain meadow conditions.

The Blaney-Criddle crop growth stage coefficient, *k*, is the ratio of lysimeter CU to the computed *f* factor. For a given site or area and a given temperature function, the *k* value averaged across years expresses the degree to which that temperature function accounts for average ET over the years. A *k* factor closest to 1.00 indicates best performance of the temperature function. Values of *k* were determined for each temperature expression within each site-year-month combination. Monthly k values were then obtained from averages across sites and years (Table 3.10). For all months, the *k* values computed from *daylight weighted mean t* and *daily maximum t* temperature variables were closer to 1.00 than the *k* values computed from the other temperature expressions. This indicated that on an average basis, the former temperature expressions accounted for a greater proportion of total consumptive use than the latter ones. Thus, there is an additional advantage to using the two alternative temperature expressions, *daylight weighted mean t* and *daily maximum t*. Not only do they correlate with variation in measured CU, but they also produce *f* values that, on an average basis, are closer to actual CU.

Table 3.10. Measured monthly lysimeter CU, calculated variables (*f*) for estimating ET, and crop growth stage coefficients (*k*) for months of May, June and July. Data based on observations from 9 lysimeters during 1999 to 2003.

Month	Temperature expression from which *f* is calculated	*f*	lysimeter CU	*k*
		--------mm--------		
May	*Conventional t*	118.2	150.6	1.27
	Daylight mean t	119.6	150.6	1.26
	Daylight weighted mean t	135.2	150.6	1.11
	Daily maximum t	159.7	150.6	0.94
June	*Conventional t*	134.6	190.8	1.42
	Daylight mean t	135.6	190.8	1.41
	Daylight weighted mean t	153.7	190.8	1.24
	Daily maximum t	178.5	190.8	1.07
July	*Conventional t*	153.9	174.8	1.14
	Daylight mean t	154.6	174.8	1.13
	Daylight weighted mean t	168.9	174.8	1.03
	Daily maximum t	198.0	174.8	0.88

For an average *k* to perform well across sites and/or years, and to avoid wide variation in individual *k* values, it is necessary that there be a linear relationship between *f* and CU. Comparing temperature expression characteristics in Table 3.9 to those in Table 3.10, we observe that, for each month, the Table 3.9 *f* factors that have higher correlation coefficients and more significant *p* values correspond to the *f* factors in Table 3.10 that have smaller *k* values (and so predict CU more closely/account better for CU on average). Those *f*'s are *daylight weighted mean t* and *daily maximum t*.

It is instructive to compare *k* values determined in this study to *k* values from previous studies conducted nearby. For the *f* factor using the original Blaney-Criddle temperature expression, *conventional t*, values of k were most similar to those recommended by Walter et al. (1990) for South Park, CO (Table 3.11), but were surprisingly dissimilar to those from previous studies in the upper Gunnison basin (Kruse and Haise, 1974) in June and July. The derivation of methods to account for variability in k values across sites and years is the subject of the second paper from this research (see Chapter 4).

Table 3.11. Blaney-Criddle crop coefficients (k) from three studies in Colorado mountain meadows.

		Kruse and Haise (1974)		Walter et al. (1990)
Month	Current study	Gunnison	South Park	Recommended k values
May	1.27	1.25	1.00	1.18
June	1.42	1.10	1.16	1.40
July	1.14	0.96	0.98	1.22

Reference ET versus crop ET

The Hargreaves reference ET equation [3.4] uses T_{diff}, the difference in maximum and minimum daily temperature, in addition to T_{mean} (previously referred to as *conventional t)* to compute reference ET. Since maximum and minimum temperatures are the only measured inputs required for this equation, it is appropriate to include the Hargreaves method when considering alternative temperature variables to optimize high-altitude ET prediction methods. However, it is important to note that the results obtained from Blaney-Criddle temperature methods and the Hargreaves method are not directly comparable. The Hargreaves equation yields a true reference crop ET estimate, with the reference crop generally defined as clipped, uniform grass. The *f* factor calculated from Blaney-Criddle methods represents a climate-driven consumptive use variable similar in function to reference crop ET; however, the Blaney-Criddle crop coefficient, *k,* involves both crop and climate effects. The product of these two variables when applied to unclipped meadow vegetation returns crop, not reference, ET.

To evaluate ET prediction equations, the typical approach is to calculate reference ET and compare it to lysimeter CU measured from a reference clipped-grass or alfalfa crop. More commonly, reference ET is estimated by a form of the Penman equation rather than directly measuring lysimeter CU. Comparing only reference values removes the effects of crop type on ET. High-altitude studies most often involve use of a non-reference method, usually some form of Blaney-Criddle, and a non reference crop, meadow grass, so other approaches must be considered.

Pochop and Burman (1987) noted that climatic conditions in mountain meadows often limit the growth of alfalfa and reference grasses, so that native grasses may be the only option for lysimeters at higher elevations. Under those circumstances, several researchers opted to ignore the prescribed clipping height. The authors of Manual 70 (Jensen et al., 1990) encountered this problem when gathering data sets of lysimeter measurements from a variety of environments for its comparison study. Estimated values from many equations were compared to ET measurements from clipped reference grasses or alfalfa. However, the study used measurements from lysimeters in South Park, CO that contained unclipped native grasses that grew to heights of 1 m or more. Inputs to the Penman-Monteith equation were adjusted accordingly, but other reference ET equations have no similar adjustment. The crop was nonetheless treated as if it were reference height for purposes of the ASCE study (Jensen et al., 1990). Carlson et al. (1991)

similarly compared reference ET equations to lysimeter measurements from unclipped native grass apparently without making adjustments.

To adapt the typical comparison process in order to compare reference and non-reference methods, the authors of ASCE (1990) Manual 70 converted SCS-modified Blaney-Criddle ET results ($ET = f\, k_c\, k_t$) to a reference value prior to making comparisons with other reference equations. The SCS-modified Blaney-Criddle ET was divided by the crop coefficient for the FAO-24 Blaney-Criddle reference ET equation to obtain a reference value. Hill et al. (1989) took the opposite approach when comparing Blaney-Criddle to a reference equation. Blaney-Criddle crop ET was compared to crop ET derived from a reference ET equation. Using lysimeter CU, Hill et al. (1989) derived a meadow-grass K_c appropriate for the Kimberley Penman reference ET equation by the standard ratio, K_c = (meadow grass lysimeter CU) / (Kimberley Penman reference ET).

Pochop and Burman (1987) recommended using evaporation pan data, or using empirical formulas without local calibration as a reference to which crop coefficients can be applied. We chose the latter method for this study, and compared Hargreaves reference ET to lysimeter CU. To look at the relative effectiveness of estimating with Hargreaves and Blaney-Criddle, we took an indirect approach. We compared the correlation coefficients between Hargreaves reference ET (calculated) and lysimeter CU (measured) to the previously presented correlation coefficients between Blaney-Criddle f values (using the different temperature expressions) and lysimeter CU.

In retrospect, a useful approach for our study would have been to install dual lysimeters at several sites. If one lysimeter of each pair had been planted with a reference crop of grass clipped to reference height, lysimeter CU from that lysimeter could have been compared directly with reference ET from Hargreaves. This could have been a useful test of the magnitude of difference between ET from meadow grass and ET from reference grass, and could have suggested whether Manual 70 (Jensen et al., 1990) and Carlson et al. (1991) were correct in their treatment of meadow grass in their evaluations.

Additionally, comparisons could have been made between Hargreaves reference ET and a form of the Penman equation, using R_s and wind speed data from an onsite weather station. But since R_s and wind measurements were not initiated until mid-June in several years, it was decided that the required estimation of inputs would lower confidence in the validity of the reference value for this comparison.

Compare Hargreaves reference ET to Blaney-Criddle ET estimates

T_{diff} values and uncalibrated (reference, rather than crop) Hargreaves reference ET values (Appendix E) were calculated for individual site-month-year combinations, and were summarized monthly across sites and years (Table 3.12). The monthly ratio of Hargreaves ET to lysimeter CU (estimated expressed as percentage of measured) and its reciprocal, the ratio of CU to ET (Hargreaves crop coefficient, K_c), indicates average prediction accuracy for a given month. By those measures, Hargreaves accuracy is best in the month of July; however the other statistics presented here modify that conclusion. Note in particular that peak measured water use occurred in June, but this trend was not reflected in the Hargreaves estimate. Also, although July Hargreaves ET was 98% of lysimeter CU, the standard deviation and range of monthly Hargreaves reference ET values were lower than the corresponding values of monthly lysimeter CU (Tables 3.8 and 3.12). That result indicates that Hargreaves did not fully account for the observed variation in lysimeter CU, despite the similarity of average lysimeter CU and Hargreaves reference ET values. Monthly plots (Fig. 3.5) also demonstrate the comparative ranges of Hargreaves reference ET values and lysimeter CU values as well.

Table 3.12. Summary of statistical parameters associated with ET predicted by the Hargreaves equation for months of May, June and July, compared to lysimeter CU. Data based on observations from 9 lysimeters during 1999 to 2003.

		Lysimeter CU or Hargreaves ET					
Month	ET method	Mean	Standard deviation	Range†	Min / Max	Harg. ET as % of CU	K_c ‡
		---mm---				--%--	
May	Lysimeter CU	150.6	28.0	112.7	96.2 / 208.8		
(n=31)	Hargreaves ET	128.1	6.2	27.9	113.0 / 141.0	88	1.17
June	Lysimeter CU	190.8	27.7	109.2	135.3 / 244.5		
(n=41)	Hargreaves ET	150.8	7.6	35.6	134.4 / 170.0	80	1.26
July	Lysimeter CU	174.9	28.0	124.3	112.6 / 236.9		
(n=41)	Hargreaves ET	170.8	12.5	47.2	144.5 / 191.8	98	1.02

† The difference between maximum and minimum observed values.
‡ Hargreaves crop coefficient, determined as the ratio of lysimeter CU / Hargreaves reference ET.

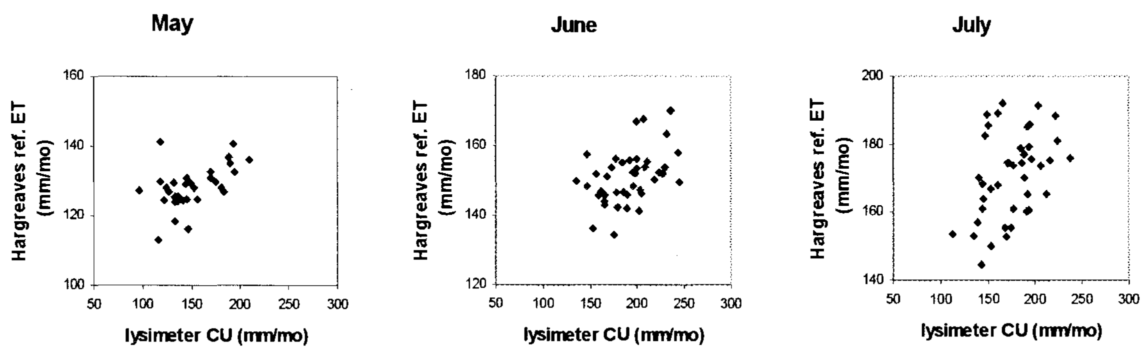

Fig. 3.5. Monthly values of Hargreaves reference ET versus lysimeter consumptive use [mm mo^{-1}].

We conducted correlation analyses between Hargreaves reference ET and lysimeter CU (Table 3.13). Correlation coefficients (r), coefficients of determination (r^2), and statistical significance of r (p) for that comparison are presented. Comparison statistics from the previous correlation analyses between lysimeter CU and Blaney-

Criddle with original and modified temperature expressions (Table 3.9) are also shown for the convenience of the reader.

Table 3.13. Correlation between lysimeter CU and ET predicted either by the Hargreaves equation or by the Blaney-Criddle equation with various temperature expressions, for months of May, June, and July. Data based on observations from nine lysimeter sites during 1999 to 2003.

Month	Statistical Parameter	f(*conventional t*)	f(*daylight mean t*)	f(*daylight weighted mean t*)	f(*daily maximum mean t*)	Hargreaves reference ET
May	r	0.33	0.36*	0.53**	0.54**	0.50**
(n=31)	r^2	0.11	0.13	0.28	0.30	0.25
	p	0.070	0.045	0.002	0.001	0.004
June	r	0.46**	0.45**	0.51**	0.45**	0.44**
(n=41)	r^2	0.21	0.20	0.26	0.21	0.19
	p	0.003	0.003	0.001	0.003	0.004
July	r	-0.23	-0.23	0.26	0.35*	0.41**
(n=41)	r^2	0.05	0.06	0.07	0.12	0.16
	p	0.156	0.139	0.107	0.024	0.008

*, ** significant at the 0.05 and 0.01 probability levels, respectively

For the months of May and July, Hargreaves and two of the modified Blaney-Criddle equations showed a distinct improvement in estimation accuracy over Blaney-Criddle with *conventional t* or with *daylight mean t*. In June, Blaney-Criddle with *daylight weighted mean t* stands out as improved, while Hargreaves and the other modifications were equal to Blaney-Criddle with *conventional t*.

More specifically, in May the original Blaney-Criddle with *conventional t* did not correlate significantly with CU. However, Hargreaves and Blaney-Criddle with *daylight weighted mean t* or *daily maximum t* each had significant correlations with increased r^2 values. For those methods, r^2 values indicated that up to three times as much of the variation in CU was explained, compared to Blaney-Criddle using f(*conventional t*). In June, ET from each of the estimation options showed significant correlations with CU.

However, only *daylight weighted mean t* showed improved r^2 values over the original Blaney-Criddle with f(*conventional t*). In July, the original method (Blaney-Criddle with *conventional t*) correlations with CU were negative and non-significant. Significant correlations were obtained with two of the alternative methods (Hargreaves, Blaney-Criddle with *daily maximum t*), and r^2 values were doubled.

Considering results from all three months, the Hargreaves equation using T_{diff} and Blaney-Criddle using the *daily maximum t* temperature expression most consistently explained the variation of lysimeter CU across months, having comparatively higher r^2 values and significant p values ($p<0.05$) for most months. The temperature expression *daylight weighted mean t* had similar r^2 values for May and June, although p values for July were non-significant. Each of those expressions was better correlated than *conventional t* and *daylight mean t,* which had non-significant p values and/or negative correlation coefficients in both May and July.

Table 3.14a groups the prediction methods by r value, considering performance over all three months. This grouping demonstrates the improved correlation coefficients of methods in the first three columns in May and July compared to the last two columns. In Table 3.14b, column headers are the temperature expressions that correspond to the methods in Table 3.14a. Table 3.14b displays correlation coefficients between R_s and T_{diff} (for Hargreaves), and between R_s and temperature expression (for Blaney-Criddle, previously shown in Table 3.6) measured at three sites (Fig 3.1). *Daylight mean t* was omitted from this analysis due to its similarity to *conventional t.* Comparing the two tables, it is evident that the methods with the best correlation between lysimeter CU and

ET or *f* are based upon the temperature expressions that had the highest correlations with R_s.

Table 3.14a. Correlation coefficient, *r*, between lysimeter CU and ET predicted either by the Hargreaves equation or by the Blaney-Criddle equation with various temperature expressions.

Month	Hargreaves ET	*f* (*daily maximum mean t*)	*f* (*daylight weighted mean t*)	*f* (*daylight mean t*)	*f* (*conventional t*)
May (*n*=31)	0.50**	0.54**	0.53**	0.36*	0.33
June (*n*=41)	0.44**	0.45**	0.51**	0.45**	0.46**
July (*n*=41)	0.41**	0.35*	0.26	-0.23	-0.23

*, ** *significant at the 0.05 and 0.01 probability levels, respectively*

Table 3.14b. Correlation coefficient, *r*, between temperature expressions and daily average R_s measured at three sites (shown in Fig. 3.1) from 1999 to 2003.

Month	T_{diff}	*daily maximum t*	*daylight weighted mean t*	*conventional t*
May (*n*=29)	0.60**	0.43*	0.50**	0.24
June (*n*=160)	0.48**	0.18*	0.22**	-0.24**
July (*n*=314)	0.49**	0.37**	0.52**	0.01

*, ** significant at the 0.05 and 0.01 probability levels, respectively.

That observation emphasizes the importance of choosing a temperature expression that is well-correlated to R_s in order to maximize the ability of estimation methods to predict lysimeter CU. In Hargreaves, R_s is approximated from R_a and T_{diff}, and thus the correlation of locally-measured R_s and T_{diff} must be strong for Hargreaves to predict well. In Blaney-Criddle, estimation results depend on the mutual correlation of R_s to both *t* and ET. Bearing that in mind, the poor correlation of *f* (*conventional t*) with lysimeter CU is not surprising, given the lack of positive correlation of *conventional t* with R_s in any month. The improved correlation of measured CU versus computed ET or *f* seen in three of the methods is substantiated by the improved correlation of their respective temperature expressions with R_s.

Alternative Blaney-Criddle temperature expressions were identified that correlated more strongly to R_s than did the original temperature expression, *conventional t*. Use of those alternative temperature expressions resulted in improved Blaney-Criddle predictability, as measured by r^2. Such usage resulted in significant relationships between estimated ET and lysimeter CU, even in months where none existed using Blaney-Criddle *conventional t*. The research established that the Hargreaves equation can predict ET in mountain meadows better than Blaney-Criddle with *conventional t*, and that Blaney-Criddle can be modified to predict as well as Hargreaves.

Conclusions

Temperature-based ET prediction methods underestimate consumptive water use of meadows at high elevations. Calibration and correction methods currently in use either have limited success or require the expense and effort of lysimeters. A simpler, more effective way to improve accuracy of ET estimates in mountain meadows is needed. Three modifications to the original Blaney-Criddle mean temperature expression were evaluated based on monthly average calculated ET, and compared to lysimeter CU at nine sites in the Gunnison basin, Colorado. The Hargreaves equation, which incorporates T_{diff} as well as T_{mean}, was also evaluated.

The original mean temperature expression, monthly mean of maximum and minimum 24-hour temperatures, does not provide a representative value of energy available to drive evapotranspiration at high elevations. The observed value of *conventional t* was substantially lower than the average of all daylight temperatures, *daylight weighted mean t*.

Based on correlations with lysimeter CU and R_s, the mean temperature expression *conventional t* and the consumptive use coefficient f(*conventional t*) did not express the variability seen in lysimeter CU. We conclude that Blaney-Criddle with the original temperature expression is a less-than-optimal predictor of ET a higher elevations. It is not sensitive to year-to-year variation in weather conditions that create variability in ET.

The modified mean temperature expression *daylight weighted mean t,* because it averages daytime temperatures over thirty minute periods, is more representative of the energy available to drive evapotranspiration. Based on correlations with ET and R_s, *daylight weighted mean t* and another modified expression, *daily maximum t,* provide similar estimates of ET that are better than those from *conventional t*. The frequency of temperature measurement required to obtain *daylight weighted mean t* is not typically available from established weather stations. However, *daily maximum t* can be easily determined from standard weather stations, and provides improved results over *conventional t*. For high elevations, the use of *daily maximum t* as the Blaney-Criddle mean temperature expression could improve Blaney-Criddle ET calculations.

The Hargreaves equation, which incorporates the variable T_{diff} as well as mean temperature, estimates ET more accurately than the Blaney-Criddle equation with the standard temperature expression, based on correlations with lysimeter CU and R_s. The two modified temperature expressions *daylight weighted mean t* and *daily maximum t* allow Blaney-Criddle to estimate ET equally as well as Hargreaves. Adjustment of the temperature function used can allow Blaney-Criddle to be employed as successfully in high elevation meadows as it is at lower altitudes.

CHAPTER 4:

MODEL-BASED CALIBRATION OF BLANEY-CRIDDLE *k*

Introduction

Accurate prediction of evapotranspiration (ET) is essential for water resources planning and management. ET depends on multiple climatologic factors including radiation, temperature, humidity, and wind speed, as well as vegetation type and growth stage. In high-altitude mountain basins, topographic variation results in the formation of microclimates that further complicate determination of basin ET (USDA, 1975).

Blaney-Criddle (Blaney and Criddle, 1962), an ET method whose sole measured input is temperature, is the most widely used equation for predicting consumptive water use by high-altitude irrigated mountain meadows. Blaney-Criddle methods produce estimates of ET that are much less accurate than combination methods, which use multiple inputs measured over short time intervals. However, acquiring those inputs is time and resource intensive; in high mountain meadows, weather stations are widely scattered and few climate variables are recorded. Temperature-based methods are thus preferable, since the required instrumentation for temperature measurements is inexpensive, accurate, and reliable over long periods and historical data is usually available from local weather stations. Blaney-Criddle procedures are important because of their general acceptance in decision support systems in Colorado, and their widespread acceptance in the legal system. Blaney-Criddle is routinely used by federal, state, and local water management agencies including the state engineers of Colorado, Utah, and Wyoming.

Blaney-Criddle predicts ET based on the product of experimentally derived crop growth stage coefficients (*k*) and a consumptive use factor, *f*, which is the product of measured mean air temperature and day length. The equation is of the form:

$$u = k\,f \qquad [4.1]$$

where ET [in] is desired:

u = monthly ET [in],

$f = (t\,\mathrm{p})/100$

t = monthly average of daily maximum and minimum air temperatures (T_{avg} [°F]), and

p = monthly percentage of annual daylight hours [%];

where ET [mm] is desired:

u = monthly ET [mm],

$f = [25.4(1.8t + 32)p/100)]$,

t = monthly average of daily maximum and minimum air temperatures (T_{avg} [°C]), and

p = monthly percentage of annual daylight hours [%].

Blaney-Criddle assumes that water use is never reduced by limited water supply.

The approach is based on energy balance theory, which assumes that net radiation is partitioned among air temperature, soil temperature, and ET. Through the mutual correlation of air temperature and ET to radiation, mean air temperature is used as an index to the amount of energy available for ET, although air temperature itself is not a direct measure of the total amount of energy available for ET (Pelton et al., 1960). Various geographic and meteorological conditions cause temperature and ET to lag radiation on a daily basis, so temperature methods such as Blaney-Criddle are better suited to monthly and seasonal estimates (Jensen et al., 1990).

Blaney-Criddle monthly crop growth stage coefficients, *k*, are crop-specific and describe changes in ET as plants mature over the growing season. The *k* coefficient was initially intended to represent crop growth stage only. Later research showed that *k* has a meteorological component as well, and is affected by climate factors such as temperature. The errors thus introduced are known to be especially high in semi-arid, high-altitude environments (Doorenbos and Pruitt, 1984; Jensen et al., 1990). Seasonal crop growth stage coefficients (*K* values) that appeared in the original publication (Blaney and Criddle, 1962) have been reasonably reproducible by multiple investigators. However, monthly or shorter-term coefficients (*k*) proposed in that same publication have not proven to be widely applicable.

Modifications were proposed in order to use Blaney-Criddle for shorter-term estimates. The SCS-modified Blaney-Criddle equation (USDA, 1970) partitioned the original monthly crop coefficient, *k*, into a temperature-based climate coefficient, k_t, and an empirical crop-growth stage coefficient, k_c. The introduction of k_t (also a function of mean monthly temperature) proved to be problematic for high-altitude environments. At higher altitudes, low night temperatures cause low mean daily temperatures. When crops respond to high daytime radiation levels in spite of the lower average temperature, consumptive use is underestimated at higher elevations. In addition, the k_t variable introduced in the SCS-modified Blaney-Criddle method tends to magnify any errors resulting from use of mean daily temperature because this variable is also the basis for the consumptive use variable, *f*. Published SCS Blaney-Criddle k_c values were shown to have both a crop and a meteorological component (Jensen, 1966), so the goal of separating crop and temperature effects was not completely achieved. For these reasons, the legal and engineering water communities in Colorado prefer the original form of Blaney-Criddle methods over the SCS-modified Blaney-Criddle for use in high-altitude mountain meadow environments.

The accuracy of Blaney-Criddle, and thus its adaptability to a given region, depends on the availability of local values of actual water use from lysimeter studies (lysimeter CU) to allow for calibrating the equation to local conditions. To accomplish this, Blaney-Criddle *f* is calculated from locally-measured temperatures, and monthly crop coefficients are then computed using the following relationship:

$$k = \text{lysimeter CU} / f. \qquad [4.2]$$

A limited number of studies have used lysimeters to locally calibrate Blaney-Criddle *k* coefficients in western mountain meadows. Burman, Rechard, and Munari (1975), comparing results from several studies in Colorado, Wyoming, and Nevada, found that ET predictions from Blaney-Criddle using locally-calibrated *k* values compared favorably to ET values obtained from other methods and to lysimeter-measured values from mountain meadows of the western U.S. Pochop and Burman (1987) calibrated *k* values using three years' lysimeter data at eight mountain meadow sites in the Upper Green River basin of Wyoming at an average elevation of 2300 m (7500 ft). Kruse and Haise (1974) measured ET by lysimeter and calibrated Blaney-Criddle and two other empirical equations. Measurements were taken at a single site on

Ohio Creek in the upper Gunnison River basin, Colorado at 2440 m (8000 ft), and at two sites in South Park near Garo, CO in the Upper South Platte River basin, Colorado at 2750 m (9000 ft), for three site-years each. Additional South Park lysimeter investigations were conducted by Walter et al. (1990) at three sites over five years (2700 m to 2870 m, 8900 ft to 9420 ft). Summarizing lysimeter data from five previous mountain meadow studies in the South Park area (near Jefferson, Fairplay, Garo, and Hartsell, CO) and in the Gunnison basin, Walter et al. derived monthly k values that are widely accepted for estimating ET in irrigated mountain meadows of Colorado. Carlson et al. (1991) measured ET for four years at two mountain meadow sites near Parshall in Grand County, Colorado (2290 m to 2390 m, 7500 to 7850 ft) and derived calibrated k values. A striking trend observed in all the Colorado studies was the variability in monthly coefficients among years (Table 4.1). Consequently, use of an average value from calibration studies could result in substantial errors in projecting irrigated meadow water use in some years.

The annual variation observed in monthly k values is not surprising since, of variables known to affect water use (radiation, wind, humidity, temperature), only temperature is considered in the Blaney-Criddle consumptive use factor (f). Few (if any) studies have been conducted to determine an objective method of accounting for the year-to-year variability observed in these crop coefficients at a given location. For monthly measurements, the temperature variables available to explain variation are the monthly mean of daily average temperature (T_{avg}), which is incorporated in the Blaney-Criddle formula as the term t, and the monthly mean of daily temperature difference (T_{diff}).

Table 4.1. Variation among locally calibrated *k* values in irrigated mountain meadows of Colorado over all years of study.

		Locally- calibrated *k* values	
Study / Region / Duration	Month	Average	Range Min-Max
Kruse and Haise Gunnison, CO (1969-1970)	May	1.19	1.17-1.20
	June	1.01	0.91-1.10
	July	0.95	0.87-1.02
	August	0.81	0.77-0.86
	September	0.79	†
Kruse and Haise South Park, CO (1969-1971)	May	1.01	0.82-1.20
	June	1.16	0.91-1.37
	July	0.98	0.84-1.13
	August	0.73	0.69-0.77
	September	0.89	0.71-1.07
Walter et al. South Park, CO (1982-1985)	May	1.38	1.12-1.65
	June	1.36	1.18-1.74
	July	1.33	1.06-1.62
	August	1.10	0.63-1. 41
	September	1.24	0.99-1.54
Walter et al. Recommended values, South Park, CO (1968-1979)	May	1.18	‡
	June	1.40	
	July	1.22	
	August	0.81	
	September	0.86	
Carlson et al. Grand County, CO (1987-1990)	May	1.08	0.98-1.21
	June	1.12	1.00-1.33
	July	1.09	0.90-1.20
	August	0.88	0.77-0.97
	September	0.97	0.85-1.04

† September measured during a single year.

‡ Recommended values are based on four studies in Gunnison and South Park basins. Range not reported here.

The influence of T_{diff} on ET has been investigated previously. T_{diff} was originally used by Hargreaves and Samani (1985) to estimate global irradiance (R_s) from solar irradiance (R_a) by providing an index to cloudiness. The equation is of the form:

$$R_s = K_{RS} R_a (T_{diff})^{0.5} \qquad [4.3]$$

where: R_s = global irradiance [mm d^{-1}]

K_{RS} = an empirical constant that varies with relative humidity

R_a = extraterrestrial irradiance expressed in evaporative equivalents

T_{diff} = difference between daily maximum and minimum temperatures [°C].

T_{diff} provides reasonably accurate estimates of R_s, which is the dominant source of energy driving evapotranspiration in most cropping situations. The Hargreaves temperature-based ET prediction method (Hargreaves and Samani, 1985) employs R_s values estimated from R_a and T_{diff}.

Since the conventional method of locally calibrating crop coefficients accounts poorly for year-to-year variability in high-altitude mountain meadows, our objective was to devise a method to more accurately develop locally calibrated *k* coefficients using available temperature data. Predictive models were developed based on data from our lysimeter studies in the upper Gunnison basin, as well as on data from previous calibration studies conducted in Colorado mountain meadows. The applicability of the modeled coefficients was field-verified by comparison to our measurements and those of previous studies.

Methods and Materials

Study Location

Irrigated hay meadows within the Gunnison River basin occur within level or gently sloping floodplains as well as terraces up to 15 m above the modern stream level. Unirrigated rolling hills at mid-elevations serve as rangeland. Higher elevations are increasingly forested. The nine sites selected for this study were representative of irrigated meadows throughout the upper Gunnison River basin and included sites on the main stem of the Gunnison and its tributaries, the Slate River, East River, Ohio Creek, Tomichi Creek, and Quartz Creek (Fig. 4.1). Descriptions and designations for the selected lysimeter sites are presented in Table 4.2. Long-term weather measurements were obtained from four weather stations in the basin: Gunnison, 2341 m (7680 ft); Cochetopa Creek, 2438 m (8000 ft); Sargents, 2582 m (8470 ft,) and Crested Butte, 2707 m (8880 ft). Average annual precipitation in the basin increased with elevation, ranging from 254 to 584 mm (10 to 23 in). At Gunnison, mean air temperature for May was 9.9°C (20.2 maximum / -0.3°C minimum); June was 14.4°C (25.6 / 3.2°C); July was 17.6°C (28.2 / 6.9°C); August was 16.5°C (27.0 / 6.0°C), and September was 12.4 (23.6 / 1.2°C) . Crested Butte mean monthly temperatures were typically 2°C lower than Gunnison temperatures (Western Regional Climate Center, 2005).

Irrigated native and improved meadows occupy about 26,325 ha or 263 km^2 of the valley floor in the upper Gunnison River basin (Kathleen (Klein) Curry, Upper Gunnison River Water Conservancy District, personal communication, 1999)), supporting the area's primary agricultural product, cattle. Grass hay and minor amounts of alfalfa hay

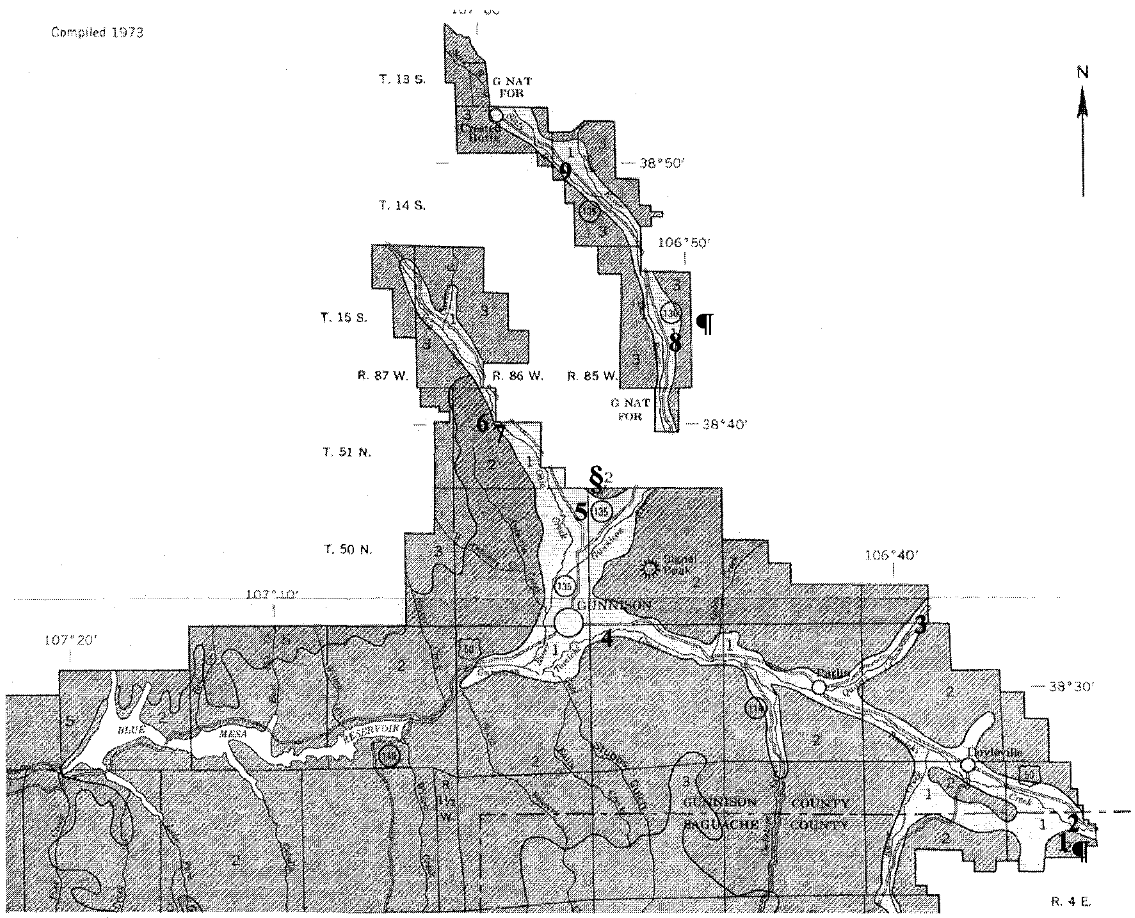

Figure 4.1. Locations of lysimeter sites and weather instrumentation, upper Gunnison basin, CO. Site numbers correspond to numbering on Table. 4.2. Weather instrumentation included continuously recording temperature logger and rain gauge.

§ Weather instrumentation included fully automated weather station.
¶ Weather instrumentation included Li-Cor pyranometer.

are the sole crops in this basin, due to the short growing season, rocky soils, and thick organic peat layers present at the soil surface. Meadow soils formed in cobbly alluvium deposited on floodplains, terraces, and alluvial fans, and soil types range from sandy loams and loams to clay loams and clays of the Evanston-Gas Creek–Irim association (USDA, 1975). These soils are deep, with rooting depths below 1.5 m, are often very cobbly or gravelly, and tend to develop 5 to 10 cm thick overlying organic mats. Water available for crops depends on soil type and location relative to the river. Meadows at

Table 4.2. Descriptions and designations for lysimeter sites.

Site designation #	Site No. †	Elev.	Latitude / Longitude	Soil series/ symbol††	Soil description
		--m (ft)--	--degrees--		org. matter depth / surface texture / subsoil texture / drainage
Upper Tomichi Creek Bottom ‡	1	2472 (8110)	38.436 106.562	Big Blue BbB	10 cm / calcareous loam / clay loam/poorly drained
Upper Tomichi Creek Upland ‡¶	2	2480 (8135)	38.426 106.565	Curecanti CuB	8 cm / loam cobbly sandy cl. loam / cobbly loam / well drained
Quartz Creek Bottom ‡	3	2542 (8340)	38.544 106.646	Irim IrB	10 cm / loam / gravelly loam / poorly drained
Lower Tomichi Creek Bottom ‡	4	2370 (7775)	38.529 106.824	Irim IrA	10 cm / loam / gravelly loam / poorly drained
Gunnison River Upland North and South ‡§	5	2408 (7900)	38.619 (N) 38.618 (S) 106.894 (N,S)	Fola FoB	8 cm / sandy loam / cobbly sandy loam / well drained
Ohio Creek Upland ‡	6	2518 (8260)	38.675 106.997	Evanston EvB	8 cm / clay loam / calcareous loam / well drained
Ohio Creek Bottom ‡	7	2472 (8110)	38.676 106.979	Irim IrA	8 cm / clay loam / cobbly clay loam / well drained
East River Upland ‡¶	8	2539 (8330)	38.740 106.850	Evanston EvB	8-10 cm /loam / sandy cobbly loam / well drained
Slate River Upland ‡	9	2649 (8690)	38.820 106.915	Fola FoB	10 cm / cobbly sandy loam / v. cobbly sandy loam / well drained

† Site numbers correspond to numbering on Fig. 4.1
‡ Weather instrumentation included continuously recording temperature logger and rain gauge
§ Weather instrumentation included automated full weather station
¶ Weather instrumentation included Li-Cor pyranometer
# "Bottom" sites are at river level and have shallow water tables (surface to 1 m) much of the year. "Upland" sites are situated on terraces above river level and have water tables that vary widely.
†† General Soil Map, Gunnison Area, Colorado (USDA, 1975)

river level (referred to as "Bottom" sites in Table 4.2) typically have shallow typically have shallow water tables (surface to 1 m) much of the year and are poorly drained. Their soils are Irim loamy skeletal, mixed, frigid Typic Haplaquolls and Big Blue fine, montmorillonitic, calcareous, frigid Typic Haplaquolls. Other meadows situated on terraces up to 15 m above modern river level (referred to as "Upland" sites) are well-drained and have water tables that vary widely with season and require irrigation for summer maintenance. Their soils are Evanston fine-loamy, mixed Aridic Argiborolls, Curecanti loamy-skeletal, mixed Aridic Argiborolls, and Fola loamy-skeletal, mixed Borollic Camborthids.

Lysimeter Installation

One or two compensating lysimeters were installed at each irrigated meadow site with an advection buffer area of established meadow at least 60 m in diameter as recommended (Aboukhaled et al., 1982). A schematic diagram of lysimeter construction is provided in Fig. 4.2. The steel tank, 1 m^2 by 76 cm deep, was placed and leveled in an excavated hole and filled successively with a 10 cm layer of gravel, the excavated soil layers, and the original 15 cm sod layer. The lysimeter lip rose approximately 8 cm above the sod surface to prevent encroachment of irrigation water from the surrounding field and to prevent any precipitation runoff. Adjacent to the lysimeter, a 20 cm diameter by 76 cm deep PVC equalizing tank with a float valve was installed to supply water to the base of the lysimeter. The adjustable float height controlled lysimeter water level. The float tank was replenished by gravity feed from a 30 cm diameter, 1.5 m deep PVC reservoir. Water level change in this reservoir corresponded to water removed from the lysimeter by evapotranspiration. Prior to replacing soil, a 50 cm diameter PVC access

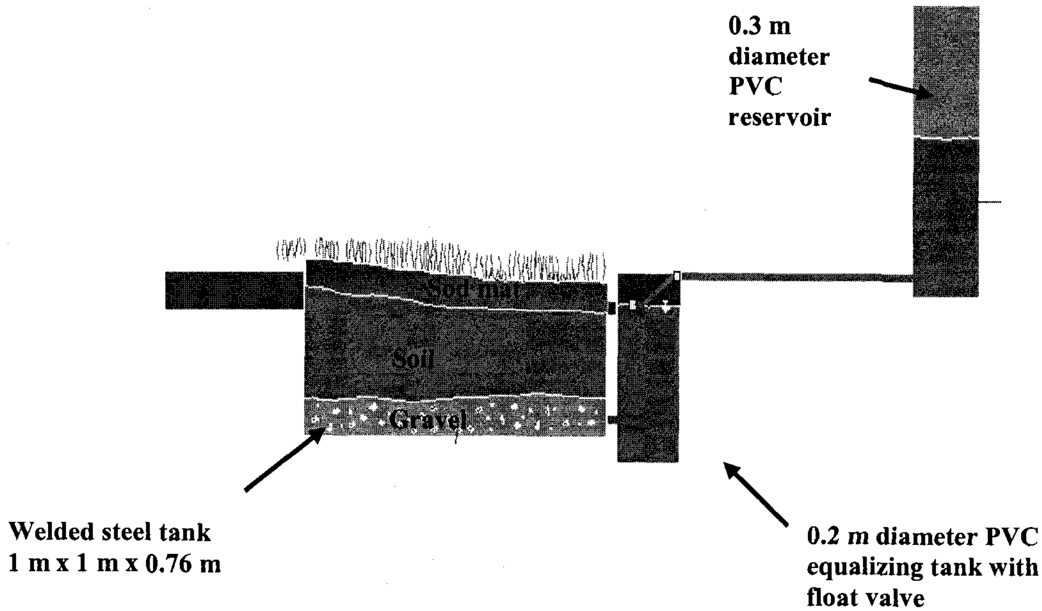

Figure 4.2. Schematic of compensating lysimeters.
After Kruse and Haise, 1974.

tube was placed in one corner of each lysimeter to allow monitoring of the lysimeter water table. A similar 50 cm diameter observation well was placed in the meadow one meter from each lysimeter to observe the field water table at depths allowed by soil profile characteristics (Table 4.2). Four of the nine sites were riverside locations where water tables often remained above maximum rooting depth when unirrigated, and five were on terrace sites with unirrigated water tables below maximum rooting depth.

Eight sites received lysimeter units at the start of the growing season in 1999; the ninth site and two duplicate units were installed between the 1999 and 2000 field seasons. At one site, a lysimeter was discovered to have been installed in a poorly producing section of a meadow. A second unit was placed 300 m south in a more representative portion of the meadow in September 1999. Plants resumed growth rapidly in the lysimeters at most sites, which resulted in a mix of vegetation similar to surrounding fields. In late June, 1999, canopy temperatures within the lysimeters were compared with those of surrounding vegetation using an infrared thermometer to test the lysimeters for any potential plant stress caused by inadequate root development. Based on these measurements, root systems within the lysimeters were assumed to be well established within approximately one month of lysimeter installation.

Weather Data Instrumentation

Instrumentation at each site consisted of a radiation-shielded thermistor temperature sensor and continuously recording temperature logger (HOBO® H8 or H8 Pro, Onset Computer Corporation, Bourne, MA) and a non-recording rain gauge [11.1 cm (4 3/8 in) funnel and 1000-ml graduated cylinder]. Rainfall amounts were manually recorded twice weekly. At two sites the data logger also recorded relative humidity from a resistance device. A fully automated weather station was installed at a centrally located site (Fig. 4.1) to record global irradiance (R_s) (LI200S photoelectric pyranometer, Li-Cor), wind speed (3001-L Wind Sentry anemometer, RM Young), temperature, and relative humidity (CS500-L platinum resistance temperature detector and INTERCAP capacitive relative humidity sensor, Vaisala) with a Campbell CR10X data logger (Campbell Scientific, Logan, UT). The automated weather station operated for portions of each field season from 1999 – 2003. An additional Li-Cor pyranometer was operated at one northern and one southern site (Fig. 4.1) during June through September, 2001 – 2003.

Irrigation and Lysimeter Operation

At the beginning of each season, water was added to the lysimeters, float tanks, and reservoirs, and the lysimeters were allowed to adjust internally until the water table measured in the lysimeter's access tube equaled the float valve depth. Once the equilibration point for a lysimeter was reached, water-use observations were begun. Our goal was to initiate measurements at each site by the time irrigation in the surrounding meadow began. This was usually on May 1; however, the lysimeters at the eight monitoring sites used in 1999 were installed just prior to the growing season, so recorded observations did not begin until June 1, 1999.

Twice-weekly site visits were made to record data and refill the water supply reservoirs. At each visit, volumetric water loss from the lysimeter was determined by recording the drop in water level in the reservoir. Lysimeter water tables were monitored through the access tube to assess proper functioning of the system. Field water table depth and precipitation were recorded, and temperature data were downloaded. Other measures obtained at each site visit included the magnitude of settling of the lysimeter soil; lysimeter vegetation height; the density, height, and approximate composition of field vegetation; and surface soil wetness of lysimeter and field. These observations were used to make adjustments as needed to maintain desired conditions within the lysimeter.

Monitoring continued until at least September 31 each year from 1999 through 2003. However, the level of the water table in these lysimeters was managed differently among sites and among years. Lysimeter water tables were maintained by adjusting float valve heights to mimic surrounding field water profile and location relative to the river. Float valves in the four lysimeters on river-level locations ("Bottom" sites) were set to maintain the water table between approximately 10 and 15 cm below the soil surface prior to the time when irrigation was terminated in the surrounding meadow in preparation for hay harvest. In the remaining lysimeters ("Upland" sites), the water table was maintained between approximately 20 and 30 cm below the soil surface prior to irrigation termination. To simulate surrounding field water conditions, the water table in the lysimeters was lowered to approximately 50 cm within two weeks of the time when irrigation was terminated on surrounding fields during the growing seasons of 1999, 2001, 2002, and 2003. The timing of the change in water table depth for each lysimeter is given in Table 4.3. In 2000, for the entire growing season, the water table depth within the lysimeters was maintained at the levels used during the irrigation season except at the Gunnison River North site where the water table depth was increased as described for the other years. A second reason for lowering the water table depth in lysimeters for at least part of the growing season was to prevent significant drifts in species composition caused by continuous flooding. This problem had been referenced in previous mountain meadow studies conducted over several consecutive years with compensating lysimeters.

Vegetation within lysimeters was maintained in a manner designed to mimic the management of the surrounding hay meadow. Lysimeter harvest coincided approximately with field harvest (Table 4.3). Lysimeter vegetation was clipped to a height of 8 cm at approximately the same time that the surrounding field was harvested to maintain water use comparable to field water use. Clippings were retained to determine yield by weight and species composition.

Table 4.3. Date that float adjustment in each lysimeter was changed to lower the depth of the water table within the lysimeter and date of lysimeter harvest.

	Year									
	1999		2000		2001		2002		2003	
Location	lower water table	harvest lysim	lower water table	harvest lysim	lower water table	harvest lysim	lower water table	harvest lysim	lower water table	harvest lysim
	(month - day)									
Upper Tomichi Cr. Bottom	Jul 26	Aug 19	‡	Jul 29	Aug 17	Aug 20	Jul 16	Jul 31	Jul 25	Aug 6
Upper Tomichi Cr.Upland	Jul 26	Aug 13	‡	Jul 25	Aug 17	Aug 20	§	§	Jul 25	Aug 6
Quartz Cr. Bottom	Jul 26	Aug 19	‡	Aug 17	Aug 21	Aug 22	§	§	Aug 8	Sep 3
Lower Tomichi Cr. Bottom	Jul 26	Aug 19	‡	Jul 21	§	§	§	§	Jul 25	Aug 13
Gunnison R. North Upland	Jul 26	Jul 26	Aug 15	Jul 21	Aug 21	Aug 23	§	§	§	§
Gunnison R. South Upland	†	†	‡	Jul 21	Aug 21	Aug 23	Jul 16	Jul 31	Jul 25	Aug 6
Ohio Cr. Upland	Jul 26	Sep 9	‡	Sep 11	Aug 21	Sep 20	§	Jul 31	Jul 25	Sep 5
Ohio Cr. Bottom	Jul 26	Sep 9	‡	Aug 5	Sep 2	Aug 23	Jul 16	Aug 12	Jul 25	Aug 20
East R. Upland	†	†	‡	Aug 27	Sep 7	Sep 10	Aug 6	Aug 19	Aug 8	Sep 3
Slate R. Upland	Aug 13	Sep 10	‡	Sep 2	Sep 7	Sep 20	Aug 6	Aug 26	Aug 25	Sep 8

† Lysimeter not installed until 2000.

‡ Water table was not lowered during the growing season.

§ Lysimeter observations omitted.

Lysimeter CU

Crop water use comprises crop evapotranspiration and the water retained in plant tissues. The following water budget equation was used:

$$\mathrm{ET} = R + I + D + S \qquad [4.4]$$

where: R = effective rainfall [mm]; I = irrigation requirement [mm]; D = drainage [mm]; and S = change in soil water content [mm]. Lysimeter-measured ET (lysimeter CU) for each of the nine sites was determined for a given observation period, typically 3 to 4 days. Irrigation requirement, consisting of the water depleted from the lysimeter reservoir (replacing water either transpired or evaporated from vegetation or soil surfaces in the lysimeter) during an observation period, was determined by multiplying the measured drop in lysimeter reservoir level (mm) by the ratio of lysimeter area to reservoir area. All precipitation received was considered part of the consumptive use because we assumed that the 8 cm lip on the lysimeters prevented any runoff from even the most extreme precipitation events. In addition, we assumed that small precipitation events resulting only in the wetting of vegetation and soil surfaces contributed to subsequent evapotranspiration and therefore offset atmospheric demand that would otherwise have been met by water coming from the soil system (through either transpiration or soil surface evaporation). This approach is the same as that used for most lysimeter studies. There is no drainage from a compensating lysimeter. Change in soil water content was assumed to be nil since a constant water table was maintained. Monthly values were determined by summing the appropriate observation periods.

Although data collection occurred continuously during the entire seasonal observation period for all installed lysimeters during each year of the study, the measurements from certain lysimeter sites and monitoring periods were not used in summarizing the overall results. Results from the Upper Tomichi Creek Upland, Quartz Creek Upland, and Ohio Creek Upland sites during the entire 2002 season were omitted because drought conditions greatly limited irrigation in the meadows surrounding these sites, and the sites lacked an advection buffer. Results from the Lower Tomichi Creek Bottom site during the entire seasons of 2001 and 2002 were not included because of vegetation damage from rodents. A transition in vegetation composition within the lysimeter at the Gunnison River Upland North site became noticeable at the beginning of the 2002 growing season and persisted throughout that and the subsequent growing season (2003). As a result, the lysimeter vegetation was not representative of the surrounding meadow, so the data from both seasons at this site were eliminated. Finally, the Gunnison River Upland North and Ohio Creek Bottom sites showed evidence of an apparent lysimeter malfunction during the first 15 days of May in 2000. Lysimeter CU was exceptionally high, greater than 150% of ET estimated by the Hargreaves equation (Hargreaves and Samani, 1985), for a period of at least two weeks. The May 2000 data from these two sites were not used in summarizing overall results. Individual observations of monthly lysimeter CU for all combinations of sites, periods of observation, and years are reported in Appendix A.

Locally-calibrated crop coefficients

Blaney-Criddle f values (Appendix D) derived from temperature measurements (T_{avg}) and monthly lysimeter CU were used to compute locally-calibrated monthly k values for each site for each year of the study according to equation [4.2].These individual k values were the ones used in our subsequent analyses unless specifically noted (Appendix F).

Additional Data

To establish the applicability of new methods to a wider area, a larger data set was thought necessary. We used sources of data from additional studies in a progressive manner to create two expanded data sets (Appendices G). We first combined results from our Gunnison lysimeter study with those of the 1974 Kruse and Haise studies in Gunnison and South Park (reference), and those of the Denver Water South Park study (Walter et al., 1990). Each of the additional studies (Fig. 4.3) was made at high mountain meadow elevations and at similar latitudes in Colorado, and was generally conducted in the same manner as our study. These studies are widely recognized but not yet incorporated into the technical literature.

We again expanded our area of consideration to include a third mountain basin. The previously described Carlson et al. (1991) study in Grand County, CO irrigated meadows took place 160 km northeast of the current study location at Gunnison at similar elevations. We combined results from this study with those previously cited (Kruse and Haise, 1974; Walter et al., 1990).

Specifically, from the Kruse and Haise work, we used data from 1968 through 1970 at Garo and data from 1969 and 1970 at Gunnison. We used individual site-year combinations, analyzed each month separately, and averaged data across multiple lysimeters at each of the two sites. We recalculated consumptive use factors from the basic data, omitting Gunnison 1971 data which were not included in the appendices of Kruse and Haise (1974). Missing May CU values (2-14 days) were extrapolated to full months. The additional South Park results used from the Walter report were from their 1.0 m^2, disturbed-soil lysimeters at the Colton Sheep Camp and Portis Ranch sites. Since multiple lysimeters were monitored at each of these sites, individual site-year combinations were included in the correlation analyses. In all instances, data from each individual month were pooled and analyzed separately. Months with missing data were omitted. Carlson et al. (1991) established two dual-lysimeter sites. We used data from four years at the Corral Creek site (2290 m), averaging across the two lysimeters. We omitted data from the second site, Lawrence Ranch, because weather records were not collected on site.

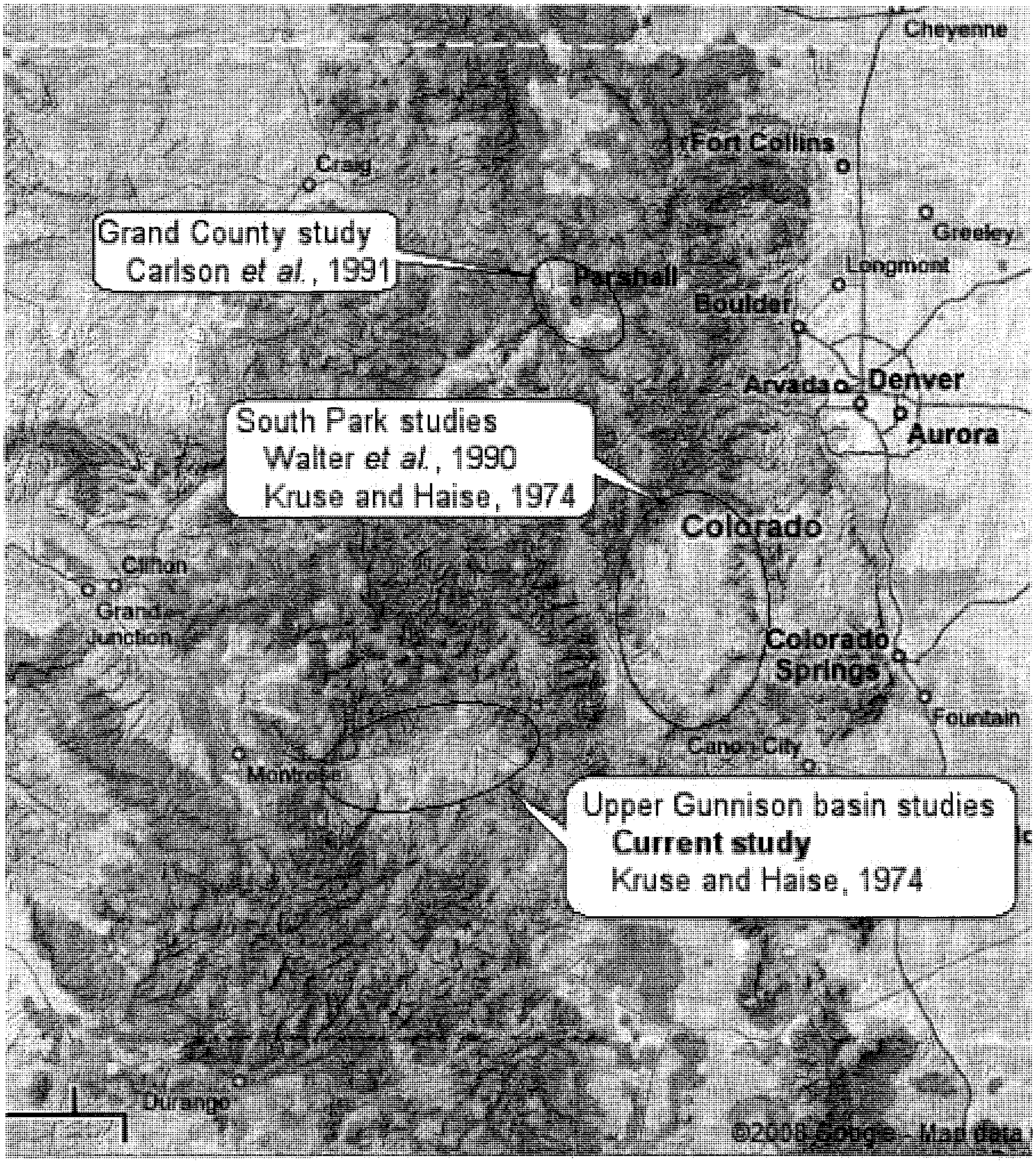

Fig. 4.3. Locations of studies from which additional data were obtained.

Standard Error of Estimate

Estimates of ET were calculated using Blaney-Criddle with locally calibrated k's derived from our measured data, and with Blaney-Criddle using modeled k's based on regressions computed in this study. Those two sets of estimates were statistically compared using standard errors of estimate, SEEs, according to:

$$SEE = \left[\frac{\sum_{i=1}^{n} \left(Y_i - \hat{Y}_i \right)^2}{n-1} \right]^{0.5} \qquad [4.5]$$

where Y_i is the average ith site lysimeter CU, $\hat{Y}_i$ is the corresponding ET estimate, and n is the total number of observations. SEE has units of [mm mo^{-1}] and n-1 degrees of freedom (Jensen et al., 1990).

Results and Discussion

Evaluation of Gunnison area data

Overall monthly averages of locally calibrated crop coefficients based on our results from the Gunnison basin are presented in Table 4.4, along with the average lysimeter CU and *f* values from which the coefficients were calculated. This table also contains monthly coefficients from an earlier study (Kruse and Haise, 1974) in the upper Gunnison basin and South Park, and coefficients derived from observations reported in a number of earlier mountain meadow lysimeter studies and summarized by Walter et al. (1990). Comparisons among the coefficients revealed both interesting trends and troubling inconsistencies. Our *k* values were most similar to those recommended by

Table 4.4. Lysimeter CU, calculated Blaney-Criddle ET, and resulting locally-calibrated crop coefficients (*k*) from the current study. Crop coefficients from the Kruse and Haise study (1974) and those recommended by Walter el al. (1990) are also included.

	Gunnison basin				Gunnison and South Park basins	
	Current Study			Kruse and Haise (1974)	Kruse and Haise (1974)	Walter et al. (1990)
Month	Lysimeter CU	Calculated ET†	*k* ‡	*k* §	*k* ¶	Recommended *k* values #
	--------- mm --------					
May	150.6	118.2	1.27	1.19	1.12	1.18
June	190.8	134.6	1.42	1.01	1.13	1.40
July	174.9	153.9	1.14	0.95	0.97	1.22
August	114.8	139.8	0.82	0.81	0.82	0.81
September	90.6	104.8	0.86	0.79	0.93	0.86

† Calculated ET for the Blaney-Criddle is the f value.
‡ Ratio of lysimeter CU to calculated ET (f value).
§ Values are average of two lysimeters in the Gunnison basin. 1971 Gunnison data were omitted.
¶ Values are average of two lysimeters at each of two sites in the Gunnison and South Park basins.
# Values summarized from five studies in the Gunnison and South park basins

Walter et al. (1990). However, the coefficients generated from our study were remarkably dissimilar to those from a previous study in the upper Gunnison basin (Kruse and Haise, 1974). More importantly, the greatest differences were observed in the coefficients for June and July, the months of highest water use. Thus, potential errors in estimates of seasonal water use could be magnified by selection of the least accurate coefficients for these months. Because all of the coefficients presented in Table 4.4 were generated from actual water use data, it follows that our conventional methods for determining locally applicable crop coefficients fail to account for one or more variables affecting water use.

To account for unexplained variability in lysimeter consumptive use, we first observed the overall range in variability of crop coefficients among the various sites used in our current study. Comparisons are made among monthly measured (lysimeter CU and temperature variables) and computed (*k*) values for each site and year. The ranges of monthly data observed over the five years of the study are presented in Table 4.5. When presented in this manner, the most noticeable feature of the results was the variability in monthly crop coefficients from year to year, which was far greater than the variation in monthly coefficients (averaged over sites and years) previously noted among studies (Table 4.4).

We next examined data from three previous studies in the same manner (Tables 4.6a through 4.6d, Appendices G1, G2, and G3). Again, variability was observed in monthly crop coefficients, both among the different studies and from year to year within the same study. The monthly variance of crop coefficients did not correlate to monthly variance of either T_{avg} or T_{diff}, for the current study or for combined data from all studies.

Table 4.5. Average and range of monthly values of lysimeter CU, calculated Blaney-Criddle crop coefficients (*k*) and temperature variables from the current study, measured at nine sites in the Gunnison basin (1999-2003).

		Lysimeter CU		*k*		T_{avg}		T_{diff}	
			Range		Range		Range		Range
Mo.	(Obs.)	Avg	Min / Max	Avg	Min / Max	Avg	Min / Max	Avg	Min / Max
		------------mm----------				------degrees C-----		------degrees C-----	
May	(n=31)	150.6	96.2 / 208.8	1.27	0.80 / 1.68	8.1	6.0 / 9.4	18.5	15.8 / 21.5
Jun	(n=41)	190.8	135.3 / 244.5	1.42	1.01 / 1.75	11.6	9.5 / 13.6	19.6	17.7 / 22.6
Jul	(n=41)	174.8	112.6 / 236.9	1.14	0.72 / 1.56	15.3	13.8 / 16.5	19.5	14.7 / 24.8
Aug	(n=41)	114.8	63.1 / 169.1	0.78	0.46 / 1.14	14.3	12.5 / 16.1	18.8	15.3 / 22.6
Sep	(n=41)	90.6	30.9 / 146.1	0.86	0.31 / 1.33	9.6	7.4 / 11.4	20.8	16.6 / 25.1

Table 4.6a. Average and range of monthly values of lysimeter CU, calculated Blaney-Criddle crop coefficients (k) and temperature variables measured at one site in the Gunnison basin during 1969 and 1970 (Kruse and Haise, 1974).

		Lysimeter CU		k		T_{avg}		T_{diff}	
			Range		Range		Range		Range
Mo.	(Obs.)	Avg	Min / Max	Avg	Min / Max	Avg	Min / Max	Avg	Min / Max
		------------mm-----------				------degrees C-----		------degrees C-----	
May	(n=2)	136.7	131.6 / 141.7	1.19	1.17 / 1.20	7.7	7.0 / 8.3	19.4	19.0 / 19.8
Jun	(n=2)	132.1	115.8 / 148.3	1.01	0.91 / 1.10	10.8	9.9 / 11.7	16.9	16.9 / 16.9
Jul	(n=2)	145.4	134.6 / 156.2	0.95	0.87 / 1.02	15.0	14.9 / 15.2	17.8	17.2 / 18.4
Aug	(n=2)	115.7	108.0 / 123.4	0.82	0.77 / 0.86	15.0	14.6 / 15.3	18.4	17.7 / 19.1
Sep	(n=1)	81.8		0.79		8.9		17.0	

Table 4.6b. Average and range of monthly values of lysimeter CU, calculated Blaney-Criddle crop coefficients (k) and temperature variables measured at one site in the South Park basin from 1969 through 1971 (Kruse and Haise, 1974).

		Lysimeter CU		k		T_{avg}		T_{diff}	
			Range		Range		Range		Range
Mo.	(Obs.)	Avg	Min / Max	Avg	Min / Max	Avg	Min / Max	Avg	Min / Max
		------------mm-----------				------degrees C-----		------degrees C-----	
May	(n=3)	116.0	80.3 / 141.7	1.01	0.82 / 1.20	7.2	3.8 / 9.7	16.9	13.7 / 18.6
Jun	(n=3)	149.0	112.5 / 177.0	1.16	0.91 / 1.37	10.1	9.2 / 10.7	16.0	13.0 / 17.5
Jul	(n=3)	144.1	126.2 / 160.3	0.98	0.84 / 1.13	13.9	12.7 / 14.5	16.1	15.3 / 16.6
Aug	(n=3)	96.4	89.2 / 107.7	0.72	0.69 / 0.77	12.8	11.1 / 14.3	17.5	16.6 / 18.0
Sep	(n=3)	86.1	73.9 / 100.1	0.90	0.71 / 1.07	7.4	6.2 / 9.3	19.3	16.5 / 22.3

Table 4.6c. Average and range of monthly values of lysimeter CU, calculated Blaney-Criddle crop coefficients (k) and temperature variables measured at two sites in the South Park basin from 1982 through 1985 (Walter et al., 1990).

	Lysimeter CU		k		T_{avg}		T_{diff}	
		Range		Range		Range		Range
Mo. (Obs.)	Avg	Min / Max	Avg	Min / Max	Avg	Min / Max	Avg	Min / Max
	------------mm----------				------degrees C-----		------degrees C-----	
May (n=7)	138.4	104.6 / 163.3	1.38	1.12 / 1.65	4.2	1.9 / 6.7	18.1	16.1 / 21.1
Jun (n=8)	161.8	137.2 / 208.3	1.37	1.18 / 1.74	8.0	6.9 / 9.2	19.0	16.1 / 21.1
Jul (n=8)	180.5	146.8 / 217.9	1.33	1.06 / 1.62	11.5	10.6 / 13.1	19.7	17.2 / 22.8
Aug (n=8)	140.4	83.8 / 178.8	1.10	0.63 / 1.41	11.6	10.3 / 12.8	20.1	17.8 / 25.0
Sep (n=6)	118.5	92.2 / 145.0	1.24	0.99 / 1.54	7.2	5.0 / 8.3	19.9	16.7 / 24.4

Table 4.6d. Average and range of monthly values of lysimeter CU, calculated Blaney-Criddle crop coefficients (k) and temperature variables measured at one site in Grand County from 1987 through 1990 (Carlson et al., 1991).

	Lysimeter CU		k		T_{avg}		T_{diff}	
		Range		Range		Range		Range
Mo. (Obs.)	Avg	Min / Max	Avg	Min / Max	Avg	Min / Max	Avg	Min / Max
	------------mm-----------				------degrees C-----		------degrees C-----	
May (n=4)	83.4	39.1 / 135.6	1.08	0.98 / 1.21	9.9	9.2 / 11.1	17.2	16.1 / 18.9
Jun (n=4)	152.5	126.6 / 193.4	1.12	1.00 / 1.33	13.7	12.2 / 15.0	19.9	18.9 / 21.1
Jul (n=4)	175.5	148.6 / 196.2	1.09	0.9 / 1.20	16.7	15.3 / 17.5	19.3	17.2 / 20.6
Aug (n=4)	126.3	114.8 / 135.1	0.88	0.77 / 0.97	15.5	14.4 / 16.4	19.3	17.8 / 20.0
Sep (n=4)	107.0	104.4 / 109.7	0.97	0.85 / 1.04	11.4	10.0 / 14.2	21.4	19.4 / 22.8

Evaluation of Gunnison – South Park Data

After noting the magnitude of the variability in monthly Blaney-Criddle crop coefficients, we focused on the temperature variables that could potentially account for this deviation. We conducted correlation analyses to determine the nature and significance of any potential relationships between monthly crop coefficients and temperature variables. For this exercise, we used a Gunnison – South Park pooled dataset combining individual monthly values from our studies and those of Kruse and Haise (reported monthly averages for the two sites at Gunnison and South Park for each year), and additional monthly averaged data reported by Walter et al. (1990) from studies at two lysimeter sites in South Park for each year. For purposes of the correlation, individual monthly values of temperature variables and k for each site and year were considered. Correlation analysis was conducted separately for each month of the season because cropping and management factors vary over time during the growing season.

The results of the correlation analyses are reported in Table 4.7. For each of the five months, the Blaney-Criddle crop coefficient (k) was more closely correlated with the monthly average difference in the maximum and minimum daily temperature (T_{diff}) than the monthly average daily temperature (T_{avg}). More importantly, T_{diff} and monthly k values were well correlated during May, June, and July, the three months that account for

Table 4.7 Correlation coefficients (r) and the significance of the relationships (p) between the monthly Blaney-Criddle crop coefficient (k) and either average daily temperature (T_{avg}) or the average daily difference in the maximum and minimum temperature (T_{diff}), for data from Gunnison and South Park, CO. (current study, Kruse and Haise 1974, Walter et al. 1990).

	k vs. T_{avg}			k vs. T_{diff}		
Month (Obs.)	r	r^2	p	r	r^2	p
May (n=43)	0.01	<0.01	0.974	0.54**	0.29	<0.001
Jun (n=54)	0.27	0.07	0.052	0.50**	0.25	<0.001
Jul (n=54)	0.43**	0.18	0.001	0.46**	0.21	<0.001
Aug (n=54)	0.37**	0.14	0.006	0.54**	0.29	<0.001
Sep (n=51)	0.11	0.01	0.445	0.28**	0.08	<0.001

*, ** significant at the 0.05 and 0.01 probability levels, respectively.

most of the irrigation water use in mountain meadows. Conversely, T_{avg} was poorly correlated with monthly crop coefficient values during all months except July.

Overall, these results demonstrated that monthly T_{diff} values were better predictors of monthly Blaney-Criddle crop coefficients than T_{avg}. Note that the r^2 value, which is the proportion of variability in k explained by the variation in temperature, was higher for k vs. T_{diff} than for k vs. T_{avg} in all months. For the months of May, June, and August, T_{diff} versus k value relationships were relatively robust, with T_{diff} accounting for up to 30% of the year-to-year variation in monthly crop coefficients. For the remaining months, the T_{diff} variable was a significant predictor of k values.

In retrospect, the superiority of T_{diff} over T_{avg} in producing more accurate estimates of monthly crop coefficients is not surprising. The only weather variable used in computing the consumptive-use factor (the f value) in the Blaney-Criddle formula is T_{avg}. Use of this variable to compute a correction factor (the crop coefficient) for consumptive use represents dual use of a single variable. The difference in the maximum and minimum daily temperature is a temperature variable that is distinctly different from T_{avg}. The variable T_{diff}, originally used by Hargreaves and Samani (1985), provides reasonably accurate estimates of global irradiance (R_s, solar irradiance measured at the earth's surface) from extraterrestrial irradiance (R_a). In most cropping situations, solar radiation is the dominant source of energy driving evaporation and transpiration, the two factors that account for consumptive water use.

Least-squares linear regression techniques were then used to determine the optimum predictive relationship between T_{diff} and monthly crop coefficients. The specific regression formulas generated through this process are presented in Table 4.8. Because standard practice is to use Blaney-Criddle in conventional units rather than SI units, regression equations are presented with temperature both in [°C] and [°F]. It should be noted that although T_{diff} is the only independent variable used to calculate the monthly crop coefficient (*k* value), the specific nature of the relationship between the crop coefficient and T_{diff} changes with each month. Thus, the calculation and use of crop coefficients on a monthly basis accounts for both climatic variation and changes in cropping conditions. These equations should provide usable estimates of *k* for the Gunnison and South Park areas of Colorado.

Table 4.8 Regression equations for estimating monthly Blaney-Criddle crop coefficients (*k*) from the average daily difference in the maximum and minimum temperature (T_{diff}) for data from Gunnison and South Park, CO. (current study, Kruse and Haise 1974, Walter et al. 1990). †

Month	Prediction equation	Prediction equation
	----------degrees F----------	----------degrees C----------
May	k = -0.181 + 0.044 (T_{diff}[°F])	k = -0.181 + 0.079 (T_{diff} [°C])
June	k = -0.096 + 0.037 (T_{diff}[°F])	k = -0.096 + 0.067 (T_{diff}[°C])
July	k = 0.417 + 0.021 (T_{diff}[°F])	k = 0.417 + 0.038 (T_{diff} [°C])
August	k = -0.222 + 0.032 (T_{diff}[°F])	k = -0.222 + 0.057 (T_{diff} [°C])
September	k = 0.246 + 0.018 (T_{diff}[°F])	k = 0.246 + 0.032 (T_{diff} [°C])

† Coefficients of determination (r^2) and significance of relationships (*p*) are given in Table 4.7.

Application to a Broader Geographic Area

The Gunnison – South Park database used to develop the predictive equations in Table 4.8 encompassed a relatively wide range of elevations and climatic conditions within meadows of the central mountains of Colorado. To investigate whether this approach could be applied to a broader geographic area, we next repeated the correlation analysis using an additional study. Carlson et al. (1991) collected ET measurements and temperature variables and derived Blaney-Criddle *k* crop coefficients at dual-lysimeter sites near Parshall in Grand County, CO from 1987-1990. Data were averaged across the two lysimeters at the Corral Creek site. Incorporation of these data expanded the area examined to include a third basin at similar elevations and somewhat higher latitude (Figure 4.3). These data were pooled with those of the current study, Kruse and Haise (1974), and Walter et al. (1990) to form the Gunnison – South Park – Grand County data set for the following correlation analysis.

The results of the correlation analysis of k vs. T_{avg} and k vs. T_{diff} are presented in Table 4.9. For three of the five months T_{diff} was closely correlated with k. Based on values of r^2, T_{diff} accounted for up to 30% of the year-to-year variation in monthly crop coefficient in May, July, and August. During those same months T_{avg} was poorly correlated with k, indicating that T_{diff} should be a better predictor of k than T_{avg}. T_{diff} was adequately-, if less-well, correlated with k in June and September. Correlations of T_{diff} with k over the larger geographical area were as strong as correlations over the more restricted Gunnison – South Park area in most months.

Least-squares linear regression techniques were again used to model predictive relationships between T_{diff} and monthly crop coefficients for the expanded area of interest. The equations developed to obtain *k* from T_{diff} are presented in Table 4.10. Note

Table 4.9. Correlation coefficients (*r*) and the significance of the relationships (*p*) between the monthly Blaney-Criddle crop coefficient (*k*) and either average daily temperature (T_{avg}) or the average daily difference in the maximum and minimum temperature (T_{diff}) for data from Gunnison, South Park, and Grand County, CO (current study, Kruse and Haise 1974, Walter et al. 1990, Carlson et al. 1991).

	k vs. T_{avg}			*k* vs. T_{diff}		
Month (Obs.)	*r*	r^2	*p*	*r*	r^2	*p*
May (*n*=47)	0.08	0.01	0.605	0.54**	0.29	<0.001
Jun (*n*=58)	0.09	0.01	0.482	0.44**	0.19	<0.001
Jul (*n*=58)	0.42**	0.17	0.001	0.47**	0.22	<0.001
Aug (*n*=58)	0.35**	0.12	0.007	0.53**	0.28	<0.001
Sep (*n*=55)	0.10	0.01	0.492	0.29*	0.08	0.031

*, ** significant at the 0.05 and 0.01 probability levels, respectively

Table 4.10. Regression equations for estimating monthly Blaney-Criddle crop coefficients (*k*) from the average daily difference in the maximum and minimum temperature (T_{diff}) for data from Gunnison, South Park, and Grand County, CO. (current study, Kruse and Haise 1974, Walter et al. 1990, Carlson et al. 1991)†

Month	Prediction equation	Prediction equation
	----------degrees F----------	----------degrees C----------
May	$k = -0.165 + 0.043\ (T_{diff}\ [°F])$	$k = -0.165 + 0.077\ (T_{diff}\ [°C])$
June	$k = 0.199 + 0.034\ (T_{diff}\ [°F])$	$k = 0.199 + 0.061\ (T_{diff}\ [°C])$
July	$k = 0.399 + 0.022\ (T_{diff}\ [°F]))$	$k = 0.399 + 0.040\ (T_{diff}\ [°C])$
August	$k = -0.207 + 0.031\ (T_{diff}\ [°F]))$	$k = -0.207 + 0.056(T_{diff}\ [°C])$
September	$k = 0.232 + 0.018\ (T_{diff}\ [°F]))$	$k = 0.232 + 0.032\ (T_{diff}\ [°C])$

† Coefficients of determination (r^2) and significance of relationships (*p*) are given in Table 4.9.

that these equations do not differ greatly from those previously presented in Table 4.8 for the more restricted geographic area. We expect that these equations will provide usable estimates of the Blaney Criddle crop coefficient, *k*, for irrigated mountain meadows of Colorado.

Comparison of errors from modeled and averaged crop coefficients

The regression equations in Table 4.10, derived from the Gunnison – South Park – Grand County dataset, were used to generate individual T_{diff} -modeled *k* values for each site-year-month data point in the current-study dataset and the overall Gunnison – South Park – Grand County dataset. The modeled *k* values were used with corresponding individual values of T_{avg} and p to create individual site-year-month Blaney-Criddle ET estimates ($ET_{modeled\ k}$). A second set of ET estimates ($ET_{averaged\ k}$) was computed using locally calibrated *k* values from the current study. For these estimates, we used the approach typically used in calibration studies of calculating a monthly *k* value averaged across sites and years (Table 4.4). Similar $ET_{averaged\ k}$ values were calculated for the Gunnison – South Park – Grand County dataset, using *k* values recommended by Walter et al. (1990) (Table 4.4). The resulting values (Appendix H) allowed us to test the approach of using the variable T_{diff} to adjust crop coefficients on both a specific location, the current Upper Gunnison basin study, and a regional area, the pooled Upper Gunnison – South Park – Grand County studies.

We conducted correlation analyses to compare the nature and significance of relationships between lysimeter CU and ET estimated using each of the *k* values. Results are presented in Table 4.11. In the months of May, July, and August, significant relationships were established with $ET_{modeled\ k}$, where none existed with $ET_{averaged\ k}$, and r^2 values indicated that up to three times as much of the variation in CU was explained, compared to $ET_{averaged\ k}$.

Table 4.11. Correlation and significance of relationship between lysimeter CU vs. estimated $ET_{averaged\ k}$ and lysimeter CU vs. estimated $ET_{modeled\ k}$.

			Lysimeter CU vs. ET (averaged k)			Lysimeter CU vs. ET (modeled k)		
Data set	Month (Obs.)		r	r^2	p	r	r^2	p
Upper Gunnison current study (local)	May	(n=31)	0.33	0.11	0.070	0.55**	0.31	0.001
	Jun	(n=41)	0.46**	0.21	0.003	0.40**	0.16	0.009
	Jul	(n=41)	0.23	0.05	0.143	0.43**	0.19	0.005
	Aug	(n=41)	0.12	0.01	0.448	0.43**	0.18	0.005
	Sep	(n=41)	0.52**	0.27	0.001	0.52**	0.27	0.001
Pooled studies (regional)	May	(n=47)	0.34*	0.11	0.021	0.59**	0.35	<0.001
	Jun	(n=58)	0.41**	0.17	0.002	0.55**	0.30	<0.001
	Jul	(n=58)	0.12	0.01	0.382	0.39**	0.15	0.003
	Aug	(n=58)	0.15	0.02	0.276	0.45**	0.20	<0.001
	Sep	(n=55)	0.16	0.02	0.251	0.35**	0.12	0.010

*, ** significant at the 0.05 and 0.01 probability levels, respectively

Standard errors of estimate, SEEs, were calculated between lysimeter CU and the various ET estimates. Results are presented in Table 4.12. The SEE values, in units of [mm mo^{-1}], indicate the goodness of fit of ET estimates and lysimeter CU. The method with the smaller SEE more closely approximates the lysimeter-measured values. Thus, when the value in the 'difference' column is a positive number, the SEE resulting from calculating $ET_{averaged\ k}$ is larger than the SEE from $ET_{modeled\ k}$.

For overall time periods, the relative SEE values demonstrated that the method using modeled k values gave estimates closer to lysimeter measurements for both the local study (1.6 mm mo^{-1}) and the regional study (3.9 mm mo^{-1}). These improvements were 1.1% and 2.7% of lysimeter CU, respectively. For monthly periods, the method using modeled *k* values performed more accurately in most months. In the local study, improvements were from 1 to 2% of lysimeter CU, and in the regional study

Table 4.12. Standard error of estimate of lysimeter CU vs. estimated $ET_{averaged\ k}$ and lysimeter CU vs. estimated $ET_{modeled\ k}$, in [mm mo^{-1}].

			SEE			
Data set	Month	Lysimeter CU	Lysimeter CU vs. ET (averaged k)	Lysimeter CU vs. ET (modeled k)	SEE Difference	Difference as % of CU
		------------------------------mm mo^{-1}	------------------------------	------------------------------	------------------------------	%
Upper Gunnison current study (local)	Season	144.0	25.3 †	23.8 §	1.6	1.1
	May	150.6	26.7	23.4	3.3	2.2
	Jun	190.6	25.5	25.8	-0.4	0.2
	Jul	174.9	29.1	25.7	3.4	1.9
	Aug	114.8	23.4	22.4	1.0	0.9
	Sep	90.6	23.1	22.4	0.7	0.8
Pooled studies (regional)	Season	144.7	27.9 ‡	24.0 §	3.9	2.7
	May	133.7	27.1	22.2	4.9	3.7
	Jun	180.8	28.9	26.1	2.8	1.5
	Jul	173.1	31.7	25.9	5.8	3.4
	Aug	126.4	27.5	23.1	4.4	3.5
	Sep	105.6	24.7	22.9	1.8	1.7

† using averaged *k* values from current study
‡ using average *k* values recommended by Walter et al. (1990)
§ using individual modeled *k* values (Table 4.11 regression equations)

improvements ranged from 1.5 to 3.7% of lysimeter CU. The month of June was the exception, in the local study only, and the difference was quite small in this case (-0.4 mm mo^{-1}, 0.2% of CU). Thus, the estimates that used modeled *k* values approximated the actual measured values more closely than estimates obtained using conventional averaged *k* values.

Should this be considered a significant improvement in accuracy? Droogers and Allen (2002) reported an earlier study by Allen (1993) that investigated possible improvements to the Hargreaves equation. In that case, Allen rejected a proposed method that provided a 3% improvement in accuracy. However, in a comparative study that ranked ET estimating methods, ASCE Manual 70 (Jensen et al., 1990) considered a difference in SEE that represented a 2.3% improvement in accuracy to be "significant", while a 1.1% increase in method performance was termed "fairly equal". Based on the criteria of Jensen et al. (1990), we chose an intermediate value of 1.7% improvement as a cutoff. The method using modeled *k* values significantly improved ET estimates in the pooled data set over the entire season and over each individual month except June. For the current study, the method using modeled *k* values significantly improved estimates in the high water-use months of May and July. Although modeled *k* values provided current study estimates for August, September, and the overall season that were improved, the magnitude of the improvement was not significant. Current study June estimates from modeled *k* values were slightly less accurate than estimates using the averaged *k* values.

Let us consider the physical basis for the more positive correlation of *k* vs. T_{diff} compared to *k* vs. T_{avg}. Other studies (Jensen et al., 1990) have determined that *k* has a climate component as well as a crop component. The quantity T_{avg} reflects the effect of air temperature on leaf temperature, latent heat of vaporization, and vapor pressure gradient, each of which affect ET. However, since T_{avg} is present in the *f* factor of the Blaney-Criddle equation, those variables are represented and should not need to be accounted for by *k*. Hargreaves and Samani (1985) used T_{diff} to estimate R_s from R_a. The rationale for use of T_{diff} is that R_a is reduced to R_s as radiation passes through and is partially absorbed by the cloudy atmosphere (Hargreaves and Allen, 2003). Percent of sunshine should be a good indicator of cloudiness and thus of absorption, but sunshine measurements are not universally available. Since T_{diff} generally decreases with increasing cloudiness, it implicitly accounts for effects of cloud cover. Hargreaves and Allen (2003) also state that T_{diff} varies directly with vapor pressure deficit and relative humidity, and varies inversely with wind run.

The results of correlations between measurements of R_s, T_{avg}, and T_{diff} made in the current study (Table 4.13, Fig 4.4) support this assertion. The variable T_{avg} showed very poor correlation to R_s. However, T_{diff} and R_s were seen to vary similarly, and the regression on R_s explained up to 48% of the variation in T_{diff}. Relating *k* to T_{diff} then allows *k* and estimated ET to vary to some extent with cloudiness, humidity, and wind, which are not otherwise addressed in the Blaney-Criddle equation. The use of T_{diff} to predict *k* could allow the Blaney-Criddle equation to account for additional variation in the climatic factors affecting ET.

Table 4.13. Regression of R_s vs. T_{diff} and R_s vs. T_{avg}.

	R_s vs. T_{avg}			R_s vs. T_{diff}		
	r	r^2	p	r	r^2	p
June	-0.24**	0.06	0.002	0.48**	0.22	<0.001
July	0.01	<0.01	0.91	0.49**	0.24	<0.001
August	0.07	<0.01	0.17	0.69**	0.48	<0.001
September	0.03	<0.01	0.62	0.68**	0.46	<0.001

*, ** significant at the 0.05 and 0.01 probability levels, respectively

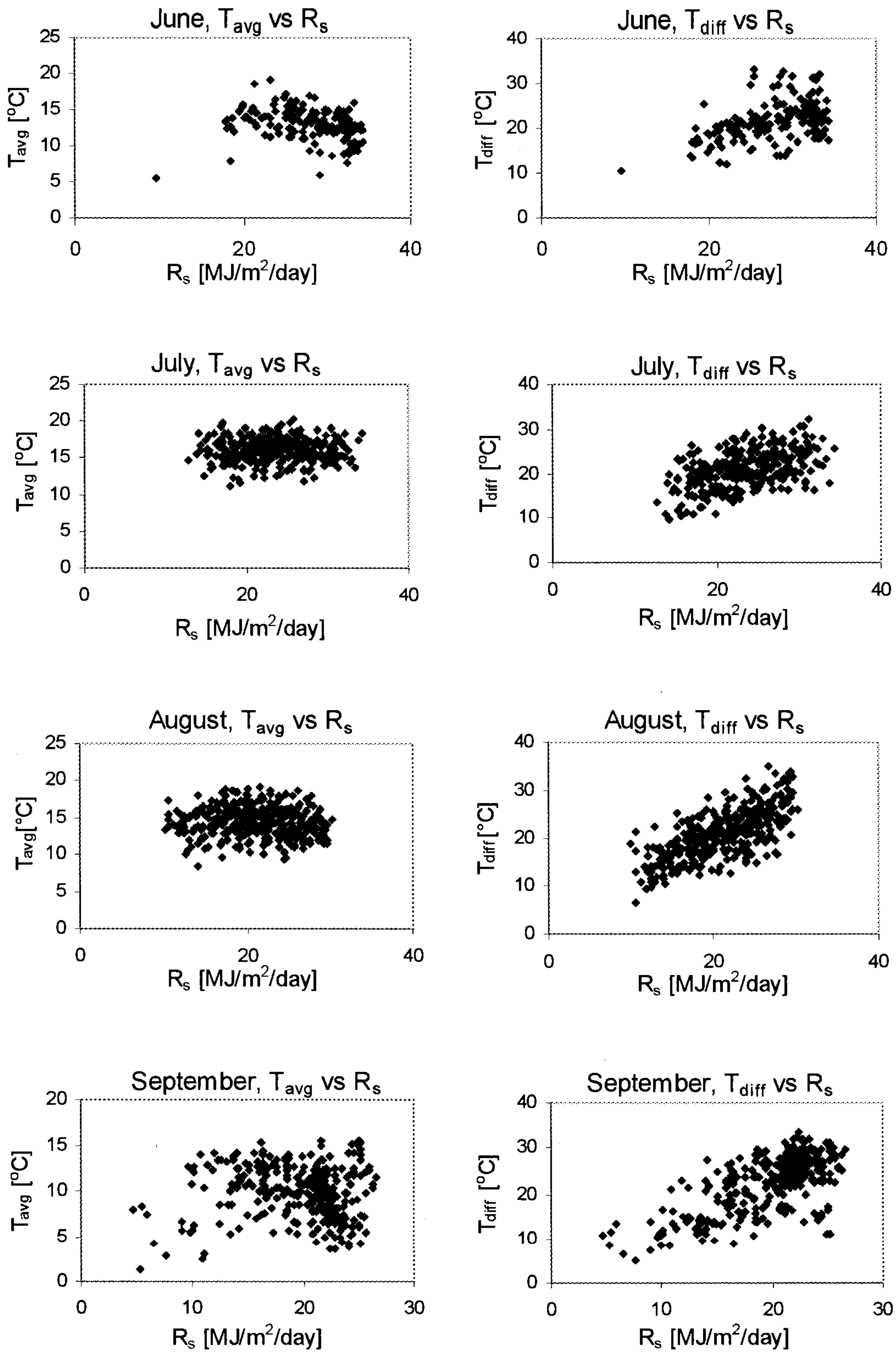

Fig. 4.4. Comparison of daily R_s versus either T_{avg} or T_{diff} for three sites in the Gunnison basin, CO (1999-2003).

Conclusions

The results from our lysimeter studies conducted during the period of 1999 to 2003 provide several types of input to support future planning and water management decisions within the upper Gunnison River basin and other high-altitude regions where irrigated mountain meadows account for significant water use. Unlike recommendations from previous studies of consumptive water use in mountain meadows, we propose the use of specific regression equations for calculating monthly crop coefficients from an alternative temperature variable, the difference in the maximum and minimum daily temperature (referred to as T_{diff}). Crop coefficients from these equations can be used with the original Blaney-Criddle formula to provide more accurate monthly and annual values of consumptive use than can be obtained with the traditional procedure of using standard monthly coefficients. Using T_{diff} to predict *k* accounts for additional weather variables, and should therefore improve water use projections and estimates of consumptive irrigation water use for annual accounting purposes.

The monthly *k* values proposed by Walter et al. (1990), although based only on studies from the Gunnison and South Park basins, are widely accepted for estimating ET in irrigated mountain meadows throughout Colorado. The proposed regression equations based on T_{diff} can be used to assess the suitability of applying Walter-recommended *k* values to regions of Colorado beyond those considered here. Observed discrepancies between Walter recommended *k* values and T_{diff} modeled *k*'s generated with local weather data could give an indication of the relative accuracy to be expected from estimations using Walter-recommended *k*'s in a particular area. The improvements in accuracy of Blaney-Criddle ET estimates that we obtained using regression equations suggest that this approach can be used in other mountain meadow regions of the western US to improve the accuracy of Blaney-Criddle methods.

Because of its ease of use, relatively low data requirements, and widespread acceptance in the legal system the Blaney-Criddle equation will continue to be used widely for predicting consumptive water use by irrigated mountain meadows. We are confident that the proposed regression equations will provide reliable estimates of monthly crop coefficients for use with the original version of the Blaney-Criddle formula in irrigated mountain meadows of Colorado. Although the extent to which these formulas can be applied outside of this region is unknown, we are hopeful that the use of this technique can be expanded to other areas.

CHAPTER 5

SUMMARY AND CONCLUSIONS

The Blaney-Criddle equation is widely used for estimates of ET over periods of ten or more days, in situations where the trade-off between reduced data requirements and decreased accuracy is acceptable. The primary problems associated with the use of temperature methods rather than combination equations are the diurnal lag of air temperature behind radiation, which affects ET estimates, and the lack of an aerodynamic term. Both of these factors contribute to significant errors in semi-arid and mountain areas. In irrigated mountain meadows, more extreme temperature ranges and the meteorologic variability inherent in mountain basins lead to increased challenges in ET prediction. At altitude, mean temperature weights low night temperatures too heavily, resulting in underestimation. These problems were not solved by elevation correction, or by the SCS modification to Blaney-Criddle. Local calibration of crop coefficients was not entirely successful either, due to variability among years.

Our goal was to improve the overall accuracy of the conventional Blaney-Criddle method in mountain meadows. Blaney-Criddle may be divided into two parts: a consumptive use factor, that incorporates the effects of meteorological inputs (temperature and day length), and a crop consumptive use coefficient (k) that was intended to represent the effects of crop growth but was later found to incorporate meteorological effects as well. We accordingly approached this problem from two directions, exploring both alternative temperature functions (addressed in Chapter 3) and alternative monthly crop coefficients (addressed in Chapter 4).

Alternative methods were tested against measurements of CU from compensating lysimeters established at nine irrigated meadow sites in the upper Gunnison basin, Colorado, which were monitored from May through September during 1999-2003. Temperature measurements were collected at each site throughout the study, and radiation was measured at three sites during most months. Estimates of ET were obtained from Blaney-Criddle, using the original temperature function and three alternative functions, and from Hargreaves. Crop coefficients, k, were derived for each of the estimates by comparison to lysimeter consumptive use. To derive crop coefficients applicable to a larger geographic area, consumptive use and temperature data were incorporated from three previous studies in Colorado irrigated mountain meadows.

In considering alternative temperature functions, we identified two modified temperature expressions that allow Blaney-Criddle to produce more accurate estimates of consumptive water use. Those two expressions are *daylight weighted mean t*, the monthly average of mean daily sunrise-to-sunset temperatures; and *daily maximum t*, the monthly average of maximum daily temperatures. These modified temperature expressions did a better job of predicting the variability of lysimeter CU than the original temperature expression, *conventional t*, the monthly mean of daily maximum and minimum temperatures. Improved accuracy was based on correlation with measured lysimeter CU. For predictions using the modified expressions, r^2 values indicated that up to three times as much of the variation in CU was explained, compared to using the conventional temperature expression (*conventional t*) to compute *f*. Accuracy obtained with the modified temperature expressions compared favorably to the accuracy of predicting ET with the Hargreaves equation.

Additionally, we sought to identify the climatological source of variability in values of *k*, the crop coefficient, and to determine a method to adjust for that variability from year to year. Based on data from our lysimeter studies in the upper Gunnison basin, as well as on data from previous calibration studies conducted in Colorado mountain meadows, we developed a model to predict locally calibrated crop coefficients using available temperature data. Regression equations specific to Colorado mountain meadows and based on an alternative temperature variable, the difference between maximum and minimum temperature (T_{diff}), predict crop coefficients that are more accurate on a year-to-year basis. The conclusions of this study were field verified by comparison of lysimeter CU from our study in the upper Gunnison basin, and from previous studies in Colorado mountain meadows, to ET predicted by either the modeled *k* or by averaged *k*'s determined by the traditional method. For predictions using $ET_{modeled\ k}$, r^2 values indicated that up to three times as much of the variation in CU was explained, compared to $ET_{averaged\ k}$. SEE's were decreased by up to 5 mm mo^{-1} (up to 4% of lysimeter CU) using $ET_{modeled\ k}$ rather than $ET_{averaged\ k}$.

Each of the two approaches, alternative temperature functions and alternatively calibrated crop coefficients, resulted in improved prediction accuracy for Blaney-Criddle in mountain meadows. Both of these methods require only readily available measured temperature values, and so are easily applicable. Depending on the source(s) of temperature measurements, modeled crop coefficients can be tailored for either local or regional applications. We are confident that the regression equations developed for crop coefficients, based on the T_{diff} variable, can be applied successfully throughout mountain basins in Colorado.

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APPENDICES

APPENDIX A: Lysimeter CU

Table A.1. Lysimeter CU measured in May at nine sites in the Gunnison basin (current study).

Location	Drainage	Year	CU
			--mm mo^{-1}--
Upper Tomichi Creek	Bottom	2000	194.2
Upper Tomichi Creek	Upland	2000	124.7
Quartz Creek	Bottom	2000	190.0
Lower Tomichi Creek	Bottom	2000	208.8
Gunnison River South	Upland	2000	193.0
Ohio Creek	Upland	2000	174.9
East River	Upland	2000	170.2
Slate River	Upland	2000	183.1
Upper Tomichi Creek	Bottom	2001	126.9
Upper Tomichi Creek	Upland	2001	137.1
Quartz Creek	Bottom	2001	153.1
Gunnison River North	Upland	2001	119.1
Gunnison River South	Upland	2001	145.1
Ohio Creek	Upland	2001	96.2
Ohio Creek	Bottom	2001	144.9
East River	Upland	2001	149.2
Slate River	Upland	2001	133.4
Upper Tomichi Creek	Bottom	2002	132.2
Gunnison River South	Upland	2002	188.5
Ohio Creek	Bottom	2002	169.8
East River	Upland	2002	157.0
Slate River	Upland	2002	147.2
Upper Tomichi Creek	Bottom	2003	141.7
Upper Tomichi Creek	Upland	2003	133.6
Quartz Creek	Bottom	2003	133.0
Lower Tomichi Creek	Bottom	2003	118.6
Gunnison River South	Upland	2003	181.5
Ohio Creek	Upland	2003	136.2
Ohio Creek	Bottom	2003	145.7
East River	Upland	2003	122.2
Slate River	Upland	2003	116.6
Average	$n = 31$		150.6

Table A.2. Lysimeter CU measured in June at nine sites in the Gunnison basin (current study).

Location	Drainage	Year	CU
			--mm mo^{-1}--
Upper Tomichi Creek	Bottom	1999	147.3
Upper Tomichi Creek	Upland	1999	189.0
Quartz Creek	Bottom	1999	165.1
Lower Tomichi Creek	Bottom	1999	195.2
Gunnison River North	Upland	1999	135.3
Ohio Creek	Upland	1999	165.5
Ohio Creek	Bottom	1999	162.2
Slate River	Upland	1999	153.1
Upper Tomichi Creek	Bottom	2000	157.3
Upper Tomichi Creek	Upland	2000	198.2
Quartz Creek	Bottom	2000	244.5
Lower Tomichi Creek	Bottom	2000	243.6
Gunnison River North	Upland	2000	207.8
Gunnison River South	Upland	2000	199.3
Ohio Creek	Upland	2000	196.0
Ohio Creek	Bottom	2000	217.9
East River	Upland	2000	223.0
Slate River	Upland	2000	201.8
Upper Tomichi Creek	Bottom	2001	185.0
Upper Tomichi Creek	Upland	2001	192.0
Quartz Creek	Bottom	2001	226.7
Gunnison River North	Upland	2001	172.5
Gunnison River South	Upland	2001	177.4
Ohio Creek	Upland	2001	146.2
Ohio Creek	Bottom	2001	199.5
East River	Upland	2001	230.2
Slate River	Upland	2001	159.0
Upper Tomichi Creek	Bottom	2002	236.1
Gunnison River South	Upland	2002	206.5
Ohio Creek	Bottom	2002	199.3
East River	Upland	2002	231.3
Slate River	Upland	2002	211.4
Upper Tomichi Creek	Bottom	2003	203.9
Upper Tomichi Creek	Upland	2003	185.7
Quartz Creek	Bottom	2003	178.9
Lower Tomichi Creek	Bottom	2003	168.4
Gunnison River South	Upland	2003	178.4
Ohio Creek	Upland	2003	203.5
Ohio Creek	Bottom	2003	165.2
East River	Upland	2003	188.9
Slate River	Upland	2003	175.3
Average	$n = 41$		190.8

Table A.3. Lysimeter CU measured in July at nine sites in the Gunnison basin (current study).

Location	Drainage	Year	CU
			--mm mo^{-1}--
Upper Tomichi Creek	Bottom	1999	112.6
Upper Tomichi Creek	Upland	1999	135.1
Quartz Creek	Bottom	1999	152.4
Lower Tomichi Creek	Bottom	1999	144.2
Gunnison River North	Upland	1999	138.9
Ohio Creek	Upland	1999	168.8
Ohio Creek	Bottom	1999	168.7
Slate River	Upland	1999	143.4
Upper Tomichi Creek	Bottom	2000	177.5
Upper Tomichi Creek	Upland	2000	195.7
Quartz Creek	Bottom	2000	191.5
Lower Tomichi Creek	Bottom	2000	192.0
Gunnison River North	Upland	2000	185.9
Gunnison River South	Upland	2000	187.7
Ohio Creek	Upland	2000	206.0
Ohio Creek	Bottom	2000	172.3
East River	Upland	2000	211.8
Slate River	Upland	2000	190.3
Upper Tomichi Creek	Bottom	2001	153.1
Upper Tomichi Creek	Upland	2001	160.8
Quartz Creek	Bottom	2001	176.4
Gunnison River North	Upland	2001	170.8
Gunnison River South	Upland	2001	140.7
Ohio Creek	Upland	2001	144.3
Ohio Creek	Bottom	2001	145.5
East River	Upland	2001	193.3
Slate River	Upland	2001	174.5
Upper Tomichi Creek	Bottom	2002	184.8
Gunnison River South	Upland	2002	150.3
Ohio Creek	Bottom	2002	146.2
East River	Upland	2002	216.3
Slate River	Upland	2002	187.7
Upper Tomichi Creek	Bottom	2003	194.9
Upper Tomichi Creek	Upland	2003	203.4
Quartz Creek	Bottom	2003	193.7
Lower Tomichi Creek	Bottom	2003	165.3
Gunnison River South	Upland	2003	160.7
Ohio Creek	Upland	2003	221.6
Ohio Creek	Bottom	2003	149.5
East River	Upland	2003	223.3
Slate River	Upland	2003	236.9
Average	n = 41		174.8

Table A.4. Lysimeter CU measured in August at nine sites in Gunnison basin (current study).

Location	Drainage	Year	CU
			--mm mo^{-1}--
Upper Tomichi Creek	Bottom	1999	63.1
Upper Tomichi Creek	Upland	1999	79.2
Quartz Creek	Bottom	1999	82.5
Lower Tomichi Creek	Bottom	1999	90.2
Gunnison River North	Upland	1999	113.0
Ohio Creek	Upland	1999	144.5
Ohio Creek	Bottom	1999	94.6
Slate River	Upland	1999	81.4
Upper Tomichi Creek	Bottom	2000	123.6
Upper Tomichi Creek	Upland	2000	132.9
Quartz Creek	Bottom	2000	132.8
Lower Tomichi Creek	Bottom	2000	100.1
Gunnison River North	Upland	2000	99.5
Gunnison River South	Upland	2000	138.3
Ohio Creek	Upland	2000	169.1
Ohio Creek	Bottom	2000	149.9
East River	Upland	2000	148.3
Slate River	Upland	2000	115.1
Upper Tomichi Creek	Bottom	2001	108.2
Upper Tomichi Creek	Upland	2001	104.6
Quartz Creek	Bottom	2001	95.7
Gunnison River North	Upland	2001	141.2
Gunnison River South	Upland	2001	103.1
Ohio Creek	Upland	2001	97.2
Ohio Creek	Bottom	2001	115.9
East River	Upland	2001	135.6
Slate River	Upland	2001	84.3
Upper Tomichi Creek	Bottom	2002	126.6
Gunnison River South	Upland	2002	143.7
Ohio Creek	Bottom	2002	120.4
East River	Upland	2002	138.1
Slate River	Upland	2002	121.2
Upper Tomichi Creek	Bottom	2003	104.7
Upper Tomichi Creek	Upland	2003	112.7
Quartz Creek	Bottom	2003	79.8
Lower Tomichi Creek	Bottom	2003	123.7
Gunnison River South	Upland	2003	120.1
Ohio Creek	Upland	2003	142.6
Ohio Creek	Bottom	2003	97.1
East River	Upland	2003	123.8
Slate River	Upland	2003	108.7
Average	$n = 41$		114.8

Table A.5. Lysimeter CU measured in September at nine sites in the Gunnison basin, (current study).

Location	Drainage	Year	CU
			--mm mo^{-1}--
Upper Tomichi Creek	Bottom	1999	30.9
Upper Tomichi Creek	Upland	1999	67.8
Quartz Creek	Bottom	1999	93.1
Lower Tomichi Creek	Bottom	1999	63.6
Gunnison River North	Upland	1999	119.6
Ohio Creek	Upland	1999	83.2
Ohio Creek	Bottom	1999	53.0
Slate River	Upland	1999	60.2
Upper Tomichi Creek	Bottom	2000	104.0
Upper Tomichi Creek	Upland	2000	110.2
Quartz Creek	Bottom	2000	108.8
Lower Tomichi Creek	Bottom	2000	106.2
Gunnison River North	Upland	2000	72.5
Gunnison River South	Upland	2000	102.9
Ohio Creek	Upland	2000	99.2
Ohio Creek	Bottom	2000	146.1
East River	Upland	2000	116.8
Slate River	Upland	2000	59.3
Upper Tomichi Creek	Bottom	2001	107.7
Upper Tomichi Creek	Upland	2001	99.0
Quartz Creek	Bottom	2001	82.3
Gunnison River North	Upland	2001	129.7
Gunnison River South	Upland	2001	142.0
Ohio Creek	Upland	2001	56.3
Ohio Creek	Bottom	2001	99.9
East River	Upland	2001	102.1
Slate River	Upland	2001	77.0
Upper Tomichi Creek	Bottom	2002	82.7
Gunnison River South	Upland	2002	115.3
Ohio Creek	Bottom	2002	90.1
East River	Upland	2002	92.6
Slate River	Upland	2002	95.6
Upper Tomichi Creek	Bottom	2003	90.0
Upper Tomichi Creek	Upland	2003	96.3
Quartz Creek	Bottom	2003	72.5
Lower Tomichi Creek	Bottom	2003	78.8
Gunnison River South	Upland	2003	116.0
Ohio Creek	Upland	2003	77.7
Ohio Creek	Bottom	2003	86.5
East River	Upland	2003	76.3
Slate River	Upland	2003	51.6
Average	$n = 41$		90.6

APPENDIX B1: Measured Temperature

Table B.1.a Temperature variables measured in May at nine sites in the Gunnison basin (current study).

Location	Drainage	Year	24 hour T_{max}	24 hour T_{min}	Daylight T_{max}	Daylight T_{min}
			degrees C			
Upper Tomichi Creek	Bottom	2000	18.2	-0.4	18.0	0.4
Upper Tomichi Creek	Upland	2000	18.2	-1.3	18.0	-0.6
Quartz Creek	Bottom	2000	18.6	-0.1	18.4	0.5
Lower Tomichi Creek	Bottom	2000	19.0	-0.1	18.8	0.5
Gunnison River South	Upland	2000	19.5	-1.0	19.3	0.0
Ohio Creek	Upland	2000	17.8	-0.2	17.7	0.5
East River	Upland	2000	18.3	-2.4	18.1	-1.3
Slate River	Upland	2000	17.4	-1.7	17.1	-0.7
Upper Tomichi Creek	Bottom	2001	17.2	-0.3	17.0	0.7
Upper Tomichi Creek	Upland	2001	17.1	-1.0	16.9	-0.2
Quartz Creek	Bottom	2001	17.5	0.2	17.3	0.9
Gunnison River North	Upland	2001	18.1	-0.4	17.9	0.4
Gunnison River South	Upland	2001	18.0	-0.5	17.8	0.3
Ohio Creek	Upland	2001	17.3	-0.5	17.1	0.1
Ohio Creek	Bottom	2001	17.5	-1.2	17.3	-0.7
East River	Upland	2001	17.4	-2.2	17.2	-1.4
Slate River	Upland	2001	15.7	-1.7	15.4	-1.1
Upper Tomichi Creek	Bottom	2002	17.2	-3.6	17.0	-2.2
Gunnison River South	Upland	2002	18.7	-2.8	18.3	-1.5
Ohio Creek	Bottom	2002	17.6	-3.2	17.3	-2.1
East River	Upland	2002	16.6	-3.6	16.4	-2.1
Slate River	Upland	2002	14.9	-3.0	14.8	-2.1
Upper Tomichi Creek	Bottom	2003	16.8	0.0	16.7	0.6
Upper Tomichi Creek	Upland	2003	16.8	-1.3	16.6	-0.3
Quartz Creek	Bottom	2003	16.8	0.5	16.7	1.1
Lower Tomichi Creek	Bottom	2003	17.8	0.0	17.6	0.5
Gunnison River South	Upland	2003	17.4	0.5	17.3	0.9
Ohio Creek	Upland	2003	16.6	-0.6	16.5	0.3
Ohio Creek	Bottom	2003	16.8	-0.7	16.7	0.0
East River	Upland	2003	16.6	-1.7	16.3	-0.6
Slate River	Upland	2003	14.5	-1.3	14.3	-0.5
Average	$n = 31$		17.4	-1.2	17.2	-0.3

Table B.1.b Temperature variables measured in June at nine sites in the Gunnison basin (current study).

Location	Drainage	Year	24 hour T_{max}	24 hour T_{min}	Daylight T_{max}	Daylight T_{min}
			--------------------degrees C	--------------------		
Upper Tomichi Creek	Bottom	1999	20.8	1.6	20.5	2.1
Upper Tomichi Creek	Upland	1999	20.4	0.2	20.2	0.9
Quartz Creek	Bottom	1999	20.4	2.5	20.2	3.0
Lower Tomichi Creek	Bottom	1999	21.7	1.7	21.4	2.0
Gunnison River North	Upland	1999	21.1	1.7	20.8	2.5
Ohio Creek	Upland	1999	19.8	0.9	19.5	1.8
Ohio Creek	Bottom	1999	20.5	1.3	20.2	2.0
Slate River	Upland	1999	18.7	0.2	18.5	0.8
Upper Tomichi Creek	Bottom	2000	21.8	2.4	21.6	3.3
Upper Tomichi Creek	Upland	2000	21.5	1.2	21.2	2.1
Quartz Creek	Bottom	2000	21.6	3.8	21.3	4.5
Lower Tomichi Creek	Bottom	2000	22.6	3.0	22.4	3.3
Gunnison River North	Upland	2000	22.1	2.9	21.7	3.7
Gunnison River South	Upland	2000	22.0	2.8	21.7	3.7
Ohio Creek	Upland	2000	20.9	1.6	20.6	2.5
Ohio Creek	Bottom	2000	21.3	2.2	21.0	3.1
East River	Upland	2000	21.5	1.3	21.2	2.3
Slate River	Upland	2000	19.7	1.5	19.4	2.0
Upper Tomichi Creek	Bottom	2001	22.1	2.0	21.8	2.6
Upper Tomichi Creek	Upland	2001	21.9	0.8	21.6	1.8
Quartz Creek	Bottom	2001	21.9	3.6	21.6	4.0
Gunnison River North	Upland	2001	22.4	2.5	22.2	3.3
Gunnison River South	Upland	2001	22.3	2.4	22.1	3.3
Ohio Creek	Upland	2001	22.4	1.9	22.1	2.9
Ohio Creek	Bottom	2001	22.2	2.0	21.9	2.3
East River	Upland	2001	21.7	1.4	21.5	1.9
Slate River	Upland	2001	20.4	0.9	20.0	1.5
Upper Tomichi Creek	Bottom	2002	24.3	1.7	24.1	2.9
Gunnison River South	Upland	2002	24.2	3.0	24.0	3.7
Ohio Creek	Bottom	2002	23.9	1.9	23.6	2.6
East River	Upland	2002	23.1	1.7	22.8	2.3
Slate River	Upland	2002	21.9	1.4	21.7	1.9
Upper Tomichi Creek	Bottom	2003	20.6	1.6	20.4	2.4
Upper Tomichi Creek	Upland	2003	20.5	0.4	20.2	1.4
Quartz Creek	Bottom	2003	20.1	2.5	19.9	3.1
Lower Tomichi Creek	Bottom	2003	21.6	2.3	21.3	2.7
Gunnison River South	Upland	2003	20.8	2.0	20.6	2.8
Ohio Creek	Upland	2003	20.5	0.5	20.3	1.2
Ohio Creek	Bottom	2003	20.5	1.2	20.3	1.6
East River	Upland	2003	19.8	0.8	19.5	1.4
Slate River	Upland	2003	18.6	0.8	18.4	1.1
Average	$n = 41$		21.4	1.8	21.1	2.4

Table B.1.c Temperature variables measured in July at nine sites in the Gunnison basin (current study).

Location	Drainage	Year	24 hour T_{max}	24 hour T_{min}	Daylight T_{max}	Daylight T_{min}
			----------------degrees C----------------			
Upper Tomichi Creek	Bottom	1999	23.4	7.9	23.1	8.6
Upper Tomichi Creek	Upland	1999	23.1	7.1	22.9	8.0
Quartz Creek	Bottom	1999	23.0	8.3	22.6	8.9
Lower Tomichi Creek	Bottom	1999	25.1	7.3	24.7	8.1
Gunnison River North	Upland	1999	23.8	7.8	23.5	8.4
Ohio Creek	Upland	1999	22.8	6.5	22.4	7.2
Ohio Creek	Bottom	1999	23.3	7.1	23.0	7.7
Slate River	Upland	1999	21.7	6.4	21.4	6.9
Upper Tomichi Creek	Bottom	2000	25.3	4.9	25.0	5.4
Upper Tomichi Creek	Upland	2000	25.2	3.1	25.0	3.9
Quartz Creek	Bottom	2000	24.5	6.3	24.2	6.7
Lower Tomichi Creek	Bottom	2000	27.0	5.0	26.7	5.4
Gunnison River North	Upland	2000	25.5	5.6	25.2	6.3
Gunnison River South	Upland	2000	25.9	5.4	25.5	6.1
Ohio Creek	Upland	2000	25.1	4.1	24.8	4.7
Ohio Creek	Bottom	2000	25.2	4.4	24.9	5.0
East River	Upland	2000	24.0	4.4	23.7	5.0
Slate River	Upland	2000	23.2	4.3	22.9	4.7
Upper Tomichi Creek	Bottom	2001	24.4	5.7	24.1	6.2
Upper Tomichi Creek	Upland	2001	24.4	4.5	24.0	5.2
Quartz Creek	Bottom	2001	24.0	7.1	23.6	7.6
Gunnison River North	Upland	2001	24.8	6.6	24.4	7.4
Gunnison River South	Upland	2001	25.0	6.3	24.6	7.2
Ohio Creek	Upland	2001	23.8	6.0	23.4	6.8
Ohio Creek	Bottom	2001	24.3	6.0	23.9	6.7
East River	Upland	2001	23.6	6.1	23.4	6.5
Slate River	Upland	2001	22.8	5.5	22.4	5.9
Upper Tomichi Creek	Bottom	2002	26.0	5.1	25.7	5.8
Gunnison River South	Upland	2002	26.9	5.5	26.6	6.2
Ohio Creek	Bottom	2002	26.4	4.9	26.1	5.4
East River	Upland	2002	25.4	5.0	25.1	5.5
Slate River	Upland	2002	24.6	4.3	24.3	4.7
Upper Tomichi Creek	Bottom	2003	26.9	4.3	26.6	5.2
Upper Tomichi Creek	Upland	2003	27.4	2.6	27.0	3.7
Quartz Creek	Bottom	2003	26.3	6.3	25.9	6.8
Lower Tomichi Creek	Bottom	2003	28.0	5.0	27.7	5.5
Gunnison River South	Upland	2003	27.4	5.4	27.0	6.0
Ohio Creek	Upland	2003	27.3	4.6	27.0	5.1
Ohio Creek	Bottom	2003	27.3	4.7	26.9	5.1
East River	Upland	2003	26.2	4.4	25.8	4.9
Slate River	Upland	2003	25.3	4.2	25.0	4.6
Average	$n = 41$		25.0	5.5	24.7	6.1

Table B.1.d Temperature variables measured in August at nine sites in the Gunnison basin (current study).

Location	Drainage	Year	24 hour T_{max}	24 hour T_{min}	Daylight† T_{max}	Daylight† T_{min}
			----------------degrees C----------------			
Upper Tomichi Creek	Bottom	1999	22.4	5.4		
Upper Tomichi Creek	Upland	1999	22.5	4.4		
Quartz Creek	Bottom	1999	22.2	6.3		
Lower Tomichi Creek	Bottom	1999	24.0	5.6		
Gunnison River North	Upland	1999	22.8	5.9		
Ohio Creek	Upland	1999	21.4	5.5		
Ohio Creek	Bottom	1999	22.3	5.5		
Slate River	Upland	1999	20.3	5.1		
Upper Tomichi Creek	Bottom	2000	25.0	4.9		
Upper Tomichi Creek	Upland	2000	25.6	3.3		
Quartz Creek	Bottom	2000	24.2	6.6		
Lower Tomichi Creek	Bottom	2000	25.5	6.8		
Gunnison River North	Upland	2000	25.9	6.0		
Gunnison River South	Upland	2000	25.6	5.8		
Ohio Creek	Upland	2000	23.8	4.9		
Ohio Creek	Bottom	2000	24.8	5.3		
East River	Upland	2000	23.8	5.1		
Slate River	Upland	2000	22.6	5.1		
Upper Tomichi Creek	Bottom	2001	23.2	4.8		
Upper Tomichi Creek	Upland	2001	24.0	3.4		
Quartz Creek	Bottom	2001	23.0	5.9		
Gunnison River North	Upland	2001	24.4	5.4		
Gunnison River South	Upland	2001	24.4	5.1		
Ohio Creek	Upland	2001	22.2	5.0		
Ohio Creek	Bottom	2001	23.5	4.8		
East River	Upland	2001	22.3	4.8		
Slate River	Upland	2001	21.5	4.9		
Upper Tomichi Creek	Bottom	2002	24.0	2.0		
Gunnison River South	Upland	2002	25.7	3.2		
Ohio Creek	Bottom	2002	24.9	2.5		
East River	Upland	2002	23.6	2.3		
Slate River	Upland	2002	22.8	2.3		
Upper Tomichi Creek	Bottom	2003	24.6	5.3		
Upper Tomichi Creek	Upland	2003	25.0	3.7		
Quartz Creek	Bottom	2003	24.0	6.4		
Lower Tomichi Creek	Bottom	2003	25.9	6.1		
Gunnison River South	Upland	2003	25.2	6.2		
Ohio Creek	Upland	2003	24.3	5.4		
Ohio Creek	Bottom	2003	25.1	5.3		
East River	Upland	2003	23.6	5.0		
Slate River	Upland	2003	21.8	5.1		
Average	$n = 41$		23.75	4.93		

† Daylight temperature values were not determined for August and September.

Table B.1.e Temperature variables measured in September at nine sites in the Gunnison basin (current study).

			24 hour		Daylight†	
Location	Drainage	Year	T_{max}	T_{min}	T_{max}	T_{min}
			-----------------degrees C-----------------			
Upper Tomichi Creek	Bottom	1999	18.8	-1.9		
Upper Tomichi Creek	Upland	1999	19.1	-3.8		
Quartz Creek	Bottom	1999	18.5	0.3		
Lower Tomichi Creek	Bottom	1999	19.3	-0.6		
Gunnison River North	Upland	1999	19.1	-1.3		
Ohio Creek	Upland	1999	17.9	-0.4		
Ohio Creek	Bottom	1999	18.5	-1.5		
Slate River	Upland	1999	16.2	-1.4		
Upper Tomichi Creek	Bottom	2000	20.8	-0.1		
Upper Tomichi Creek	Upland	2000	21.5	-1.8		
Quartz Creek	Bottom	2000	20.6	1.3		
Lower Tomichi Creek	Bottom	2000	21.3	0.7		
Gunnison River North	Upland	2000	22.2	0.3		
Gunnison River South	Upland	2000	22.0	0.2		
Ohio Creek	Upland	2000	21.0	0.4		
Ohio Creek	Bottom	2000	21.2	-0.4		
East River	Upland	2000	20.6	-0.7		
Slate River	Upland	2000	19.3	0.2		
Upper Tomichi Creek	Bottom	2001	20.7	-1.5		
Upper Tomichi Creek	Upland	2001	21.4	-3.3		
Quartz Creek	Bottom	2001	20.2	0.6		
Gunnison River North	Upland	2001	23.3	-0.5		
Gunnison River South	Upland	2001	23.3	-0.6		
Ohio Creek	Upland	2001	21.1	0.1		
Ohio Creek	Bottom	2001	21.2	-1.5		
East River	Upland	2001	21.4	-1.5		
Slate River	Upland	2001	20.1	-0.9		
Upper Tomichi Creek	Bottom	2002	19.1	0.6		
Gunnison River South	Upland	2002	20.3	1.4		
Ohio Creek	Bottom	2002	19.3	1.1		
East River	Upland	2002	18.6	0.9		
Slate River	Upland	2002	17.3	0.7		
Upper Tomichi Creek	Bottom	2003	19.7	-2.2		
Upper Tomichi Creek	Upland	2003	20.4	-4.7		
Quartz Creek	Bottom	2003	19.3	-0.5		
Lower Tomichi Creek	Bottom	2003	20.5	-0.8		
Gunnison River South	Upland	2003	20.2	-1.8		
Ohio Creek	Upland	2003	19.3	-1.1		
Ohio Creek	Bottom	2003	19.6	-2.1		
East River	Upland	2003	19.3	-2.3		
Slate River	Upland	2003	18.3	-2.0		
Average	$n = 41$		20.0	-0.8		

† Daylight temperature values were not determined for August and September.

APPENDIX B2: Temperature expressions, t

Table B.2.a. Blaney-Criddle temperature expressions, *t*, calculated in May at nine sites in the Gunnison basin (current study).

Location	Drainage	Year	*Conven-tional t*	*Daylight mean t*	*Daylight weighted mean t*	*Daily maximum t*	p
			--------------------degrees C--------------------				
Upper Tomichi Creek	Bottom	2000	8.9	9.2	12.6	18.2	9.98
Upper Tomichi Creek	Upland	2000	8.4	8.7	12.5	18.2	9.98
Quartz Creek	Bottom	2000	9.3	9.5	13.0	18.6	9.98
Lower Tomichi Creek	Bottom	2000	9.4	9.7	13.2	19.0	9.98
Gunnison River South	Upland	2000	9.3	9.7	13.2	19.5	9.99
Ohio Creek	Upland	2000	8.8	9.1	12.4	17.8	9.99
East River	Upland	2000	7.9	8.4	12.2	18.3	9.99
Slate River	Upland	2000	7.9	8.2	11.8	17.4	10.00
Upper Tomichi Creek	Bottom	2001	8.5	8.8	12.1	17.2	9.98
Upper Tomichi Creek	Upland	2001	8.0	8.4	12.0	17.1	9.98
Quartz Creek	Bottom	2001	8.9	9.1	12.2	17.5	9.98
Gunnison River North	Upland	2001	8.9	9.2	12.4	18.1	9.99
Gunnison River South	Upland	2001	8.8	9.1	12.3	18.0	9.99
Ohio Creek	Upland	2001	8.4	8.6	12.0	17.3	9.99
Ohio Creek	Bottom	2001	8.1	8.3	12.0	17.5	9.99
East River	Upland	2001	7.6	7.9	11.6	17.4	9.99
Slate River	Upland	2001	7.0	7.2	10.5	15.7	10.00
Upper Tomichi Creek	Bottom	2002	6.8	7.4	11.7	17.2	9.98
Gunnison River South	Upland	2002	7.9	8.4	12.4	18.7	9.99
Ohio Creek	Bottom	2002	7.2	7.6	11.9	17.6	9.99
East River	Upland	2002	6.5	7.2	11.1	16.6	9.99
Slate River	Upland	2002	6.0	6.3	10.1	14.9	10.00
Upper Tomichi Creek	Bottom	2003	8.4	8.7	11.5	16.8	9.98
Upper Tomichi Creek	Upland	2003	7.7	8.1	11.3	16.8	9.98
Quartz Creek	Bottom	2003	8.7	8.9	11.4	16.8	9.98
Lower Tomichi Creek	Bottom	2003	8.9	9.1	12.2	17.8	9.98
Gunnison River South	Upland	2003	9.0	9.1	11.9	17.4	9.99
Ohio Creek	Upland	2003	8.0	8.4	11.2	16.6	9.99
Ohio Creek	Bottom	2003	8.0	8.4	11.4	16.8	9.99
East River	Upland	2003	7.5	7.8	10.7	16.6	9.99
Slate River	Upland	2003	6.6	6.9	9.8	14.5	10.00
Average	$n = 31$		8.1	8.4	11.8	17.4	

Table B.2.b. Blaney-Criddle temperature expressions, *t*, calculated in June at nine sites in the Gunnison basin (current study).

Location	Drainage	Year	*Conventional t*	*Daylight mean t*	*Daylight weighted mean t*	*Daily maximum t*	p
			--------------------degrees C--------------------				
Upper Tomichi Creek	Bottom	1999	11.2	11.3	15.0	20.8	10.02
Upper Tomichi Creek	Upland	1999	10.3	10.5	14.7	20.4	10.02
Quartz Creek	Bottom	1999	11.5	11.6	15.1	20.4	10.03
Lower Tomichi Creek	Bottom	1999	11.7	11.7	15.9	21.7	10.03
Gunnison River North	Upland	1999	11.4	11.7	15.2	21.1	10.04
Ohio Creek	Upland	1999	10.4	10.6	14.4	19.8	10.04
Ohio Creek	Bottom	1999	10.9	11.1	14.9	20.5	10.04
Slate River	Upland	1999	9.5	9.6	13.5	18.7	10.05
Upper Tomichi Creek	Bottom	2000	12.1	12.4	16.3	21.8	10.02
Upper Tomichi Creek	Upland	2000	11.3	11.7	15.9	21.5	10.02
Quartz Creek	Bottom	2000	12.7	12.9	16.5	21.6	10.03
Lower Tomichi Creek	Bottom	2000	12.8	12.8	17.0	22.6	10.03
Gunnison River North	Upland	2000	12.5	12.7	16.3	22.1	10.04
Gunnison River South	Upland	2000	12.4	12.7	16.3	22.0	10.04
Ohio Creek	Upland	2000	11.2	11.6	15.8	20.9	10.04
Ohio Creek	Bottom	2000	11.7	12.0	16.0	21.3	10.04
East River	Upland	2000	11.4	11.7	15.7	21.5	10.04
Slate River	Upland	2000	10.6	10.7	14.6	19.7	10.05
Upper Tomichi Creek	Bottom	2001	12.1	12.2	16.3	22.1	10.02
Upper Tomichi Creek	Upland	2001	11.4	11.7	16.1	21.9	10.02
Quartz Creek	Bottom	2001	12.8	12.8	16.5	21.9	10.03
Gunnison River North	Upland	2001	12.5	12.7	16.5	22.4	10.04
Gunnison River South	Upland	2001	12.4	12.7	16.4	22.3	10.04
Ohio Creek	Upland	2001	12.1	12.5	16.6	22.4	10.04
Ohio Creek	Bottom	2001	12.1	12.1	16.4	22.2	10.04
East River	Upland	2001	11.6	11.7	15.9	21.7	10.04
Slate River	Upland	2001	10.7	10.8	14.9	20.4	10.05
Upper Tomichi Creek	Bottom	2002	13.0	13.5	18.3	24.3	10.02
Gunnison River South	Upland	2002	13.6	13.8	18.0	24.2	10.04
Ohio Creek	Bottom	2002	12.9	13.1	17.8	23.9	10.04
East River	Upland	2002	12.4	12.6	17.0	23.1	10.04
Slate River	Upland	2002	11.7	11.8	16.4	21.9	10.05
Upper Tomichi Creek	Bottom	2003	11.1	11.4	15.0	20.6	10.02
Upper Tomichi Creek	Upland	2003	10.4	10.8	14.8	20.5	10.02
Quartz Creek	Bottom	2003	11.3	11.5	14.8	20.1	10.03
Lower Tomichi Creek	Bottom	2003	11.9	12.0	15.8	21.6	10.03
Gunnison River South	Upland	2003	11.4	11.7	15.0	20.8	10.04
Ohio Creek	Upland	2003	10.5	10.8	14.7	20.5	10.04
Ohio Creek	Bottom	2003	10.8	10.9	14.8	20.5	10.04
East River	Upland	2003	10.3	10.5	14.1	19.8	10.04
Slate River	Upland	2003	9.7	9.7	13.3	18.6	10.05
Average	$n = 41$		11.6	11.8	15.7	21.4	

Table B.2.c. Blaney-Criddle temperature expressions, *t*, calculated in July at nine sites in the Gunnison basin (current study).

Location	Drainage	Year	*Conventional t*	*Daylight mean t*	*Daylight weighted mean t*	*Daily maximum t*	p
			--------------------degrees C--------------------				
Upper Tomichi Creek	Bottom	1999	15.6	15.8	17.6	23.4	10.18
Upper Tomichi Creek	Upland	1999	15.1	15.5	17.4	23.1	10.18
Quartz Creek	Bottom	1999	15.7	15.8	17.5	23.0	10.18
Lower Tomichi Creek	Bottom	1999	16.2	16.4	18.9	25.1	10.18
Gunnison River North	Upland	1999	15.8	15.9	17.9	23.8	10.19
Ohio Creek	Upland	1999	14.7	14.8	17.2	22.8	10.19
Ohio Creek	Bottom	1999	15.2	15.3	17.5	23.3	10.19
Slate River	Upland	1999	14.1	14.1	16.2	21.7	10.20
Upper Tomichi Creek	Bottom	2000	15.1	15.2	18.6	25.3	10.18
Upper Tomichi Creek	Upland	2000	14.2	14.4	18.4	25.2	10.18
Quartz Creek	Bottom	2000	15.4	15.4	18.4	24.5	10.18
Lower Tomichi Creek	Bottom	2000	16.0	16.0	19.8	27.0	10.18
Gunnison River North	Upland	2000	15.6	15.7	18.7	25.5	10.19
Gunnison River South	Upland	2000	15.6	15.8	18.8	25.9	10.19
Ohio Creek	Upland	2000	14.6	14.7	18.4	25.1	10.19
Ohio Creek	Bottom	2000	14.8	14.9	18.5	25.2	10.19
East River	Upland	2000	14.2	14.3	17.5	24.0	10.20
Slate River	Upland	2000	13.8	13.8	17.1	23.2	10.20
Upper Tomichi Creek	Bottom	2001	15.1	15.2	17.9	24.4	10.18
Upper Tomichi Creek	Upland	2001	14.4	14.6	17.8	24.4	10.18
Quartz Creek	Bottom	2001	15.5	15.6	18.1	24.0	10.18
Gunnison River North	Upland	2001	15.7	15.9	18.4	24.8	10.19
Gunnison River South	Upland	2001	15.7	15.9	18.4	25.0	10.19
Ohio Creek	Upland	2001	14.9	15.1	17.8	23.8	10.19
Ohio Creek	Bottom	2001	15.2	15.3	18.0	24.3	10.19
East River	Upland	2001	14.9	15.0	17.4	23.6	10.20
Slate River	Upland	2001	14.2	14.2	16.7	22.8	10.20
Upper Tomichi Creek	Bottom	2002	15.6	15.8	19.4	26.0	10.18
Gunnison River South	Upland	2002	16.2	16.4	19.7	26.9	10.19
Ohio Creek	Bottom	2002	15.6	15.7	19.4	26.4	10.19
East River	Upland	2002	15.2	15.3	18.6	25.4	10.20
Slate River	Upland	2002	14.4	14.5	18.0	24.6	10.20
Upper Tomichi Creek	Bottom	2003	15.6	15.9	19.6	26.9	10.18
Upper Tomichi Creek	Upland	2003	15.0	15.4	19.7	27.4	10.18
Quartz Creek	Bottom	2003	16.3	16.4	19.6	26.3	10.18
Lower Tomichi Creek	Bottom	2003	16.5	16.6	20.6	28.0	10.18
Gunnison River South	Upland	2003	16.4	16.5	20.0	27.4	10.19
Ohio Creek	Upland	2003	15.9	16.0	20.3	27.3	10.19
Ohio Creek	Bottom	2003	16.0	16.0	20.1	27.3	10.19
East River	Upland	2003	15.3	15.4	19.1	26.2	10.20
Slate River	Upland	2003	14.7	14.8	18.5	25.3	10.20
Average	$n = 41$		15.3	15.4	18.5	25.0	

Table B.2.d. Blaney-Criddle temperature expressions, t, calculated in August at nine sites in the Gunnison basin (current study).

Location	Drainage	Year	T_{avg} or *Conventional t*	*Daylight mean t* †	*Daylight weighted mean t* †	*Daily maximum t* †	p
			--------------------degrees C--------------------				
Upper Tomichi Creek	Bottom	1999	13.9				9.52
Upper Tomichi Creek	Upland	1999	13.5				9.52
Quartz Creek	Bottom	1999	14.2				9.52
Lower Tomichi Creek	Bottom	1999	14.8				9.52
Gunnison River North	Upland	1999	14.3				9.52
Ohio Creek	Upland	1999	13.5				9.53
Ohio Creek	Bottom	1999	13.9				9.53
Slate River	Upland	1999	12.7				9.53
Upper Tomichi Creek	Bottom	2000	14.9				9.52
Upper Tomichi Creek	Upland	2000	14.4				9.52
Quartz Creek	Bottom	2000	15.4				9.52
Lower Tomichi Creek	Bottom	2000	16.1				9.52
Gunnison River North	Upland	2000	15.9				9.52
Gunnison River South	Upland	2000	15.7				9.52
Ohio Creek	Upland	2000	14.4				9.53
Ohio Creek	Bottom	2000	15.0				9.53
East River	Upland	2000	14.5				9.53
Slate River	Upland	2000	13.8				9.53
Upper Tomichi Creek	Bottom	2001	14.0				9.52
Upper Tomichi Creek	Upland	2001	13.7				9.52
Quartz Creek	Bottom	2001	14.5				9.52
Gunnison River North	Upland	2001	14.9				9.52
Gunnison River South	Upland	2001	14.7				9.52
Ohio Creek	Upland	2001	13.6				9.53
Ohio Creek	Bottom	2001	14.2				9.53
East River	Upland	2001	13.5				9.53
Slate River	Upland	2001	13.2				9.53
Upper Tomichi Creek	Bottom	2002	13.0				9.52
Gunnison River South	Upland	2002	14.5				9.52
Ohio Creek	Bottom	2002	13.7				9.53
East River	Upland	2002	12.9				9.53
Slate River	Upland	2002	12.5				9.53
Upper Tomichi Creek	Bottom	2003	15.0				9.52
Upper Tomichi Creek	Upland	2003	14.4				9.52
Quartz Creek	Bottom	2003	15.2				9.52
Lower Tomichi Creek	Bottom	2003	16.0				9.52
Gunnison River South	Upland	2003	15.7				9.52
Ohio Creek	Upland	2003	14.8				9.53
Ohio Creek	Bottom	2003	15.2				9.53
East River	Upland	2003	14.3				9.53
Slate River	Upland	2003	13.5				9.53
Average	$n = 41$		14.3				

† Alternative temperature expressions were not determined for months of August and September.

Table B.2.e. Blaney-Criddle temperature expressions, *t*, calculated in September at nine sites in the Gunnison basin (current study).

Location	Drainage	Year	T_{avg} or *Conventional t*	*Daylight mean t* †	*Daylight weighted mean t* †	*Daily maximum t* †	p
			---------degrees C---------				
Upper Tomichi Creek	Bottom	1999	13.9				8.36
Upper Tomichi Creek	Upland	1999	13.5				8.36
Quartz Creek	Bottom	1999	14.2				8.37
Lower Tomichi Creek	Bottom	1999	14.8				8.36
Gunnison River North	Upland	1999	14.3				8.37
Ohio Creek	Upland	1999	13.5				8.37
Ohio Creek	Bottom	1999	13.9				8.37
Slate River	Upland	1999	12.7				8.37
Upper Tomichi Creek	Bottom	2000	14.9				8.36
Upper Tomichi Creek	Upland	2000	14.4				8.36
Quartz Creek	Bottom	2000	15.4				8.37
Lower Tomichi Creek	Bottom	2000	16.1				8.36
Gunnison River North	Upland	2000	15.9				8.37
Gunnison River South	Upland	2000	15.7				8.37
Ohio Creek	Upland	2000	14.4				8.37
Ohio Creek	Bottom	2000	15.0				8.37
East River	Upland	2000	14.5				8.37
Slate River	Upland	2000	13.8				8.37
Upper Tomichi Creek	Bottom	2001	14.0				8.36
Upper Tomichi Creek	Upland	2001	13.7				8.36
Quartz Creek	Bottom	2001	14.5				8.37
Gunnison River North	Upland	2001	14.9				8.37
Gunnison River South	Upland	2001	14.7				8.37
Ohio Creek	Upland	2001	13.6				8.37
Ohio Creek	Bottom	2001	14.2				8.37
East River	Upland	2001	13.5				8.37
Slate River	Upland	2001	13.2				8.37
Upper Tomichi Creek	Bottom	2002	13.0				8.36
Gunnison River South	Upland	2002	14.5				8.37
Ohio Creek	Bottom	2002	13.7				8.37
East River	Upland	2002	12.9				8.37
Slate River	Upland	2002	12.5				8.37
Upper Tomichi Creek	Bottom	2003	15.0				8.36
Upper Tomichi Creek	Upland	2003	14.4				8.36
Quartz Creek	Bottom	2003	15.2				8.37
Lower Tomichi Creek	Bottom	2003	16.0				8.36
Gunnison River South	Upland	2003	15.7				8.37
Ohio Creek	Upland	2003	14.8				8.37
Ohio Creek	Bottom	2003	15.2				8.37
East River	Upland	2003	14.3				8.37
Slate River	Upland	2003	13.5				8.37
Average	$n = 41$		14.3				

† Alternative temperature expressions were not determined for months of August and September.

APPENDIX C: R_s measurements

Table C.1. R_S measured in May at one site in the Gunnison basin, 2000 to 2001.

Year	Day	East River Upland	Gunnison River North Upland	Upper Tomichi Creek Upland
		-------------------MJ m^{-2} d^{-1}-------------------		
2000	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10		31.2	
	11		27.6	
	12		32.5	
	13		27.3	
	14		25.8	
	15		22.8	
	16		32.1	
	17		20.3	
	18		19.6	
	19		21.1	
	20		31.2	
	21		29.8	
	22		31.6	
	23		32.7	
	24		25.6	
	25		18.5	
	26		18.2	
	27		33.7	
	28		32.0	
	29		30.9	
	30		34.1	
	31		33.8	
2001	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		28.4	
	26		21.4	
	27		24.2	
	28		26.6	
	29		22.6	
	30		31.3	
	31		32.3	

Table C.2. R_S measured in June at three sites in the Gunnison basin, 2000 to 2002.

Year	Day	East River Upland	Gunnison River North Upland	Upper Tomichi Creek Upland
			-------------------MJ m^{-2} d^{-1}-------------------	
2000	1		29.3	
	2		28.3	
	3		32.7	
	4		34.0	
	5		22.5	
	6		32.7	
	7		33.2	
	8		26.1	
	9		29.5	
	10		30.3	
	11		26.1	
	12		29.9	
	13		25.6	
	14		32.5	
	15		33.7	
	16		33.6	
	17		34.2	
	18		23.3	
	19		18.0	
	20		33.0	
	21		34.1	
	22		25.9	
	23		25.0	
	24		24.1	
	25		22.5	
	26		17.8	
	27		18.8	
	28		28.8	
	29		29.8	
	30		25.6	
2001	1			
	2		27.1	
	3		29.6	
	4		30.5	
	5		31.9	
	6		31.9	
	7		25.6	
	8		23.6	
	9		31.3	
	10		31.4	
	11		32.6	
	12		27.1	
	13		9.7	
	14		29.0	
	15		32.5	
	16		32.2	
	17		31.7	
	18		32.5	
	19		31.7	
	20		26.6	
	21	29.3	32.1	
	22	29.4	27.1	29.6
	23	27.3	25.6	28.0
	24	25.8	19.9	20.8
	25	23.0	26.4	21.2
	26	25.2	21.1	20.0
	27	20.2	20.0	28.1
	28	22.2	23.9	25.6
	29	26.5	24.9	21.5
	30	26.7	25.0	31.2

Year	Day	East River Upland	Gunnison River North Upland	Upper Tomichi Creek Upland
		--------------------MJ m^{-2} d^{-1}--------------------		
2002	1			
	2			
	3			
	4			18.4
	5			32.4
	6			32.8
	7	30.6		25.5
	8	31.8		27.6
	9	33.1		32.3
	10	32.6		32.1
	11	33.4		32.9
	12	33.7		33.2
	13	33.1		32.5
	14	30.8		31.0
	15	25.8		29.8
	16	31.2		33.0
	17	32.1		32.4
	18	32.8		28.9
	19	28.9		25.5
	20	23.1		23.2
	21	18.0		21.3
	22	25.9		23.8
	23	32.0		29.9
	24	32.0		32.5
	25	25.3		28.4
	26	21.0		28.0
	27	22.1		19.4
	28	25.3		24.9
	29	29.5		30.1
	30	26.6		28.4

Table C.3. R_S measured in July at three sites in the Gunnison basin, 1999 to 2003.

Year	Day	East River Upland	Gunnison River North Upland	Upper Tomichi Creek Upland
			---MJ m^{-2} d^{-1}---	
1999	1			
	2		19.3	
	3		28.3	
	4		29.6	
	5		34.3	
	6		26.5	
	7		31.4	
	8		16.3	
	9		28.8	
	10		33.8	
	11		20.0	
	12		32.9	
	13		29.2	
	14		15.3	
	15		20.7	
	16		26.4	
	17		25.5	
	18		13.9	
	19		19.8	
	20		31.8	
	21		23.7	
	22		22.8	
	23		26.0	
	24		24.6	
	25		22.3	
	26		23.8	
	27		26.9	
	28		24.9	
	29		17.0	
	30		22.3	
	31		21.4	
2000	1		29.3	
	2		22.8	
	3		30.8	
	4		33.4	
	5		32.8	
	6		31.8	
	7		18.1	
	8		25.0	
	9		21.6	
	10		28.5	
	11		32.2	
	12		20.1	
	13		24.8	
	14		24.3	
	15		25.2	
	16		25.3	
	17		21.5	
	18		30.2	
	19		31.0	
	20		28.0	
	21		27.9	
	22		31.2	
	23		26.2	
	24		22.1	
	25		27.4	
	26		22.2	
	27		21.0	
	28		26.1	
	29		23.3	
	30		19.8	
	31		29.5	

Year	Day	East River Upland	Gunnison River North Upland	Upper Tomichi Creek Upland
		--------------------MJ m^{-2} d^{-1}--------------------		
2001	1	17.0	19.0	23.7
	2	24.0	23.0	23.3
	3	28.7	25.8	24.6
	4	22.2	22.0	22.9
	5	23.6	26.1	25.9
	6	27.7	23.9	28.8
	7	25.8	24.2	27.9
	8	22.5	22.3	20.4
	9	24.4	21.9	19.8
	10	25.1	21.8	28.2
	11	22.3	24.5	23.1
	12	19.4	20.3	18.7
	13	20.6	19.6	18.7
	14	17.9	17.3	18.2
	15	22.0	21.0	19.1
	16	30.7	29.5	27.0
	17	19.9	21.1	17.9
	18	27.5	23.5	28.3
	19	24.8	23.6	20.7
	20	21.8	20.4	18.9
	21	19.4	22.4	18.5
	22	25.5	25.1	25.4
	23	22.3	21.4	19.1
	24	15.8	18.2	12.9
	25	24.0	22.3	22.1
	26	14.2	15.2	15.6
	27	27.8	27.6	30.7
	28	28.5	28.6	31.0
	29	30.3	27.2	29.5
	30	17.9	17.2	15.5
	31	17.2	18.2	18.9
2002	1	27.4	30.9	30.2
	2	21.2	22.9	17.7
	3	20.9	24.2	20.3
	4	22.9	22.6	18.5
	5	14.6	17.4	19.4
	6	23.0	22.0	21.8
	7	25.6	25.5	22.4
	8	16.8	22.0	24.3
	9	18.3	21.4	20.2
	10	21.6	23.9	26.6
	11	30.5	28.7	26.4
	12	32.5	32.2	31.7
	13	24.0	25.3	25.6
	14	17.5	16.7	15.2
	15	16.2	20.6	16.9
	16	21.4	29.1	29.4
	17	20.6	25.2	22.0
	18	29.2	29.9	22.3
	19	25.2	30.4	25.5
	20	21.9	22.4	21.9
	21	24.4	32.0	29.4
	22	15.3	18.8	19.8
	23	19.8	25.7	24.3
	24	26.8	24.9	28.1
	25	15.1	14.9	14.3
	26	26.8	27.2	28.0
	27	24.0	23.2	26.9
	28	28.0	28.7	27.1
	29	30.4	30.9	31.2
	30	29.9	29.3	26.8
	31	26.6	30.9	30.6

Year	Day	East River Upland	Gunnison River North Upland	Upper Tomichi Creek Upland
		--------------------MJ m^{-2} d^{-1}--------------------		
2003	1		28.6	23.6
	2		31.3	23.1
	3		30.4	21.5
	4		31.0	27.3
	5		24.3	24.7
	6		22.4	19.1
	7		30.2	21.7
	8		28.0	18.8
	9		30.1	27.0
	10		24.5	21.2
	11		27.4	26.8
	12		21.1	20.1
	13		23.2	21.8
	14	21.2	22.3	16.5
	15	18.4	16.8	27.0
	16	18.6	20.6	23.0
	17	22.7	22.7	30.1
	18	26.0	25.8	19.7
	19	17.0	17.0	23.6
	20	21.3	23.7	23.1
	21	23.4	16.9	21.5
	22	20.2	17.3	27.3
	23	17.6	15.4	24.7
	24	28.2	22.9	19.1
	25	18.0	17.7	21.7
	26	20.5	15.9	18.8
	27	16.5	14.0	27.0
	28	20.9	18.5	21.2
	29	20.5	19.5	26.8
	30	26.0	24.4	20.1
	31	22.2	17.5	21.8

Table C.4. R_S measured in August at three sites in the Gunnison basin, 1999 to 2003.

Year	Day	East River Upland	Gunnison River North Upland	Upper Tomichi Creek Upland
		-------------------MJ m^{-2} d^{-1}-------------------		
1999	1		27.1	
	2		24.1	
	3		18.5	
	4		10.6	
	5		27.5	
	6		20.9	
	7		27.5	
	8		25.3	
	9		19.9	
	10		12.1	
	11		24.0	
	12		26.9	
	13		30.3	
	14		17.3	
	15		16.9	
	16		25.3	
	17		18.3	
	18		22.7	
	19		15.9	
	20		13.0	
	21		18.3	
	22		19.6	
	23		20.3	
	24		23.9	
	25		19.9	
	26		24.4	
	27		17.4	
	28		10.5	
	29		23.3	
	30		21.3	
	31		19.1	
2000	1		20.4	
	2		21.4	
	3		19.9	
	4		20.0	
	5		22.5	
	6		28.8	
	7		20.3	
	8		27.1	
	9		26.2	
	10		23.8	
	11		21.8	
	12		19.8	
	13		24.9	
	14		22.8	
	15		20.5	
	16		21.6	
	17		19.9	
	18		14.0	
	19			
	20			
	21			
	22			
	23			
	24			
	25			
	26			
	27			
	28			
	29			
	30			
	31			

Year	Day	East River Upland	Gunnison River North Upland	Upper Tomichi Creek Upland
		--------------------MJ m^{-2} d^{-1}	--------------------	
2001	1	20.6	21.8	18.5
	2	22.0	24.0	22.9
	3	23.8	23.6	23.7
	4	17.6	19.0	22.3
	5	23.2	24.7	22.4
	6	23.9	22.8	18.7
	7	16.4	21.5	18.9
	8	17.5	19.1	18.0
	9	11.2	18.0	13.4
	10	16.1	14.7	17.6
	11	23.3	24.7	25.9
	12	20.3	23.3	26.6
	13	18.7	16.2	17.2
	14	14.1	13.0	12.5
	15	24.5	25.6	26.6
	16	22.5	23.9	24.0
	17	20.3	27.7	23.8
	18	26.9	26.6	26.0
	19	21.0	16.3	24.5
	20	11.7	13.9	17.1
	21	22.5	18.9	15.9
	22	17.1	15.0	14.1
	23	21.9	25.4	24.5
	24	25.2	25.0	25.7
	25	21.1	22.8	20.4
	26	26.2	26.6	25.3
	27	20.9	21.8	23.4
	28	19.2	21.7	21.7
	29	17.1	21.4	18.6
	30	22.1	22.8	18.8
	31	13.3	10.1	17.6
2002	1	12.0	10.6	10.5
	2	17.1	17.6	16.6
	3	14.0	14.8	15.7
	4	21.9	20.5	19.7
	5	14.0	11.7	14.4
	6	25.2	26.4	21.3
	7	19.1	21.9	14.0
	8	25.2	21.9	22.1
	9	29.3	28.8	29.5
	10	29.6	29.4	29.7
	11	29.5	29.5	29.2
	12	28.6	28.4	28.6
	13	26.7	26.2	25.8
	14	29.0	29.0	29.1
	15	28.9	29.0	29.3
	16	28.3	28.4	27.6
	17	26.4	26.2	27.4
	18	22.0	19.2	21.6
	19	19.9	22.5	19.4
	20	11.8	12.5	12.7
	21	14.9	15.8	17.6
	22	19.0	24.5	19.0
	23	20.0	22.6	22.1
	24	27.6	27.2	27.6
	25	24.9	24.1	23.9
	26	26.0	27.7	26.6
	27	26.9	26.7	26.5
	28	16.8	15.6	12.9
	29	12.7	13.1	15.4
	30	24.4	23.8	24.7
	31	20.2	20.2	21.9

Year	Day	East River Upland	Gunnison River North Upland	Upper Tomichi Creek Upland
		--------------------MJ m^{-2} d^{-1}--------------------		
2003	1	20.4	21.9	25.4
	2	20.8	20.5	23.3
	3	17.3	20.3	19.1
	4	23.5	22.7	28.0
	5	22.1	21.5	24.5
	6	18.1	17.2	17.7
	7	18.6	16.4	20.8
	8	18.4	20.1	27.7
	9	19.4	17.0	28.0
	10	19.1	18.2	24.2
	11	17.9	20.0	24.7
	12	17.1	17.4	20.3
	13	18.5	17.5	24.7
	14	26.6	25.5	28.3
	15	20.8	21.9	24.2
	16	14.7	13.6	19.7
	17	15.0	14.6	20.3
	18	12.4	12.1	15.7
	19	25.8	25.3	28.2
	20	26.3	25.4	28.1
	21	17.4	15.6	18.2
	22	17.3	14.1	15.6
	23	15.5	15.8	19.0
	24	19.2	24.0	24.6
	25	15.4	14.8	17.5
	26	17.7	22.8	18.6
	27	14.5	14.9	19.4
	28	12.5	13.2	12.5
	29	21.1	23.7	23.8
	30	15.8	16.4	19.9
	31	22.6	25.5	26.7

Table C.5. R_S measured in September at three sites in the Gunnison basin, 1999 to 2003.

Year	Day	East River Upland	Gunnison River North Upland	Upper Tomichi Creek Upland
			--------------------MJ m^{-2} d^{-1}--------------------	
1999	1		11.9	
	2		16.9	
	3		21.0	
	4		25.6	
	5		26.2	
	6		24.6	
	7		25.9	
	8		25.7	
	9		20.9	
	10		18.4	
	11		19.4	
	12		22.7	
	13		24.0	
	14		15.8	
	15		13.4	
	16		17.9	
	17		19.8	
	18		16.7	
	19		9.1	
	20		20.7	
	21		23.7	
	22		21.7	
	23		16.3	
	24		14.2	
	25		22.1	
	26		21.9	
	27		21.9	
	28		22.6	
	29		22.3	
	30		22.0	
2000	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
	11			
	12			
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	25			
	26			
	27			
	28			
	29			
	30			

Year	Day	East River Upland	Gunnison River North Upland	Upper Tomichi Creek Upland
		-------------------MJ m^{-2} d^{-1}-------------------		
2001	1	16.0	19.9	21.7
	2	14.3	16.3	20.8
	3	22.1	25.1	24.0
	4	22.4	21.6	16.0
	5	20.1	18.7	21.4
	6	15.1	16.4	17.5
	7	25.1	24.3	23.8
	8	22.8	25.0	21.1
	9	25.7	25.2	24.3
	10	25.5	24.9	23.8
	11	19.2	24.1	23.6
	12	20.7	18.5	19.5
	13	16.2	14.0	17.4
	14	23.0	16.4	20.5
	15	24.2	21.9	22.9
	16	20.5	18.5	20.9
	17	15.4	10.0	13.5
	18	17.6	16.4	19.5
	19	21.8	21.8	22.5
	20	23.0	22.1	22.7
	21	22.4	19.5	21.7
	22	18.8	17.6	20.4
	23	20.3	22.1	22.5
	24	20.6	21.7	22.1
	25	19.8	21.0	21.3
	26	21.8	21.1	21.4
	27	21.9	21.3	21.8
	28	16.4	19.1	17.0
	29	16.6	18.3	14.0
	30	16.7	16.4	16.6
2002	1	24.6	19.9	21.2
	2	26.0	16.3	26.6
	3	17.5	25.1	11.8
	4	21.1	21.6	21.7
	5	24.5	18.7	25.2
	6	15.8	16.4	15.1
	7	12.2	24.3	16.2
	8	20.6	25.0	15.6
	9	10.7	25.2	13.7
	10	13.6	24.9	14.8
	11	9.7	24.1	12.6
	12	13.5	18.5	14.7
	13	13.3	14.0	12.4
	14	20.3	16.4	18.3
	15	23.7	21.9	23.8
	16	22.6	18.5	22.6
	17	19.6	10.0	18.5
	18	10.0	16.4	10.1
	19	18.7	21.8	19.5
	20	22.9	22.1	23.4
	21	22.6	19.5	23.2
	22	22.4	17.6	23.0
	23	22.2	22.1	22.9
	24	22.3	21.7	22.8
	25	12.4	21.0	14.2
	26	17.1	21.1	15.7
	27	11.1	21.3	10.9
	28	15.0	19.1	13.5
	29	9.0	18.3	9.7
	30	18.5	16.4	20.8

Year	Day	East River Upland	Gunnison River North Upland	Upper Tomichi Creek Upland
		MJ m^{-2} d^{-1}		
2003	1	22.3	23.5	26.3
	2	25.2	21.6	22.9
	3	16.8	13.1	14.2
	4	21.5	24.6	22.8
	5	15.0	16.1	15.9
	6	13.9	11.3	17.2
	7	10.0	14.7	11.0
	8	21.6	22.1	22.5
	9	5.9	5.4	4.7
	10	7.6	6.5	5.3
	11	13.4	19.1	17.3
	12	20.7	23.7	24.6
	13	18.5	16.2	19.4
	14	24.1	24.4	25.2
	15	23.4	21.8	24.4
	16	20.9	22.5	23.1
	17	18.4	20.1	21.4
	18	22.9	23.4	24.0
	19	22.5	22.8	23.5
	20	20.9	21.9	20.8
	21	22.2	22.7	23.2
	22	22.2	22.6	23.3
	23	22.0	22.3	23.0
	24	21.6	21.9	22.7
	25	21.9	22.2	22.7
	26	21.6	21.8	22.3
	27	21.0	21.4	21.9
	28	21.2	21.1	21.5
	29	20.9	21.1	21.1
	30	18.2	18.5	18.7

APPENDIX D: Consumptive use factors, f

Table D.1. Blaney-Criddle consumptive use factor, *f*, calculated in May at nine sites in the Gunnison basin (current study) using each of four temperature variables, *t*.

Location		Year	*f* (*conventional t*)	*f* (*daylight mean t*)	*f* (*daylight weighted mean t*)	*f* (*daily maximum mean t*)
			----------mm mo^{-1}----------			
Upper Tomichi Creek	Bottom	2000	121.8	123.0	138.7	163.3
Upper Tomichi Creek	Upland	2000	119.6	120.8	138.1	163.1
Quartz Creek	Bottom	2000	123.4	124.4	140.5	165.2
Lower Tomichi Creek	Bottom	2000	124.2	125.2	141.5	166.9
Gunnison River South	Upland	2000	123.5	125.4	141.5	169.5
Ohio Creek	Upland	2000	121.4	122.8	137.8	161.9
East River	Upland	2000	117.5	119.7	137.1	164.1
Slate River	Upland	2000	117.3	118.7	135.2	159.6
Upper Tomichi Creek	Bottom	2001	119.8	121.4	136.4	158.7
Upper Tomichi Creek	Upland	2001	117.7	119.2	135.7	158.1
Quartz Creek	Bottom	2001	121.6	122.6	136.9	166.5
Gunnison River North	Upland	2001	121.7	123.0	137.7	162.9
Gunnison River South	Upland	2001	121.2	122.6	137.1	162.4
Ohio Creek	Upland	2001	119.5	120.4	135.9	159.1
Ohio Creek	Bottom	2001	118.3	119.0	136.2	160.3
East River	Upland	2001	116.0	117.3	134.4	159.7
Slate River	Upland	2001	113.3	114.0	129.4	151.8
Upper Tomichi Creek	Bottom	2002	112.1	114.8	134.5	158.6
Gunnison River South	Upland	2002	117.4	119.5	137.9	164.9
Ohio Creek	Bottom	2002	113.9	115.9	135.6	160.3
East River	Upland	2002	110.9	114.0	132.0	156.2
Slate River	Upland	2002	108.5	110.1	127.4	148.7
Upper Tomichi Creek	Bottom	2003	119.3	120.7	133.5	157.3
Upper Tomichi Creek	Upland	2003	116.3	118.2	132.7	156.7
Quartz Creek	Bottom	2003	120.7	121.9	133.3	157.3
Lower Tomichi Creek	Bottom	2003	121.6	122.6	136.6	161.5
Gunnison River South	Upland	2003	122.2	122.8	135.3	160.2
Ohio Creek	Upland	2003	117.7	119.4	132.5	156.3
Ohio Creek	Bottom	2003	117.8	119.4	133.1	157.4
East River	Upland	2003	115.3	116.7	129.9	155.9
Slate River	Upland	2003	111.5	112.8	126.1	146.6
Average	$n = 31$		118.2	119.6	135.2	159.7

Table D.2 Blaney-Criddle consumptive use factor, *f*, calculated in June at nine sites in the Gunnison basin (current study) using each of four temperature variables, *t*.

Location	Drainage	Year	*f* (*conventional t*)	*f* (*daylight mean t*)	*f* (*daylight weighted mean t*)	*f* (*daily maximum mean t*)
			------------------------mm mo^{-1}------------------------			
Upper Tomichi Creek	Bottom	1999	132.8	133.4	150.3	175.5
Upper Tomichi Creek	Upland	1999	128.8	129.8	148.7	173.8
Quartz Creek	Bottom	1999	134.1	134.8	150.7	174.1
Lower Tomichi Creek	Bottom	1999	135.0	135.2	154.6	179.7
Gunnison River North	Upland	1999	133.9	135.1	151.3	177.1
Ohio Creek	Upland	1999	129.1	130.4	147.9	171.2
Ohio Creek	Bottom	1999	131.6	132.5	149.9	174.4
Slate River	Upland	1999	125.1	125.9	143.5	166.5
Upper Tomichi Creek	Bottom	2000	137.1	138.4	156.0	180.3
Upper Tomichi Creek	Upland	2000	133.4	134.9	154.4	178.8
Quartz Creek	Bottom	2000	139.9	140.7	157.1	179.4
Lower Tomichi Creek	Bottom	2000	140.3	140.3	159.3	184.1
Gunnison River North	Upland	2000	138.9	140.0	156.6	183.9
Gunnison River South	Upland	2000	138.3	139.8	156.5	183.7
Ohio Creek	Upland	2000	133.2	134.6	154.1	176.0
Ohio Creek	Bottom	2000	135.5	136.8	155.1	177.9
East River	Upland	2000	133.9	135.5	153.6	181.4
Slate River	Upland	2000	130.4	131.0	149.0	171.0
Upper Tomichi Creek	Bottom	2001	136.7	137.4	156.3	181.4
Upper Tomichi Creek	Upland	2001	133.5	135.2	155.3	180.4
Quartz Creek	Bottom	2001	140.1	140.2	157.4	177.7
Gunnison River North	Upland	2001	138.8	140.0	157.1	183.3
Gunnison River South	Upland	2001	138.3	139.9	157.0	183.1
Ohio Creek	Upland	2001	137.3	138.9	158.0	183.0
Ohio Creek	Bottom	2001	137.2	137.2	157.0	182.1
East River	Upland	2001	134.7	135.5	154.8	180.5
Slate River	Upland	2001	130.6	131.2	150.2	173.7
Upper Tomichi Creek	Bottom	2002	141.1	143.3	165.5	191.8
Gunnison River South	Upland	2002	143.9	145.1	164.3	191.5
Ohio Creek	Bottom	2002	140.7	141.7	163.5	189.9
East River	Upland	2002	138.6	139.4	159.9	186.4
Slate River	Upland	2002	135.4	135.8	157.0	181.4
Upper Tomichi Creek	Bottom	2003	132.3	133.8	150.2	175.0
Upper Tomichi Creek	Upland	2003	129.3	131.0	149.2	174.2
Quartz Creek	Bottom	2003	133.3	134.1	149.6	172.6
Lower Tomichi Creek	Bottom	2003	136.2	136.6	154.0	179.2
Gunnison River South	Upland	2003	133.9	135.1	150.6	176.0
Ohio Creek	Upland	2003	129.9	131.0	149.2	175.0
Ohio Creek	Bottom	2003	131.3	131.7	149.5	174.6
East River	Upland	2003	128.8	129.6	146.4	171.4
Slate River	Upland	2003	126.2	126.4	142.8	166.1
Average	$n = 41$		134.6	135.6	153.7	178.5

Table D.3 Blaney-Criddle consumptive use factor, *f*, calculated in July at nine sites in the Gunnison basin (current study) using each of four temperature variables, *t*.

Location		Year	*f* (*conventional t*)	*f* (*daylight mean t*)	*f* (*daylight weighted mean t*)	*f* (*daily maximum mean t*)
			------------------------mm mo^{-1}			------------------------
Upper Tomichi Creek	Bottom	1999	155.5	156.3	164.6	190.0
Upper Tomichi Creek	Upland	1999	153.2	154.6	163.5	189.4
Quartz Creek	Bottom	1999	155.7	156.2	164.3	188.1
Lower Tomichi Creek	Bottom	1999	158.2	159.2	170.8	198.0
Gunnison River North	Upland	1999	156.4	157.1	166.3	192.1
Ohio Creek	Upland	1999	151.2	152.0	162.9	187.4
Ohio Creek	Bottom	1999	153.6	154.4	164.6	189.9
Slate River	Upland	1999	148.5	148.8	158.7	182.5
Upper Tomichi Creek	Bottom	2000	152.8	153.4	169.4	198.9
Upper Tomichi Creek	Upland	2000	148.7	149.9	168.5	199.0
Quartz Creek	Bottom	2000	154.3	154.7	168.6	195.5
Lower Tomichi Creek	Bottom	2000	157.2	157.4	174.9	207.0
Gunnison River North	Upland	2000	155.4	156.1	169.8	200.1
Gunnison River South	Upland	2000	155.7	156.5	170.6	197.3
Ohio Creek	Upland	2000	150.9	151.6	168.6	198.2
Ohio Creek	Bottom	2000	151.9	152.4	169.0	198.8
East River	Upland	2000	149.2	149.8	164.5	193.2
Slate River	Upland	2000	147.1	147.3	162.8	189.9
Upper Tomichi Creek	Bottom	2001	152.9	153.3	165.9	194.9
Upper Tomichi Creek	Upland	2001	149.9	150.7	165.4	194.4
Quartz Creek	Bottom	2001	155.2	155.4	166.9	198.7
Gunnison River North	Upland	2001	155.9	157.0	168.4	196.6
Gunnison River South	Upland	2001	155.8	156.8	168.6	197.4
Ohio Creek	Upland	2001	152.2	153.2	165.8	192.0
Ohio Creek	Bottom	2001	153.5	154.1	166.8	194.4
East River	Upland	2001	152.2	152.7	164.1	198.9
Slate River	Upland	2001	148.9	148.9	161.0	187.6
Upper Tomichi Creek	Bottom	2002	155.1	156.2	172.8	202.4
Gunnison River South	Upland	2002	158.1	159.1	174.7	206.6
Ohio Creek	Bottom	2002	155.7	156.1	173.5	204.5
East River	Upland	2002	153.7	154.2	169.4	200.0
Slate River	Upland	2002	150.3	150.4	167.0	196.1
Upper Tomichi Creek	Bottom	2003	155.1	156.7	174.0	206.4
Upper Tomichi Creek	Upland	2003	152.5	154.3	174.4	208.6
Quartz Creek	Bottom	2003	158.6	159.1	174.2	203.6
Lower Tomichi Creek	Bottom	2003	159.5	160.1	178.5	211.6
Gunnison River South	Upland	2003	159.2	159.8	175.9	208.8
Ohio Creek	Upland	2003	157.1	157.6	177.2	208.5
Ohio Creek	Bottom	2003	157.2	157.5	176.4	208.3
East River	Upland	2003	154.2	154.6	171.9	203.3
Slate River	Upland	2003	151.6	152.1	169.2	199.7
Average	$n = 41$		153.9	154.6	168.9	198.0

Table D.4 Blaney-Criddle consumptive use factor, f, calculated in August at nine sites in the Gunnison basin (current study) using the conventional temperature variable, t.

Location		Year	f(conventional t)	f(daylight mean t) †	f(daylight weighted mean t) †	f(daily maximum mean t)
			------------------------mm mo^{-1}------------------------			
Upper Tomichi Creek	Bottom	1999	137.8			
Upper Tomichi Creek	Upland	1999	135.9			
Quartz Creek	Bottom	1999	139.3			
Lower Tomichi Creek	Bottom	1999	141.8			
Gunnison River North	Upland	1999	139.8			
Ohio Creek	Upland	1999	136.2			
Ohio Creek	Bottom	1999	137.9			
Slate River	Upland	1999	132.9			
Upper Tomichi Creek	Bottom	2000	142.4			
Upper Tomichi Creek	Upland	2000	140.2			
Quartz Creek	Bottom	2000	144.4			
Lower Tomichi Creek	Bottom	2000	147.7			
Gunnison River North	Upland	2000	146.8			
Gunnison River South	Upland	2000	145.7			
Ohio Creek	Upland	2000	140.0			
Ohio Creek	Bottom	2000	143.0			
East River	Upland	2000	140.5			
Slate River	Upland	2000	137.7			
Upper Tomichi Creek	Bottom	2001	138.4			
Upper Tomichi Creek	Upland	2001	136.9			
Quartz Creek	Bottom	2001	140.3			
Gunnison River North	Upland	2001	142.4			
Gunnison River South	Upland	2001	141.5			
Ohio Creek	Upland	2001	136.6			
Ohio Creek	Bottom	2001	139.1			
East River	Upland	2001	136.3			
Slate River	Upland	2001	134.9			
Upper Tomichi Creek	Bottom	2002	133.8			
Gunnison River South	Upland	2002	140.3			
Ohio Creek	Bottom	2002	137.1			
East River	Upland	2002	133.9			
Slate River	Upland	2002	132.1			
Upper Tomichi Creek	Bottom	2003	142.5			
Upper Tomichi Creek	Upland	2003	140.0			
Quartz Creek	Bottom	2003	143.4			
Lower Tomichi Creek	Bottom	2003	147.0			
Gunnison River South	Upland	2003	145.9			
Ohio Creek	Upland	2003	142.0			
Ohio Creek	Bottom	2003	143.6			
East River	Upland	2003	139.6			
Slate River	Upland	2003	136.2			
Average	$n = 41$		139.8			

† Alternative temperature expressions were not determined for months of August and September.

Table D.5 Blaney-Criddle consumptive use factor, f, calculated in September at nine sites in the Gunnison basin (current study) using the conventional temperature variable, t.

Location		Year	f(conventional t)	f(daylight mean t)	f(daylight weighted mean t) †	f(daily maximum mean t) †
			---mm mo^{-1}---			
Upper Tomichi Creek	Bottom	1999	100.2			
Upper Tomichi Creek	Upland	1999	97.2			
Quartz Creek	Bottom	1999	104.0			
Lower Tomichi Creek	Bottom	1999	103.8			
Gunnison River North	Upland	1999	102.0			
Ohio Creek	Upland	1999	101.4			
Ohio Creek	Bottom	1999	100.4			
Slate River	Upland	1999	96.1			
Upper Tomichi Creek	Bottom	2000	107.6			
Upper Tomichi Creek	Upland	2000	105.6			
Quartz Creek	Bottom	2000	109.9			
Lower Tomichi Creek	Bottom	2000	110.0			
Gunnison River North	Upland	2000	111.0			
Gunnison River South	Upland	2000	110.4			
Ohio Creek	Upland	2000	109.0			
Ohio Creek	Bottom	2000	107.7			
East River	Upland	2000	105.9			
Slate River	Upland	2000	105.3			
Upper Tomichi Creek	Bottom	2001	104.7			
Upper Tomichi Creek	Upland	2001	102.7			
Quartz Creek	Bottom	2001	107.8			
Gunnison River North	Upland	2001	111.6			
Gunnison River South	Upland	2001	111.4			
Ohio Creek	Upland	2001	108.6			
Ohio Creek	Bottom	2001	105.7			
East River	Upland	2001	106.1			
Slate River	Upland	2001	104.7			
Upper Tomichi Creek	Bottom	2002	105.7			
Gunnison River South	Upland	2002	109.6			
Ohio Creek	Bottom	2002	106.9			
East River	Upland	2002	105.2			
Slate River	Upland	2002	102.5			
Upper Tomichi Creek	Bottom	2003	101.5			
Upper Tomichi Creek	Upland	2003	98.1			
Quartz Creek	Bottom	2003	104.0			
Lower Tomichi Creek	Bottom	2003	105.7			
Gunnison River South	Upland	2003	103.3			
Ohio Creek	Upland	2003	102.7			
Ohio Creek	Bottom	2003	101.4			
East River	Upland	2003	100.7			
Slate River	Upland	2003	99.1			
Average	$n = 41$		104.8			

† Alternative temperature expressions were not determined for months of August and September.

APPENDIX E: Hargreaves Reference ET and temperature variables

Table E.1. Hargreaves temperature expressions T_{mean}, T_{diff}, and Hargreaves reference ET, calculated in May at nine sites in the Gunnison basin (current study).

Location		Year	T_{mean} †	T_{diff}	Hargreaves reference ET
			-----degrees C-----		--mm mo^{-1}--
Upper Tomichi Creek	Bottom	2000	8.9	18.6	132.6
Upper Tomichi Creek	Upland	2000	8.4	19.5	127.8
Quartz Creek	Bottom	2000	9.3	18.7	134.9
Lower Tomichi Creek	Bottom	2000	9.4	19.0	136.1
Gunnison River South	Upland	2000	9.3	20.5	140.7
Ohio Creek	Upland	2000	8.8	18.1	129.8
East River	Upland	2000	7.9	20.8	132.6
Slate River	Upland	2000	7.9	19.1	126.9
Upper Tomichi Creek	Bottom	2001	8.5	17.5	126.7
Upper Tomichi Creek	Upland	2001	8.0	18.1	125.5
Quartz Creek	Bottom	2001	8.9	17.3	128.0
Gunnison River North	Upland	2001	8.9	18.5	141.0
Gunnison River South	Upland	2001	8.8	18.5	130.8
Ohio Creek	Upland	2001	8.4	17.8	127.3
Ohio Creek	Bottom	2001	8.1	18.7	129.0
East River	Upland	2001	7.6	19.7	129.3
Slate River	Upland	2001	7.0	17.3	118.1
Upper Tomichi Creek	Bottom	2002	6.8	20.8	129.3
Gunnison River South	Upland	2002	7.9	21.5	136.9
Ohio Creek	Bottom	2002	7.2	20.8	130.6
East River	Upland	2002	6.5	20.2	124.7
Slate River	Upland	2002	6.0	17.9	116.1
Upper Tomichi Creek	Bottom	2003	8.4	16.8	124.5
Upper Tomichi Creek	Upland	2003	7.7	18.1	125.2
Quartz Creek	Bottom	2003	8.7	16.3	124.0
Lower Tomichi Creek	Bottom	2003	8.9	17.8	129.5
Gunnison River South	Upland	2003	9.0	16.9	127.8
Ohio Creek	Upland	2003	8.0	17.2	124.0
Ohio Creek	Bottom	2003	8.0	17.5	124.7
East River	Upland	2003	7.5	18.3	124.2
Slate River	Upland	2003	6.6	15.8	113.0
Average	*n* = 31		8.1	18.5	128.1

†T_{mean} is the equivalent of the Blaney-Criddle T_{avg}, and the expression *conventional t.*

Table E.2. Hargreaves temperature expressions T_{mean}, T_{diff}, and Hargreaves reference ET, calculated in June at nine sites in the Gunnison basin (current study).

Location	Drainage	Year	T_{mean} †	T_{diff}	Hargreaves reference ET
			-----degrees C-----		--mm mo^{-1}--
Upper Tomichi Creek	Bottom	1999	11.2	19.2	148.1
Upper Tomichi Creek	Upland	1999	10.3	20.2	145.8
Quartz Creek	Bottom	1999	11.5	17.9	144.0
Lower Tomichi Creek	Bottom	1999	11.7	20.0	152.1
Gunnison River North	Upland	1999	11.4	19.4	149.6
Ohio Creek	Upland	1999	10.4	18.9	142.7
Ohio Creek	Bottom	1999	10.9	19.2	146.8
Slate River	Upland	1999	9.5	18.5	136.1
Upper Tomichi Creek	Bottom	2000	12.1	19.4	151.6
Upper Tomichi Creek	Upland	2000	11.3	20.3	151.6
Quartz Creek	Bottom	2000	12.7	17.8	149.4
Lower Tomichi Creek	Bottom	2000	12.8	19.6	157.7
Gunnison River North	Upland	2000	12.5	19.1	153.7
Gunnison River South	Upland	2000	12.4	19.2	153.2
Ohio Creek	Upland	2000	11.2	19.4	148.3
Ohio Creek	Bottom	2000	11.7	19.1	150.1
East River	Upland	2000	11.4	20.2	152.1
Slate River	Upland	2000	10.6	18.2	141.0
Upper Tomichi Creek	Bottom	2001	12.1	20.1	154.9
Upper Tomichi Creek	Upland	2001	11.4	21.1	155.7
Quartz Creek	Bottom	2001	12.8	18.3	151.6
Gunnison River North	Upland	2001	12.5	19.9	153.7
Gunnison River South	Upland	2001	12.4	19.9	156.2
Ohio Creek	Upland	2001	12.1	20.5	157.5
Ohio Creek	Bottom	2001	12.1	20.2	156.0
East River	Upland	2001	11.6	20.4	153.7
Slate River	Upland	2001	10.7	19.4	145.8
Upper Tomichi Creek	Bottom	2002	13.0	22.6	169.9
Gunnison River South	Upland	2002	13.6	21.2	167.4
Ohio Creek	Bottom	2002	12.9	22.0	166.9
East River	Upland	2002	12.4	21.5	163.1
Slate River	Upland	2002	11.7	20.5	155.2
Upper Tomichi Creek	Bottom	2003	11.1	19.0	146.1
Upper Tomichi Creek	Upland	2003	10.4	20.1	146.6
Quartz Creek	Bottom	2003	11.3	17.7	142.0
Lower Tomichi Creek	Bottom	2003	11.9	19.3	151.1
Gunnison River South	Upland	2003	11.4	18.8	146.3
Ohio Creek	Upland	2003	10.5	20.1	147.1
Ohio Creek	Bottom	2003	10.8	19.3	145.8
East River	Upland	2003	10.3	19.0	141.7
Slate River	Upland	2003	9.7	17.8	134.4
Average	$n = 41$		11.6	19.6	150.8

†T_{mean} is the equivalent of the Blaney-Criddle T_{avg}, and the expression *conventional t*.

Table E.3. Hargreaves temperature expressions T_{mean}, T_{diff}, and Hargreaves reference ET, calculated in July at nine sites in the Gunnison basin (current study).

Location		Year	T_{mean} †	T_{diff}	Hargreaves reference ET
			-----degrees C-----		--mm mo^{-1}--
Upper Tomichi Creek	Bottom	1999	15.6	15.5	153.7
Upper Tomichi Creek	Upland	1999	15.1	16.0	152.9
Quartz Creek	Bottom	1999	15.7	14.7	149.9
Lower Tomichi Creek	Bottom	1999	16.2	17.9	168.1
Gunnison River North	Upland	1999	15.8	16.0	157.0
Ohio Creek	Upland	1999	14.7	16.3	152.9
Ohio Creek	Bottom	1999	15.2	16.2	155.2
Slate River	Upland	1999	14.1	15.2	144.5
Upper Tomichi Creek	Bottom	2000	15.1	20.4	173.5
Upper Tomichi Creek	Upland	2000	14.2	22.1	175.5
Quartz Creek	Bottom	2000	15.4	18.2	165.1
Lower Tomichi Creek	Bottom	2000	16.0	22.1	185.2
Gunnison River North	Upland	2000	15.6	19.9	174.5
Gunnison River South	Upland	2000	15.6	20.5	177.0
Ohio Creek	Upland	2000	14.6	21.0	173.5
Ohio Creek	Bottom	2000	14.8	20.8	174.5
East River	Upland	2000	14.2	19.6	165.4
Slate River	Upland	2000	13.8	19.0	160.3
Upper Tomichi Creek	Bottom	2001	15.1	18.7	166.9
Upper Tomichi Creek	Upland	2001	14.4	19.8	167.6
Quartz Creek	Bottom	2001	15.5	16.8	160.8
Gunnison River North	Upland	2001	15.7	18.2	174.5
Gunnison River South	Upland	2001	15.7	18.7	170.2
Ohio Creek	Upland	2001	14.9	17.7	161.0
Ohio Creek	Bottom	2001	15.2	18.2	163.8
East River	Upland	2001	14.9	17.6	160.5
Slate River	Upland	2001	14.2	17.3	155.4
Upper Tomichi Creek	Bottom	2002	15.6	20.9	178.8
Gunnison River South	Upland	2002	16.2	21.4	185.4
Ohio Creek	Bottom	2002	15.6	21.6	182.4
East River	Upland	2002	15.2	20.5	175.3
Slate River	Upland	2002	14.4	20.3	170.2
Upper Tomichi Creek	Bottom	2003	15.6	22.6	185.7
Upper Tomichi Creek	Upland	2003	15.0	24.8	191.3
Quartz Creek	Bottom	2003	16.3	19.9	179.1
Lower Tomichi Creek	Bottom	2003	16.5	23.0	191.8
Gunnison River South	Upland	2003	16.4	22.1	189.0
Ohio Creek	Upland	2003	15.9	22.7	188.2
Ohio Creek	Bottom	2003	16.0	22.6	188.7
East River	Upland	2003	15.3	21.8	180.8
Slate River	Upland	2003	14.7	21.1	176.0
Average	$n = 41$		15.3	19.5	170.8

†T_{mean} is the equivalent of the Blaney-Criddle T_{avg}, and the expression *conventional t.*

Table E.4. Hargreaves temperature expressions T_{mean}, T_{diff}, and Hargreaves reference ET, calculated in August at nine sites in the Gunnison basin (current study).

Location		Year	T_{mean} †	T_{diff}	Hargreaves reference ET
			-----degrees C-----		--mm mo^{-1}--
Upper Tomichi Creek	Bottom	1999	13.9	17.0	137.4
Upper Tomichi Creek	Upland	1999	13.5	18.2	139.4
Quartz Creek	Bottom	1999	14.2	15.9	133.9
Lower Tomichi Creek	Bottom	1999	14.8	18.4	147.1
Gunnison River North	Upland	1999	14.3	17.0	138.7
Ohio Creek	Upland	1999	13.5	15.9	131.6
Ohio Creek	Bottom	1999	13.9	16.8	136.1
Slate River	Upland	1999	12.7	15.3	124.7
Upper Tomichi Creek	Bottom	2000	14.9	20.1	156.2
Upper Tomichi Creek	Upland	2000	14.4	22.3	161.5
Quartz Creek	Bottom	2000	15.4	17.6	147.1
Lower Tomichi Creek	Bottom	2000	16.1	18.6	154.7
Gunnison River North	Upland	2000	15.9	19.9	160.0
Gunnison River South	Upland	2000	15.7	19.8	158.0
Ohio Creek	Upland	2000	14.4	18.9	148.3
Ohio Creek	Bottom	2000	15.0	19.5	153.4
East River	Upland	2000	14.5	18.7	147.8
Slate River	Upland	2000	13.8	17.5	139.7
Upper Tomichi Creek	Bottom	2001	14.0	18.4	143.5
Upper Tomichi Creek	Upland	2001	13.7	20.7	149.9
Quartz Creek	Bottom	2001	14.5	17.2	141.0
Gunnison River North	Upland	2001	14.9	19.1	160.0
Gunnison River South	Upland	2001	14.7	19.3	150.1
Ohio Creek	Upland	2001	13.6	17.2	136.7
Ohio Creek	Bottom	2001	14.2	18.7	145.3
East River	Upland	2001	13.5	17.5	137.2
Slate River	Upland	2001	13.2	16.6	132.3
Upper Tomichi Creek	Bottom	2002	13.0	22.0	151.9
Gunnison River South	Upland	2002	14.5	22.6	161.0
Ohio Creek	Bottom	2002	13.7	22.3	155.7
East River	Upland	2002	12.9	21.3	148.8
Slate River	Upland	2002	12.5	20.5	143.8
Upper Tomichi Creek	Bottom	2003	15.0	19.3	152.7
Upper Tomichi Creek	Upland	2003	14.4	21.3	157.2
Quartz Creek	Bottom	2003	15.2	17.6	147.3
Lower Tomichi Creek	Bottom	2003	16.0	19.8	159.3
Gunnison River South	Upland	2003	15.7	19.0	154.2
Ohio Creek	Upland	2003	14.8	18.9	149.4
Ohio Creek	Bottom	2003	15.2	19.8	156.2
East River	Upland	2003	14.3	18.6	146.3
Slate River	Upland	2003	13.5	16.7	134.6
Average	$n = 41$		14.3	18.8	147.1

†T_{mean} is the equivalent of the Blaney-Criddle T_{avg}, and the expression *conventional t*.

Table E.5. Hargreaves temperature expressions T_{mean}, T_{diff}, and Hargreaves reference ET, calculated in September at nine sites in the Gunnison basin (current study).

Location		Year	T_{mean} †	T_{diff}	Hargreaves reference ET
			-----degrees C-----		--mm mo^{-1}--
Upper Tomichi Creek	Bottom	1999	8.4	20.7	100.1
Upper Tomichi Creek	Upland	1999	7.6	22.9	102.4
Quartz Creek	Bottom	1999	9.4	18.2	97.8
Lower Tomichi Creek	Bottom	1999	9.4	19.9	101.9
Gunnison River North	Upland	1999	8.9	20.4	101.9
Ohio Creek	Upland	1999	8.7	18.3	96.3
Ohio Creek	Bottom	1999	8.5	20.0	98.6
Slate River	Upland	1999	7.4	17.6	88.4
Upper Tomichi Creek	Bottom	2000	10.3	20.8	108.7
Upper Tomichi Creek	Upland	2000	9.8	23.3	112.8
Quartz Creek	Bottom	2000	11.0	19.3	106.4
Lower Tomichi Creek	Bottom	2000	11.0	20.6	111.0
Gunnison River North	Upland	2000	11.2	21.9	114.8
Gunnison River South	Upland	2000	11.1	21.9	115.1
Ohio Creek	Upland	2000	10.7	20.6	110.2
Ohio Creek	Bottom	2000	10.4	21.5	110.2
East River	Upland	2000	9.9	21.3	107.2
Slate River	Upland	2000	9.8	19.1	110.2
Upper Tomichi Creek	Bottom	2001	9.6	22.2	108.5
Upper Tomichi Creek	Upland	2001	9.1	24.7	112.5
Quartz Creek	Bottom	2001	10.4	19.6	105.4
Gunnison River North	Upland	2001	11.4	23.8	114.8
Gunnison River South	Upland	2001	11.3	23.9	120.7
Ohio Creek	Upland	2001	10.6	20.9	110.0
Ohio Creek	Bottom	2001	9.8	22.7	111.0
East River	Upland	2001	10.0	22.9	111.5
Slate River	Upland	2001	9.6	21.0	105.2
Upper Tomichi Creek	Bottom	2002	9.9	18.5	100.3
Gunnison River South	Upland	2002	10.9	18.9	105.4
Ohio Creek	Bottom	2002	10.2	18.2	100.6
East River	Upland	2002	9.7	17.7	97.0
Slate River	Upland	2002	9.0	16.6	92.2
Upper Tomichi Creek	Bottom	2003	8.8	22.0	104.1
Upper Tomichi Creek	Upland	2003	7.9	25.1	107.4
Quartz Creek	Bottom	2003	9.4	19.8	101.6
Lower Tomichi Creek	Bottom	2003	9.9	21.3	106.4
Gunnison River South	Upland	2003	9.2	22.0	104.6
Ohio Creek	Upland	2003	9.1	20.4	101.6
Ohio Creek	Bottom	2003	8.7	21.7	102.4
East River	Upland	2003	8.5	21.6	100.8
Slate River	Upland	2003	8.1	20.3	97.0
Average	$n = 41$		9.6	20.8	105.2

†T_{mean} is the equivalent of the Blaney-Criddle T_{avg}, and the expression *conventional t.*

APPENDIX F: Blaney-Criddle k and Hargreaves K_c

Table F.1. Blaney-Criddle crop coefficients, k and Hargreaves crop coefficients, K_c, calculated in May at nine sites in the Gunnison basin (current study).

			Blaney-Criddle k				K_c
Location	Drainage	Year	*Conventional t*	*Daylight mean t*	*Daylight weighted mean t*	*Daily maximum t*	Hargreaves
Upper Tomichi Creek	Bottom	2000	1.59	1.58	1.40	1.19	1.46
Upper Tomichi Creek	Upland	2000	1.04	1.03	0.90	0.76	0.98
Quartz Creek	Bottom	2000	1.54	1.53	1.35	1.15	1.41
Lower Tomichi Creek	Bottom	2000	1.68	1.67	1.48	1.25	1.53
Gunnison River South	Upland	2000	1.56	1.54	1.36	1.14	1.37
Ohio Creek	Upland	2000	1.44	1.42	1.27	1.08	1.35
East River	Upland	2000	1.45	1.42	1.24	1.04	1.28
Slate River	Upland	2000	1.56	1.54	1.35	1.15	1.44
Upper Tomichi Creek	Bottom	2001	1.06	1.05	0.93	0.80	1.00
Upper Tomichi Creek	Upland	2001	1.16	1.15	1.01	0.87	1.09
Quartz Creek	Bottom	2001	1.26	1.25	1.12	0.92	1.20
Gunnison River North	Upland	2001	0.98	0.97	0.87	0.73	0.84
Gunnison River South	Upland	2001	1.20	1.18	1.06	0.89	1.11
Ohio Creek	Upland	2001	0.80	0.80	0.71	0.60	0.76
Ohio Creek	Bottom	2001	1.22	1.22	1.06	0.90	1.12
East River	Upland	2001	1.29	1.27	1.11	0.93	1.15
Slate River	Upland	2001	1.18	1.17	1.03	0.88	1.13
Upper Tomichi Creek	Bottom	2002	1.18	1.15	0.98	0.83	1.02
Gunnison River South	Upland	2002	1.61	1.58	1.37	1.14	1.38
Ohio Creek	Bottom	2002	1.49	1.46	1.25	1.06	1.30
East River	Upland	2002	1.41	1.38	1.19	1.01	1.26
Slate River	Upland	2002	1.36	1.34	1.16	0.99	1.27
Upper Tomichi Creek	Bottom	2003	1.19	1.17	1.06	0.90	1.14
Upper Tomichi Creek	Upland	2003	1.15	1.13	1.01	0.85	1.07
Quartz Creek	Bottom	2003	1.10	1.09	1.00	0.85	1.07
Lower Tomichi Creek	Bottom	2003	0.98	0.97	0.87	0.73	0.92
Gunnison River South	Upland	2003	1.49	1.48	1.34	1.13	1.42
Ohio Creek	Upland	2003	1.16	1.14	1.03	0.87	1.10
Ohio Creek	Bottom	2003	1.24	1.22	1.09	0.93	1.17
East River	Upland	2003	1.06	1.05	0.94	0.78	0.98
Slate River	Upland	2003	1.05	1.03	0.92	0.80	1.03
Average	$n = 31$		1.27	1.26	1.11	0.94	1.17

Table F.2. Blaney-Criddle crop coefficients, k and Hargreaves crop coefficients, K_c, calculated in June at nine sites in the Gunnison basin (current study).

			Blaney-Criddle k				K_c
Location	Drainage	Year	*Conventional t*	*Daylight mean t*	*Daylight weighted mean t*	*Daily maximum t*	Hargreaves
Upper Tomichi Creek	Bottom	1999	1.11	1.10	0.98	0.84	1.00
Upper Tomichi Creek	Upland	1999	1.47	1.46	1.27	1.09	1.30
Quartz Creek	Bottom	1999	1.23	1.23	1.10	0.95	1.15
Lower Tomichi Creek	Bottom	1999	1.45	1.44	1.26	1.09	1.28
Gunnison River North	Upland	1999	1.01	1.00	0.89	0.76	0.90
Ohio Creek	Upland	1999	1.28	1.27	1.12	0.97	1.16
Ohio Creek	Bottom	1999	1.23	1.22	1.08	0.93	1.10
Slate River	Upland	1999	1.22	1.22	1.07	0.92	1.12
Upper Tomichi Creek	Bottom	2000	1.15	1.14	1.01	0.87	1.04
Upper Tomichi Creek	Upland	2000	1.49	1.47	1.28	1.11	1.31
Quartz Creek	Bottom	2000	1.75	1.74	1.56	1.36	1.64
Lower Tomichi Creek	Bottom	2000	1.74	1.74	1.53	1.32	1.54
Gunnison River North	Upland	2000	1.50	1.48	1.33	1.13	1.35
Gunnison River South	Upland	2000	1.44	1.43	1.27	1.09	1.30
Ohio Creek	Upland	2000	1.47	1.46	1.27	1.11	1.32
Ohio Creek	Bottom	2000	1.61	1.59	1.40	1.22	1.45
East River	Upland	2000	1.66	1.65	1.45	1.23	1.47
Slate River	Upland	2000	1.55	1.54	1.35	1.18	1.43
Upper Tomichi Creek	Bottom	2001	1.35	1.35	1.18	1.02	1.19
Upper Tomichi Creek	Upland	2001	1.44	1.42	1.24	1.06	1.23
Quartz Creek	Bottom	2001	1.62	1.62	1.44	1.28	1.49
Gunnison River North	Upland	2001	1.24	1.23	1.10	0.94	1.12
Gunnison River South	Upland	2001	1.28	1.27	1.13	0.97	1.14
Ohio Creek	Upland	2001	1.06	1.05	0.93	0.80	0.93
Ohio Creek	Bottom	2001	1.45	1.45	1.27	1.10	1.28
East River	Upland	2001	1.71	1.70	1.49	1.28	1.50
Slate River	Upland	2001	1.22	1.21	1.06	0.92	1.09
Upper Tomichi Creek	Bottom	2002	1.67	1.65	1.43	1.23	1.39
Gunnison River South	Upland	2002	1.43	1.42	1.26	1.08	1.23
Ohio Creek	Bottom	2002	1.42	1.41	1.22	1.05	1.19
East River	Upland	2002	1.67	1.66	1.45	1.24	1.42
Slate River	Upland	2002	1.56	1.56	1.35	1.17	1.36
Upper Tomichi Creek	Bottom	2003	1.54	1.52	1.36	1.17	1.40
Upper Tomichi Creek	Upland	2003	1.44	1.42	1.24	1.07	1.27
Quartz Creek	Bottom	2003	1.34	1.33	1.20	1.04	1.26
Lower Tomichi Creek	Bottom	2003	1.24	1.23	1.09	0.94	1.11
Gunnison River South	Upland	2003	1.33	1.32	1.18	1.01	1.22
Ohio Creek	Upland	2003	1.57	1.55	1.36	1.16	1.38
Ohio Creek	Bottom	2003	1.26	1.25	1.10	0.95	1.13
East River	Upland	2003	1.47	1.46	1.29	1.10	1.33
Slate River	Upland	2003	1.39	1.39	1.23	1.06	1.30
Average	$n = 41$		1.42	1.41	1.24	1.07	1.26

Table F.3. Blaney-Criddle crop coefficients, k and Hargreaves crop coefficients, K_c, calculated in July at nine sites in the Gunnison basin (current study).

Location		Year	Blaney-Criddle k: *Conventional t*	*Daylight mean t*	*Daylight weighted mean t*	*Daily maximum t*	K_c: Hargreaves
Upper Tomichi Creek	Bottom	1999	0.72	0.72	0.68	0.59	0.73
Upper Tomichi Creek	Upland	1999	0.88	0.87	0.83	0.71	0.88
Quartz Creek	Bottom	1999	0.98	0.98	0.93	0.81	1.02
Lower Tomichi Creek	Bottom	1999	0.91	0.91	0.84	0.73	0.86
Gunnison River North	Upland	1999	0.89	0.88	0.84	0.72	0.88
Ohio Creek	Upland	1999	1.12	1.11	1.04	0.90	1.10
Ohio Creek	Bottom	1999	1.10	1.09	1.02	0.89	1.09
Slate River	Upland	1999	0.97	0.96	0.90	0.79	0.99
Upper Tomichi Creek	Bottom	2000	1.16	1.16	1.05	0.89	1.02
Upper Tomichi Creek	Upland	2000	1.32	1.31	1.16	0.98	1.12
Quartz Creek	Bottom	2000	1.24	1.24	1.14	0.98	1.16
Lower Tomichi Creek	Bottom	2000	1.22	1.22	1.10	0.93	1.04
Gunnison River North	Upland	2000	1.20	1.19	1.09	0.93	1.07
Gunnison River South	Upland	2000	1.21	1.20	1.10	0.95	1.06
Ohio Creek	Upland	2000	1.37	1.36	1.22	1.04	1.19
Ohio Creek	Bottom	2000	1.13	1.13	1.02	0.87	0.99
East River	Upland	2000	1.42	1.41	1.29	1.10	1.28
Slate River	Upland	2000	1.29	1.29	1.17	1.00	1.19
Upper Tomichi Creek	Bottom	2001	1.00	1.00	0.92	0.79	0.92
Upper Tomichi Creek	Upland	2001	1.07	1.07	0.97	0.83	0.96
Quartz Creek	Bottom	2001	1.14	1.14	1.06	0.89	1.10
Gunnison River North	Upland	2001	1.10	1.09	1.01	0.87	0.98
Gunnison River South	Upland	2001	0.90	0.90	0.83	0.71	0.83
Ohio Creek	Upland	2001	0.95	0.94	0.87	0.75	0.90
Ohio Creek	Bottom	2001	0.95	0.94	0.87	0.75	0.89
East River	Upland	2001	1.27	1.27	1.18	0.97	1.20
Slate River	Upland	2001	1.17	1.17	1.08	0.93	1.12
Upper Tomichi Creek	Bottom	2002	1.19	1.18	1.07	0.91	1.03
Gunnison River South	Upland	2002	0.95	0.94	0.86	0.73	0.81
Ohio Creek	Bottom	2002	0.94	0.94	0.84	0.71	0.80
East River	Upland	2002	1.41	1.40	1.28	1.08	1.23
Slate River	Upland	2002	1.25	1.25	1.12	0.96	1.10
Upper Tomichi Creek	Bottom	2003	1.26	1.24	1.12	0.94	1.05
Upper Tomichi Creek	Upland	2003	1.33	1.32	1.17	0.98	1.06
Quartz Creek	Bottom	2003	1.22	1.22	1.11	0.95	1.08
Lower Tomichi Creek	Bottom	2003	1.04	1.03	0.93	0.78	0.86
Gunnison River South	Upland	2003	1.01	1.01	0.91	0.77	0.85
Ohio Creek	Upland	2003	1.41	1.41	1.25	1.06	1.18
Ohio Creek	Bottom	2003	0.95	0.95	0.85	0.72	0.79
East River	Upland	2003	1.45	1.44	1.30	1.10	1.23
Slate River	Upland	2003	1.56	1.56	1.40	1.19	1.35
Average	$n = 41$		1.14	1.13	1.03	0.88	1.02

Table F.4. Blaney-Criddle crop coefficients, k and Hargreaves crop coefficients, K_c, calculated in August at nine sites in the Gunnison basin (current study).

			Blaney-Criddle k				K_c
Location		Year	*Conventional t*	*Daylight mean t*†	*Daylight weighted mean t*†	*Daily maximum t*†	Hargreaves
Upper Tomichi Creek	Bottom	1999	0.46				0.46
Upper Tomichi Creek	Upland	1999	0.58				0.57
Quartz Creek	Bottom	1999	0.59				0.62
Lower Tomichi Creek	Bottom	1999	0.64				0.61
Gunnison River North	Upland	1999	0.81				0.81
Ohio Creek	Upland	1999	1.06				1.10
Ohio Creek	Bottom	1999	0.69				0.69
Slate River	Upland	1999	0.61				0.65
Upper Tomichi Creek	Bottom	2000	0.87				0.79
Upper Tomichi Creek	Upland	2000	0.95				0.82
Quartz Creek	Bottom	2000	0.92				0.90
Lower Tomichi Creek	Bottom	2000	0.68				0.65
Gunnison River North	Upland	2000	0.68				0.62
Gunnison River South	Upland	2000	0.95				0.88
Ohio Creek	Upland	2000	1.21				1.14
Ohio Creek	Bottom	2000	1.05				0.98
East River	Upland	2000	1.06				1.00
Slate River	Upland	2000	0.84				0.82
Upper Tomichi Creek	Bottom	2001	0.78				0.75
Upper Tomichi Creek	Upland	2001	0.76				0.70
Quartz Creek	Bottom	2001	0.68				0.68
Gunnison River North	Upland	2001	0.99				0.88
Gunnison River South	Upland	2001	0.73				0.69
Ohio Creek	Upland	2001	0.71				0.71
Ohio Creek	Bottom	2001	0.83				0.80
East River	Upland	2001	0.99				0.99
Slate River	Upland	2001	0.62				0.64
Upper Tomichi Creek	Bottom	2002	0.95				0.83
Gunnison River South	Upland	2002	1.02				0.89
Ohio Creek	Bottom	2002	0.88				0.77
East River	Upland	2002	1.03				0.93
Slate River	Upland	2002	0.92				0.84
Upper Tomichi Creek	Bottom	2003	0.73				0.69
Upper Tomichi Creek	Upland	2003	0.80				0.72
Quartz Creek	Bottom	2003	0.56				0.54
Lower Tomichi Creek	Bottom	2003	0.84				0.78
Gunnison River South	Upland	2003	0.82				0.78
Ohio Creek	Upland	2003	1.00				0.96
Ohio Creek	Bottom	2003	0.68				0.62
East River	Upland	2003	0.89				0.85
Slate River	Upland	2003	0.80				0.81
Average	$n = 41$		0.82				0.78

† Alternative temperature expressions were not determined for months of August and September.

Table F.5. Blaney-Criddle crop coefficients, k and Hargreaves crop coefficients, K_c, calculated in September at nine sites in the Gunnison basin (current study).

			Blaney-Criddle k				K_c
Location		Year	*Conventional t*	*Daylight mean t*†	*Daylight weighted mean t*†	*Daily maximum t*†	Hargreaves
Upper Tomichi Creek	Bottom	1999	0.31				0.31
Upper Tomichi Creek	Upland	1999	0.70				0.66
Quartz Creek	Bottom	1999	0.89				0.95
Lower Tomichi Creek	Bottom	1999	0.61				0.62
Gunnison River North	Upland	1999	1.17				1.17
Ohio Creek	Upland	1999	0.82				0.86
Ohio Creek	Bottom	1999	0.53				0.54
Slate River	Upland	1999	0.63				0.68
Upper Tomichi Creek	Bottom	2000	0.97				0.96
Upper Tomichi Creek	Upland	2000	1.04				0.98
Quartz Creek	Bottom	2000	0.99				1.02
Lower Tomichi Creek	Bottom	2000	0.97				0.96
Gunnison River North	Upland	2000	0.65				0.63
Gunnison River South	Upland	2000	0.93				0.89
Ohio Creek	Upland	2000	0.91				0.90
Ohio Creek	Bottom	2000	1.36				1.33
East River	Upland	2000	1.10				1.09
Slate River	Upland	2000	0.56				0.54
Upper Tomichi Creek	Bottom	2001	1.03				0.99
Upper Tomichi Creek	Upland	2001	0.96				0.88
Quartz Creek	Bottom	2001	0.76				0.78
Gunnison River North	Upland	2001	1.16				1.13
Gunnison River South	Upland	2001	1.27				1.18
Ohio Creek	Upland	2001	0.52				0.51
Ohio Creek	Bottom	2001	0.95				0.90
East River	Upland	2001	0.96				0.92
Slate River	Upland	2001	0.74				0.73
Upper Tomichi Creek	Bottom	2002	0.78				0.82
Gunnison River South	Upland	2002	1.05				1.09
Ohio Creek	Bottom	2002	0.84				0.90
East River	Upland	2002	0.88				0.95
Slate River	Upland	2002	0.93				1.04
Upper Tomichi Creek	Bottom	2003	0.89				0.86
Upper Tomichi Creek	Upland	2003	0.98				0.90
Quartz Creek	Bottom	2003	0.70				0.71
Lower Tomichi Creek	Bottom	2003	0.75				0.74
Gunnison River South	Upland	2003	1.12				1.11
Ohio Creek	Upland	2003	0.76				0.76
Ohio Creek	Bottom	2003	0.85				0.84
East River	Upland	2003	0.76				0.76
Slate River	Upland	2003	0.52				0.53
Average	$n = 41$		0.86				0.86

† Alternative temperature expressions were not determined for months of August and September.

APPENDIX G1: Additional data from Kruse and Haise, 1974

Table G.1.a. Lysimeter CU, calculated Blaney-Criddle crop coefficients (*k*) and temperature variables from earlier studies conducted by Kruse and Haise (1974) in the upper Gunnison basin (1969-70).

Month	Site/Year	Lysimeter CU§	*k* †	T_{max} ‡	T_{min}	T_{avg}	T_{diff}
		---mm---		----------------degrees C----------			-------
May	Gunnison 1969	141.7	1.20	18.3	-1.6	8.4	19.8
	Gunnison 1970	131.6	1.17	16.5	-2.5	7.0	19.0
June	Gunnison 1969	115.8	0.91	18.4	1.5	9.9	16.9
	Gunnison 1970	148.3	1.10	20.2	3.2	11.7	16.9
July	Gunnison 1969	156.2	1.03	24.1	5.7	14.9	18.4
	Gunnison 1970	134.6	0.87	23.8	6.6	15.2	17.2
Aug	Gunnison 1969	108.0	0.77	24.1	5.1	14.6	19.1
	Gunnison 1970	123.4	0.86	24.1	6.5	15.3	17.7
Sep	Gunnison 1970	81.8	0.79	17.4	0.4	8.9	17.0

† *k* values calculated as ratio of lysimeter CU to calculated Blaney-Criddle *f* value.

‡ T_{max}, maximum daily temperature; T_{min}, minimum daily temperature; T_{avg}, average of maximum and minimum daily temperature; T_{diff}, average daily difference in maximum and minimum temperature. All values are monthly averages.

§ CU values are averages of two lysimeters at one site.

Table G.1.b. Lysimeter CU, calculated Blaney-Criddle crop coefficients (*k*) and temperature variables from earlier studies conducted by Kruse and Haise (1974) in South Park (1968-70).

Month	Site/Year	Lysimeter CU §	*k* †	T_{max} ‡	T_{min}	T_{avg}	T_{diff}
		---mm---		-----------------degrees C------------------			
May	So. Park Garo 1968	80.3	0.82	10.7	-3.0	3.8	13.7
	So. Park Garo 1969	126.0	1.01	18.9	0.5	9.7	18.4
	So. Park Garo 1970	141.7	1.20	17.4	-1.2	8.1	18.6
June	So. Park Garo 1968	177.0	1.37	19.1	1.7	10.4	17.5
	So. Park Garo 1969	112.5	0.91	15.7	2.7	9.2	13.0
	So. Park Garo 1970	157.5	1.21	19.4	2.0	10.7	17.4
July	So. Park Garo 1968	160.3	1.13	21.0	4.4	12.7	16.6
	So. Park Garo 1969	126.2	0.84	22.0	6.8	14.4	15.3
	So. Park Garo 1970	145.8	0.97	22.7	6.2	14.5	16.5
Aug	So. Park Garo 1968	89.2	0.71	19.4	2.8	11.1	16.6
	So. Park Garo 1969	107.7	0.77	23.3	5.3	14.3	18.0
	So. Park Garo 1970	92.2	0.69	22.0	4.2	13.1	17.7
Sep	So. Park Garo 1968	100.1	1.07	17.8	-4.5	6.7	22.3
	So. Park Garo 1969	73.9	0.71	17.6	1.1	9.3	16.5
	So. Park Garo 1970	84.3	0.92	15.8	-3.4	6.2	19.2

† *k* values calculated as ratio of lysimeter CU to calculated Blaney-Criddle *f* value.

‡ T_{max}, maximum daily temperature; T_{min}, minimum daily temperature; T_{avg}, average of maximum and minimum daily temperature; T_{diff}, average daily difference in maximum and minimum temperature. All values are monthly averages.

§ CU values are averages of two lysimeters at one site.

APPENDIX G2: Additional data from Walter et al., 1990

Table G.2. Lysimeter CU, calculated Blaney-Criddle crop coefficients (*k*) and temperature variables from earlier studies conducted by Walter et al. (1990) in South Park at two sites (1982-1985).

Month	Site/Year	Lysimeter CU §	*k* †	T_{max} ‡	T_{min}	T_{avg}	T_{diff}
		---mm---		----------------degrees C----------------			
May	So. Park Colton 1982	155.2	1.50	14.4	-4.4	5.0	18.9
	So. Park Colton 1983	156.0	1.65	12.2	-6.1	3.1	18.3
	So. Park Colton 1985	158.5	1.43	15.6	-2.2	6.7	17.8
	So. Park Portis 1982	104.6	1.12	11.1	-5.6	2.8	16.7
	So. Park Portis 1983	105.4	1.17	10.0	-6.1	1.9	16.1
	So. Park Portis 1984	163.3	1.62	15.0	-6.1	4.4	21.1
	So. Park Portis 1985	125.7	1.18	14.4	-3.3	5.6	17.8
June	So. Park Colton 1982	150.9	1.22	18.3	0.0	9.2	18.3
	So. Park Colton 1983	157.5	1.34	17.8	-2.2	7.8	20.0
	So. Park Colton 1984	181.4	1.50	18.9	-1.7	8.6	20.6
	So. Park Colton 1985	208.3	1.74	18.9	-2.2	8.3	21.1
	So. Park Portis 1982	137.2	1.18	16.7	-1.7	7.5	18.3
	So. Park Portis 1983	138.2	1.22	15.0	-1.1	6.9	16.1
	So. Park Portis 1984	146.3	1.26	17.2	-2.2	7.5	19.4
	So. Park Portis 1985	175.0	1.46	17.2	-0.6	8.3	17.8
July	So. Park Colton 1982	163.3	1.19	22.2	1.1	11.7	21.1
	So. Park Colton 1983	168.7	1.22	23.3	0.6	11.9	22.8
	So. Park Colton 1984	198.6	1.39	23.3	2.8	13.1	20.6
	So. Park Colton 1985	217.9	1.62	20.6	1.7	11.1	18.9
	So. Park Portis 1982	170.4	1.28	21.1	0.6	10.8	20.6
	So. Park Portis 1983	146.8	1.06	20.6	3.3	11.9	17.2
	So. Park Portis 1984	201.9	1.50	20.6	1.7	11.1	18.9
	So. Park Portis 1985	176.3	1.34	19.4	1.7	10.6	17.8
Aug	So. Park Colton 1982	83.8	0.63	21.7	3.9	12.8	17.8
	So. Park Colton 1983	122.4	0.93	22.8	2.2	12.5	20.6
	So. Park Colton 1984	173.0	1.33	21.7	2.8	12.2	18.9
	So. Park Colton 1985	178.8	1.41	23.9	-1.1	11.4	25.0
	So. Park Portis 1982	109.2	0.87	20.0	2.2	11.1	17.8
	So. Park Portis 1983	165.9	1.30	21.7	1.7	11.7	20.0
	So. Park Portis 1984	127.3	1.04	19.4	1.1	10.3	18.3
	So. Park Portis 1985	162.8	1.32	21.7	-0.6	10.6	22.2

Month	Site/Year	Lysimeter CU §	k †	T_{max} ‡	T_{min}	T_{avg}	T_{diff}
		---mm---		-----------------degrees C-----------------			
Sep	So. Park Colton 1982	98.8	0.99	17.2	-0.6	8.3	17.8
	So. Park Colton 1983	145.0	1.45	20.6	-3.9	8.3	24.4
	So. Park Colton 1984	133.1	1.36	17.8	-2.2	7.8	20.0
	So. Park Portis 1982	92.2	1.03	13.9	-2.8	5.6	16.7
	So. Park Portis 1983	107.7	1.09	18.3	-2.2	8.1	20.6
	So. Park Port 1984	134.1	1.54	15.0	-5.0	5.0	20.0

† *k* calculated as ratio of lysimeter CU to calculated Blaney-Criddle f value.

‡ T_{max}, maximum daily temperature; T_{min}, minimum daily temperature; T_{avg}, average of maximum and minimum daily temperature; T_{diff}, average daily difference in maximum and minimum temperature. All values are monthly averages.

§ CU values are averages of multiple lysimeters at individual sites.

APPENDIX G3: Additional data from Carlson et al., 1991

Table G.3. Lysimeter CU, calculated Blaney-Criddle crop coefficients (k) and temperature variables from earlier studies in Grand County (1987-1990), Carlson et al. (1991).

Month	Site/Year	Lysimeter CU §	k †	T_{max} ‡	T_{min}	T_{avg}	T_{diff}
		---mm---		------------------ degrees C ------------------			
May ¶	Grand Co. 1987	71.4	1.06	17.2	1.1	9.2	16.1
	Grand Co. 1988	87.5	0.98	18.9	0.0	9.4	18.9
	Grand Co. 1989	135.6	1.08	18.3	1.1	9.7	17.2
	Grand Co. 1990	39.1	1.21	19.4	2.8	11.1	16.7
Jun	Grand Co. 1987	193.4	1.33	23.3	2.8	13.1	20.6
	Grand Co. 1988	126.6	1.13	24.4	5.6	15.0	18.9
	Grand Co. 1989	140.3	1.00	21.7	2.8	12.2	18.9
	Grand Co. 1990	149.5	1.01	25.0	3.9	14.4	21.1
Jul	Grand Co. 1987	167.3	1.08	25.6	5.0	15.3	20.6
	Grand Co. 1988	189.9	1.18	26.7	6.7	16.7	20.0
	Grand Co. 1989	196.2	1.20	27.2	7.8	17.5	19.4
	Grand Co. 1990	148.6	0.90	26.1	8.9	17.5	17.2
Aug	Grand Co. 1987	135.1	0.97	24.4	4.4	14.4	20.0
	Grand Co. 1988	114.8	0.77	26.1	6.7	16.4	19.4
	Grand Co. 1989	128.4	0.90	24.4	6.7	15.6	17.8
	Grand Co. 1990	126.7	0.86	25.6	5.6	15.6	20.0
Sep	Grand Co. 1987	109.6	1.04	21.7	-1.1	10.3	22.8
	Grand Co. 1988	104.4	0.99	20.6	-0.6	10.0	21.1
	Grand Co. 1989	109.7	1.00	22.2	0.0	11.1	22.2
	Grand Co. 1990	104.4	0.85	23.9	4.4	14.2	19.4

† *k* calculated as ratio of lysimeter CU to calculated Blaney-Criddle *f* value.

‡ T_{max}, maximum daily temperature; T_{min}, minimum daily temperature; T_{avg}, average of maximum and minimum daily temperature; T_{diff}, average daily difference in maximum and minimum temperature. All values are monthly averages.

§ CU values are averages of two lysimeters at one site.

¶ Temperature values represent incomplete recording periods: May 15-31, 1987; May 15-31, 1988; May 25-31, 1990. ET values represent incomplete reporting periods: May 15-31, 1987; May 10-31, 1988; May 25-31, 1990. To calculate *k* values for periods of less than one month, p values were adjusted accordingly.

APPENDIX H: ET estimated with averaged and modeled k values

Table H.1. May ET estimated three ways using measured temperature data from four studies and either averaged or modeled k values.

Location	Drainage	Year	ET $_{\text{averaged } k}$ (Walter et al.)	ET $_{\text{averaged } k}$ (current study)	ET $_{\text{modeled } k}$
			------------------mm mo^{-1}------------------		
Upper Tomichi Creek†	Bottom	2000	143.8	154.7	155.4
Upper Tomichi Creek	Upland	2000	141.1	151.9	161.0
Quartz Creek	Bottom	2000	145.6	156.7	158.5
Lower Tomichi Creek	Bottom	2000	146.6	157.8	162.8
Gunnison River South	Upland	2000	145.7	156.8	176.2
Ohio Creek	Upland	2000	143.2	154.2	150.1
East River	Upland	2000	138.6	149.2	169.8
Slate River	Upland	2000	138.4	149.0	154.6
Upper Tomichi Creek	Bottom	2001	141.3	152.1	142.7
Upper Tomichi Creek	Upland	2001	138.8	149.4	146.1
Quartz Creek	Bottom	2001	143.5	154.4	143.1
Gunnison River North	Upland	2001	143.6	154.6	154.4
Gunnison River South	Upland	2001	143.1	154.0	153.9
Ohio Creek	Upland	2001	141.0	151.7	145.4
Ohio Creek	Bottom	2001	139.6	150.2	152.4
East River	Upland	2001	136.9	147.4	157.7
Slate River	Upland	2001	133.7	143.9	133.7
Upper Tomichi Creek	Bottom	2002	132.3	142.4	162.4
Gunnison River South	Upland	2002	138.5	149.1	176.2
Ohio Creek	Bottom	2002	134.4	144.7	164.9
East River	Upland	2002	130.9	140.9	155.3
Slate River	Upland	2002	128.0	137.8	133.1
Upper Tomichi Creek	Bottom	2003	140.7	151.5	135.9
Upper Tomichi Creek	Upland	2003	137.2	147.7	143.9
Quartz Creek	Bottom	2003	142.4	153.2	132.9
Lower Tomichi Creek	Bottom	2003	143.5	154.4	147.5
Gunnison River South	Upland	2003	144.1	155.1	140.3
Ohio Creek	Upland	2003	138.9	149.5	137.5
Ohio Creek	Bottom	2003	139.0	149.6	140.5
East River	Upland	2003	136.1	146.4	144.5
Slate River	Upland	2003	131.5	141.6	118.5
Gunnison‡		1969	140.8		163.9
Gunnison		1970	133.3		148.0
So. Park Garo‡		1968	116.0		87.9
So. Park Garo		1969	147.6		157.9
So. Park Garo		1970	138.8		150.7
So. Park Colton§		1982	122.3		134.7
So. Park Colton		1983	111.8		119.1
So. Park Colton		1985	131.2		135.0
So. Park Portis§		1982	110.3		105.4
So. Park Portis		1983	105.9		97.3
So. Park Portis		1984	119.3		148.8
So. Park Portis		1985	125.3		128.8

Location	Drainage	Year	ET averaged k (Walter et al.)	ET averaged k (current study)	ET modeled k
			-------------------	mm mo^{-1}	-------------------
Grand Co. ¶		1987	145.4		133.6
Grand Co.		1988	146.9		161.8
Grand Co.		1989	148.4		147.2
Grand Co.		1990	155.9		148.9

† Sites from current study unless otherwise noted.
‡ Sites from Kruse and Haise, 1970.
§ Sites from Walter et al., 1990.
¶ Sites from Pollara et al., 1991.

Table H.2. June ET estimated three ways using measured temperature data from four studies and either averaged or modeled *k* values.

Location	Drainage	Year	ET averaged *k* (Walter et al.)	ET averaged *k* (current study)	ET modeled *k*
			---------------------	mm mo^{-1}	---------------------
Upper Tomichi Creek†	Bottom	1999	185.9	188.5	180.1
Upper Tomichi Creek	Upland	1999	180.3	182.8	182.7
Quartz Creek	Bottom	1999	187.7	190.4	171.9
Lower Tomichi Creek	Bottom	1999	189.0	191.7	189.8
Gunnison River North	Upland	1999	187.4	190.1	183.6
Ohio Creek	Upland	1999	180.8	183.4	173.3
Ohio Creek	Bottom	1999	184.3	186.9	178.5
Slate River	Upland	1999	175.2	177.7	164.4
Upper Tomichi Creek	Bottom	2000	192.0	194.7	188.0
Upper Tomichi Creek	Upland	2000	186.7	189.4	190.0
Quartz Creek	Bottom	2000	195.8	198.6	178.0
Lower Tomichi Creek	Bottom	2000	196.4	199.2	194.3
Gunnison River North	Upland	2000	194.4	197.2	188.2
Gunnison River South	Upland	2000	193.6	196.4	188.0
Ohio Creek	Upland	2000	186.5	189.2	182.3
Ohio Creek	Bottom	2000	189.8	192.5	183.6
East River	Upland	2000	187.5	190.2	189.7
Slate River	Upland	2000	182.6	185.2	169.3
Upper Tomichi Creek	Bottom	2001	191.4	194.2	192.8
Upper Tomichi Creek	Upland	2001	186.9	189.6	197.0
Quartz Creek	Bottom	2001	196.1	198.9	182.6
Gunnison River North	Upland	2001	194.3	197.0	194.1
Gunnison River South	Upland	2001	193.7	196.5	194.2
Ohio Creek	Upland	2001	192.2	194.9	197.2
Ohio Creek	Bottom	2001	192.0	194.8	194.2
East River	Upland	2001	188.6	191.3	192.4
Slate River	Upland	2001	182.9	185.5	179.1
Upper Tomichi Creek	Bottom	2002	197.5	200.3	220.7
Gunnison River South	Upland	2002	201.5	204.4	212.5
Ohio Creek	Bottom	2002	197.0	199.8	214.6
East River	Upland	2002	194.1	196.9	207.2
Slate River	Upland	2002	189.5	192.2	194.6
Upper Tomichi Creek	Bottom	2003	185.2	187.9	177.8
Upper Tomichi Creek	Upland	2003	181.0	183.6	182.8
Quartz Creek	Bottom	2003	186.7	189.3	168.9
Lower Tomichi Creek	Bottom	2003	190.6	193.4	185.8
Gunnison River South	Upland	2003	187.5	190.2	178.6
Ohio Creek	Upland	2003	181.9	184.5	183.2
Ohio Creek	Bottom	2003	183.8	186.4	179.1
East River	Upland	2003	180.3	182.9	173.5
Slate River	Upland	2003	176.7	179.2	160.6
Gunnison‡		1969	178.0		155.3
Gunnison		1970	189.5		165.3

Location	Drainage	Year	ET averaged k (Walter et al.)	ET averaged k (current study)	ET modeled k
			---------------------mm mo^{-1}---------------------		
So. Park Garo‡		1968	180.9		162.2
So. Park Garo		1969	173.3		121.9
So. Park Garo		1970	182.7		163.5
So. Park Colton§		1982	173.0		161.4
So. Park Colton		1983	164.1		164.9
So. Park Colton		1984	169.4		174.3
So. Park Colton		1985	167.6		176.5
So. Park Portis§		1982	162.3		151.4
So. Park Portis		1983	158.7		132.9
So. Park Portis		1984	162.3		159.2
So. Park Portis		1985	167.6		152.4
Grand Co. ¶		1987	199.1		204.9
Grand Co.		1988	211.7		202.6
Grand Co.		1989	193.8		185.4
Grand Co.		1990	208.1		219.1

† Sites from current study unless otherwise noted.
‡ Sites from Kruse and Haise, 1970.
§ Sites from Walter et al., 1990.
¶ Sites from Pollara et al., 1991.

Table H.3. July ET estimated three ways using measured temperature data from four studies and either averaged or modeled *k* values.

Location	Drainage	Year	ET averaged *k* (Walter et al.)	ET averaged *k* (current study)	ET modeled *k*
			--------------------mm mo^{-1}--------------------		
Upper Tomichi Creek†	Bottom	1999	189.0	176.6	155.6
Upper Tomichi Creek	Upland	1999	186.2	174.0	156.1
Quartz Creek	Bottom	1999	189.1	176.7	150.5
Lower Tomichi Creek	Bottom	1999	192.2	179.6	172.6
Gunnison River North	Upland	1999	189.9	177.4	159.0
Ohio Creek	Upland	1999	183.5	171.5	155.6
Ohio Creek	Bottom	1999	186.4	174.2	157.3
Slate River	Upland	1999	180.1	168.3	146.7
Upper Tomichi Creek	Bottom	2000	185.8	173.6	181.7
Upper Tomichi Creek	Upland	2000	180.8	168.9	186.8
Quartz Creek	Bottom	2000	187.4	175.1	170.3
Lower Tomichi Creek	Bottom	2000	190.9	178.4	197.0
Gunnison River North	Upland	2000	188.7	176.3	181.8
Gunnison River South	Upland	2000	189.0	176.6	185.6
Ohio Creek	Upland	2000	183.2	171.2	182.5
Ohio Creek	Bottom	2000	184.4	172.3	183.0
East River	Upland	2000	181.0	169.2	172.3
Slate River	Upland	2000	178.4	166.7	166.5
Upper Tomichi Creek	Bottom	2001	185.8	173.6	171.9
Upper Tomichi Creek	Upland	2001	182.2	170.3	175.0
Quartz Creek	Bottom	2001	188.5	176.1	163.1
Gunnison River North	Upland	2001	189.3	176.9	171.7
Gunnison River South	Upland	2001	189.1	176.7	174.7
Ohio Creek	Upland	2001	184.7	172.6	165.2
Ohio Creek	Bottom	2001	186.3	174.1	169.5
East River	Upland	2001	184.6	172.5	164.0
Slate River	Upland	2001	180.6	168.8	158.8
Upper Tomichi Creek	Bottom	2002	188.5	176.2	187.5
Gunnison River South	Upland	2002	191.9	179.3	194.0
Ohio Creek	Bottom	2002	189.0	176.6	191.9
East River	Upland	2002	186.5	174.3	183.1
Slate River	Upland	2002	182.2	170.3	177.5
Upper Tomichi Creek	Bottom	2003	188.6	176.2	198.0
Upper Tomichi Creek	Upland	2003	185.4	173.2	207.5
Quartz Creek	Bottom	2003	192.6	180.0	185.8
Lower Tomichi Creek	Bottom	2003	193.7	181.0	205.5
Gunnison River South	Upland	2003	193.3	180.6	199.6
Ohio Creek	Upland	2003	190.6	178.1	200.4
Ohio Creek	Bottom	2003	190.8	178.3	200.2
East River	Upland	2003	187.0	174.8	191.2
Slate River	Upland	2003	183.8	171.8	184.3
Gunnison‡		1969	184.6		168.8
Gunnison		1970	187.0		164.0

Location	Drainage	Year	ET averaged *k* (Walter et al.)	ET averaged *k* (current study)	ET modeled *k*
			---------------------mm mo^{-1}	---------------------	---------------------
So. Park Garo‡		1968	172.9		148.0
So. Park Garo		1969	182.5		148.6
So. Park Garo		1970	182.7		155.8
So. Park Colton§		1982	166.9		167.1
So. Park Colton		1983	168.4		177.7
So. Park Colton		1984	174.7		171.9
So. Park Colton		1985	163.7		152.4
So. Park Portis§		1982	162.1		159.5
So. Park Portis		1983	168.4		147.8
So. Park Portis		1984	163.7		152.4
So. Park Portis		1985	160.6		143.7
Grand Co. ¶		1987	188.4		185.4
Grand Co.		1988	196.4		189.7
Grand Co.		1989	201.1		190.7
Grand Co.		1990	201.1		176.4

† Sites from current study unless otherwise noted.
‡ Sites from Kruse and Haise, 1970.
§ Sites from Walter et al., 1990.
¶ Sites from Pollara et al., 1991.

Table H.4. August ET estimated three ways using measured temperature data from four studies and either averaged or modeled k values.

Location	Drainage	Year	ET averaged k (Walter et al.)	ET averaged k (current study)	ET modeled k
			--------mm mo^{-1}--------		
Upper Tomichi Creek†	Bottom	1999	111.6	113.0	102.9
Upper Tomichi Creek	Upland	1999	110.1	111.4	110.6
Quartz Creek	Bottom	1999	112.8	114.2	95.5
Lower Tomichi Creek	Bottom	1999	114.8	116.2	117.5
Gunnison River North	Upland	1999	113.3	114.6	104.4
Ohio Creek	Upland	1999	110.3	111.6	93.7
Ohio Creek	Bottom	1999	111.7	113.1	101.6
Slate River	Upland	1999	107.6	109.0	86.6
Upper Tomichi Creek	Bottom	2000	115.3	116.7	131.8
Upper Tomichi Creek	Upland	2000	113.6	115.0	146.8
Quartz Creek	Bottom	2000	117.0	118.4	112.7
Lower Tomichi Creek	Bottom	2000	119.6	121.1	124.1
Gunnison River North	Upland	2000	118.9	120.4	134.0
Gunnison River South	Upland	2000	118.0	119.5	132.0
Ohio Creek	Upland	2000	113.4	114.8	119.7
Ohio Creek	Bottom	2000	115.8	117.2	126.9
East River	Upland	2000	113.8	115.2	118.3
Slate River	Upland	2000	111.6	112.9	107.0
Upper Tomichi Creek	Bottom	2001	112.1	113.5	114.2
Upper Tomichi Creek	Upland	2001	110.9	112.2	130.6
Quartz Creek	Bottom	2001	113.6	115.0	106.3
Gunnison River North	Upland	2001	115.3	116.7	123.1
Gunnison River South	Upland	2001	114.6	116.0	124.0
Ohio Creek	Upland	2001	110.7	112.0	103.9
Ohio Creek	Bottom	2001	112.7	114.0	117.5
East River	Upland	2001	110.4	111.8	105.8
Slate River	Upland	2001	109.3	110.6	97.8
Upper Tomichi Creek	Bottom	2002	108.4	109.7	138.0
Gunnison River South	Upland	2002	113.7	115.1	149.1
Ohio Creek	Bottom	2002	111.0	112.4	143.9
East River	Upland	2002	108.4	109.8	132.7
Slate River	Upland	2002	107.0	108.3	125.2
Upper Tomichi Creek	Bottom	2003	115.4	116.8	125.3
Upper Tomichi Creek	Upland	2003	113.4	114.8	138.6
Quartz Creek	Bottom	2003	116.2	117.6	112.5
Lower Tomichi Creek	Bottom	2003	119.0	120.5	133.5
Gunnison River South	Upland	2003	118.2	119.6	125.5
Ohio Creek	Upland	2003	115.0	116.5	121.7
Ohio Creek	Bottom	2003	116.3	117.8	130.6
East River	Upland	2003	113.1	114.5	117.4
Slate River	Upland	2003	110.3	111.7	99.7
Gunnison‡		1969	114.3		122.1
Gunnison		1970	116.7		113.2

Location	Drainage	Year	ET averaged *k* (Walter et al.)	ET averaged *k* (current study)	ET modeled *k*
			--------------------mm mo^{-1}--------------------		
So. Park Garo‡		1968	101.7		91.6
So. Park Garo		1969	112.9		112.3
So. Park Garo		1970	108.7		106.1
So. Park Colton§		1982	107.6		105.3
So. Park Colton		1983	106.6		124.9
So. Park Colton		1984	105.7		111.5
So. Park Colton		1985	102.7		152.0
So. Park Portis§		1982	101.7		99.6
So. Park Portis		1983	103.7		117.5
So. Park Portis		1984	98.8		100.5
So. Park Portis		1985	99.8		128.4
Grand Co. ¶		1987	114.0		129.1
Grand Co.		1988	120.8		132.2
Grand Co.		1989	117.9		115.4
Grand Co.		1990	117.9		133.5

† Sites from current study unless otherwise noted.
‡ Sites from Kruse and Haise, 1970.
§ Sites from Walter et al., 1990.
¶ Sites from Pollara et al., 1991.

Table H.5. September ET estimated three ways using measured temperature data from four studies and either averaged or modeled k values.

Location	Drainage	Year	ET $_{averaged\ k}$ (Walter et al.)	ET $_{averaged\ k}$ (current study)	ET $_{modeled\ k}$
			------------------	mm mo^{-1}	------------------
Upper Tomichi Creek†	Bottom	1999	86.1	86.1	91.5
Upper Tomichi Creek	Upland	1999	83.6	83.6	95.8
Quartz Creek	Bottom	1999	89.4	89.4	86.5
Lower Tomichi Creek	Bottom	1999	89.2	89.2	91.9
Gunnison River North	Upland	1999	87.7	87.7	92.1
Ohio Creek	Upland	1999	87.2	87.2	84.7
Ohio Creek	Bottom	1999	86.3	86.3	89.4
Slate Creek	Upland	1999	82.7	82.7	78.1
Upper Tomichi Creek	Bottom	2000	92.5	92.5	98.7
Upper Tomichi Creek	Upland	2000	90.8	90.8	105.7
Quartz Creek	Bottom	2000	94.5	94.5	95.2
Lower Tomichi Creek	Bottom	2000	94.6	94.6	100.2
Gunnison River North	Upland	2000	95.4	95.4	105.8
Gunnison River South	Upland	2000	95.0	95.0	105.2
Ohio Creek	Upland	2000	93.7	93.7	99.4
Ohio Creek	Bottom	2000	92.6	92.6	101.4
East River	Upland	2000	91.1	91.1	98.9
Slate River	Upland	2000	90.6	90.6	90.6
Upper Tomichi Creek	Bottom	2001	90.1	90.1	100.9
Upper Tomichi Creek	Upland	2001	88.4	88.4	107.4
Quartz Creek	Bottom	2001	92.7	92.7	94.7
Gunnison River North	Upland	2001	96.0	96.0	113.5
Gunnison River South	Upland	2001	95.8	95.8	113.7
Ohio Creek	Upland	2001	93.4	93.4	100.1
Ohio Creek	Bottom	2001	90.9	90.9	103.5
East River	Upland	2001	91.2	91.2	104.5
Slate River	Upland	2001	90.1	90.1	96.9
Upper Tomichi Creek	Bottom	2002	90.9	90.9	89.0
Gunnison River South	Upland	2002	94.2	94.2	93.5
Ohio Creek	Bottom	2002	92.0	92.0	88.7
East River	Upland	2002	90.5	90.5	85.8
Slate River	Upland	2002	88.2	88.2	79.9
Upper Tomichi Creek	Bottom	2003	87.3	87.3	96.9
Upper Tomichi Creek	Upland	2003	84.4	84.4	104.0
Quartz Creek	Bottom	2003	89.4	89.4	92.0
Lower Tomichi Creek	Bottom	2003	90.9	90.9	98.8
Gunnison River South	Upland	2003	88.8	88.8	98.7
Ohio Creek	Upland	2003	88.3	88.3	92.8
Ohio Creek	Bottom	2003	87.2	87.2	96.1
East River	Upland	2003	86.6	86.6	94.9
Slate River	Upland	2003	85.2	85.2	89.1
Gunnison‡		1970	87.8		80.7
So. Park Garo‡		1968	80.5		90.4
So. Park Garo		1969	89.3		80.5

Location	Drainage	Year	ET averaged *k* (Walter et al.)	ET averaged *k* (current study)	ET modeled *k*
			------------------mm mo^{-1}------------------		
So. Park Garo		1970	79.0		79.3
So. Park Colton§		1982	86.0		81.8
So. Park Colton		1983	86.0		103.7
So. Park Colton		1984	84.2		87.2
So. Park Portis§		1982	76.9		69.8
So. Park Portis		1983	85.1		89.9
So. Park Portis		1984	75.1		77.7
Grand Co.¶		1987	92.6		105.7
Grand Co.		1988	91.6		98.8
Grand Co.		1989	95.3		106.8
Grand Co.		1990	105.4		106.9

† Sites from current study unless otherwise noted.
‡ Sites from Kruse and Haise, 1970.
§ Sites from Walter et al., 1990.
¶ Sites from Pollara et al., 1991.