DISSERTATION

ALFALFA REFERENCE CROP EVAPOTRANSPIRATION IN COLORADO AND ITS USE FOR IRRIGATION SCHEDULING

Submitted by

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ABSTRACT

ALFALFA REFERENCE CROP EVAPOTRANSPIRATION IN COLORADO AND ITS USE FOR IRRIGATION SCHEDULING

The goal of irrigation scheduling is efficient use of water such that water is applied to the field for optimal crop production. Previous studies have optimized irrigation scheduling using different models to manage sprinkler irrigation. This research evaluated approaches for obtaining alfalfa reference evapotranspiration (ET_r) and its use in a new irrigation scheduling model for a furrow irrigation system. The objectives of this research were to: 1) Compare seasonal trends of daily ET_r from the American Society of Civil Engineers Standardized Penman-Monteith (ASCE-SPM) equation and the Penman-Kimberly (PK) equation along a climatic gradient in Colorado, 2) Verify the agreement between calculated ET_r from the ASCE-SPM equation and measured ET_r from a lysimeter during the 2010 season for the Arkansas Valley of Colorado and correct the lysimeter ET_r for alfalfa overgrowth, and 3) Test the ASCE-SPM ETr along with a locally adapted Kcr curve for corn in an irrigation scheduling spreadsheet tool for simulating the daily soil water deficit of furrow irrigated corn in northeast Colorado.

The two reference ET equations were compared using R^2, Root-Mean-Square Error (RMSE), Relative Error (RE), and index of agreement (d). The R^2 values ranged from 0.93 to 0.99; d ranged from 0.98 to 0.99, RMSE ranged from 0.29 to 0.75 mm/d, and RE ranged from -6.35 to 1.91 %. In a comparison of the ASCE-SPM and PK equations at the Fort Collins and

Rogers Mesa sites in 2011, differences were observed between the energy balance and aerodynamic terms of each equation. The energy budget calculated by the ASCE-SPM was generally 28% lower than the energy budget calculated by the PK equation at both locations for 2011. On the other hand, the aerodynamic term calculated by the ASCE-SPM equation was from 27 – 28 % higher than the aerodynamic term calculated from PK during most of 2011 at both locations.

The second objective of this research compared alfalfa ET measured with a lysimeter in the center of a 4.06 ha furrow irrigated field at the Colorado State University Arkansas Valley Research Center in Rocky Ford, CO to the calculated values from the ASCE-SPM equation in periods of reference conditions in 2010. Four days were selected when alfalfa in the lysimeter was 50 – 55 cm tall, unstressed, completely covering the ground, but with its canopy extending beyond the outer walls of the lysimeter. On these dates, hourly lysimeter ET_r was 0.08 to 0.11 mm/h higher than ASCE-SPM ET_r. The theoretical surface area of the lysimeter was 9.181 m^2, while the observed effective canopy area was up to 12.461 m^2 due to overgrowth. Surface area corrections for the overgrowth increased the index of agreement (d) between hourly lysimeter ET_r and ASCE-SPM ET_r from the 0.96 – 0.98 range to the 0.99 – 1.0 range. These results showed that it is important to use the correct effective canopy area when computing ET_r from a weighing lysimeter.

The CIS model for calculating water deficit under a furrow irrigation system with the addition of some data from field measurements such as soil moisture content, gross irrigation, climate data, and plant height and leaf area index generated good results. The water deficit under corn was simulated at the Limited Irrigation Research Farm (LIRF) located near Greeley, Colorado during the years 2010, 2011 and 2012. Daily corn crop ET (ET_c) calculated from daily ASCE-SPM ET_r and a locally-derived crop coefficient curve (K_{cr}) were used by the CIS for daily soil water deficit calculations via water balance. This data was used to test a furrow irrigation system via the CIS model and to simulate the field irrigation by predicting the time and the amount of water for the next irrigation. The results showed good agreement between calculated and measured deficits where index of agreement (d) ranged from 0.5 to 0.99 for most years of this study, specifically when measurements of soil water content (SWC) were inserted bi-weekly or monthly. The RMSE did not exceed 2.54 mm when using SWC once per season in 2011, while bi-weekly measurements recorded d to be 0.96 in 2010, 0.99 in 2011 and 0.70 in 2012. Also, the CIS showed that irrigation water usage could be reduced by 30 to 50% through use of CIS.

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CHAPTER ONE: INTRODUCTION

The agriculture sector is the biggest water consumer in most countries that are interested in increasing agricultural production (Rosegrant et al., 2002). The competition for water resources from other sectors, such as municipal, has become one of the greatest challenges facing agricultural production (Rahaman and Varis, 2005). The rapid growth in population is accompanied by an increase in food demand and a reduction in the water quota for the agricultural sector (Bilsborrow, 1987). Under such conditions, it is important to use irrigation water more efficiently (Sinclair et al., 1984). Therefore, irrigation management increasingly relies on highly efficient tools to help reduce water use in agriculture (Cifre et al., 2005).

Evapotranspiration (ET) is the amount of water lost from plants and soils (Reynolds et al., 2004). The amount of water transpiration from plants into the atmosphere via stomata depends on water potential, humidity, availability of water in the soil, atmospheric moisture, and the temperature in the air and soil (Satoh et al., 2013). Plants use transpiration to cool plant cells (Han and Young, 2014). The climate plays an important role in controlling ET through factors such as solar radiation, temperature, wind, humidity and vapor pressure (Irmak et al., 2012). Water requirements depend on the evapotranspiration rate (Lopes and Bonaccurso, 2012). The quantity of water used for the synthesis of plant tissue is only 1% of the water absorbed, and the rest is lost by transpiration or water vapor which is not included in the processes of growth (Briggs and Smithson, 1986). The total amount of water which is needed by plants is very important in estimating the amount of irrigation water required in the different stages of plant life (Fereres and Soriano, 2007). The ET rate increases when soil water content is high because more water is available to the plants (Van Donk et al., 2010). There is a direct correlation between evapotranspiration rate and soil water content, where higher ET rates are normally found after irrigation or precipitation due to availability of more water (Ferrante et al., 2014).

The ASCE standardized Penman-Monteith equation (ASCE-SPM) is one of many equations used to calculate evapotranspiration (Allen et al., 2005; Cobaner, 2011). Good results have been obtained from the ASCE-SPM equation during the reference stage when the plants are at standard height and without stress. The standardized reference ET can be calculated for (1) a short crop (similar to grass) or (2) a tall crop (similar to alfalfa) (Abtew and Melesse, 2013). ET_{os} is the reference for short crops having a height of 12 cm, whereas ET_{rs} is the reference for tall crops having a height of 50 cm. In addition, this equation can work in both hourly and daily time steps (Abtew and Melesse, 2013).

The best way to calculate crop ET from the field is with a lysimeter which provides precise crop ET measurements (López-Urrea et al., 2012). Precision weighing lysimeters are used to measure ET in the field using mass balance (Ding et al., 2010). Many studies have been conducted to compare measured ET using lysimeter data and calculated reference ET using 1982 Penman Kimberly (PK), FAO-56 Penman, and ASCE-SPM equations (Kumar et al., 2011). These studies concluded that all of those equations are sufficiently accurate to recommend their use for calculating reference evapotranspiration (Davidov and Moteva, 2010).

Increasing ET is a consequence of increasing water availability for consumption in the field (Chen et al., 2010). Irrigation management plays an important role in providing the appropriate quantity of water to plants when needed (Hensley et al., 2011). Irrigation scheduling determines how much and when water is needed (Incrocci et al., 2014). Reducing water consumption in agriculture depends on irrigation management through irrigation scheduling (Knox et al., 2012). Irrigation scheduling focuses on when and how much water should be applied to the field before plants reach Management Allowed Depletion (MAD), and MAD is the amount of depletion of available water in the plant root zone (plant available water) that can be tolerated before applying water (Hillyer, 2011). Land should be irrigated so that soil water content is between field capacity and MAD and available to plants (Kumar et al., 2014).

Reference Evapotranspiration (Ref-ET) is a program (http://www.kimberly.uidaho.edu/ref-et/) that can be used to calculate ET_r, with inputs of climatic data, and Colorado Agricultural Meteorological Network (CoAgMet) has been providing hourly and daily climate data since 1990 (Gleason, 2013). CoAgMet is also providing hourly and daily ET data using the ASCE-SPM and PK equations. Calculating accurate ET leads to obtaining good irrigation scheduling (Jayasinghe, 2013).

Accurate ET_r leads to accurate crop ET (ET_c) estimates, which are used in calculating the soil water balance for irrigation scheduling. ET_c cannot be calculated without a crop coefficient (K_c). In Colorado the crop coefficients have been developed only for the PK equation (Gleason, 2013). The ET_c equation follows

$$ET_c = ET_r * K_{cr} \qquad \text{Eq. (1)}$$

where ET_c is crop evapotranspiration (mm/d); ET_r is alfalfa reference evapotranspiration (mm/d) and K_{cr} is the alfalfa-based crop coefficient (Al Wahaibi, 2011). Gleason (2013) adapted a K_c curve for corn (*Zea mays L.*) for use with ASCE-SPM ET_r under northeastern Colorado conditions.

Before using equation (1) for irrigation scheduling, one should test the accuracy of ET_{rs} from the ASCE-SPM equation under field conditions because using untested ET could lead to inaccurate estimates of crop water requirement. The introduction of ET_r from ASCE-SPM on the CoAgMet website has created a need to compare those values with the ET_r from the PK equation under local Colorado climate conditions. Measured ET_r from a lysimeter presents an actual ET from the field and can also be compared to ASCE-SPM ET_r to verify their agreement.

The Colorado Irrigation Scheduler (CIS; Gleason, 2013) is a spreadsheet irrigation scheduling tool that uses the ASCE-SPM ET_{rs} calculated by CoAgMet for estimating daily ET_c. There is a need to test the CIS for furrow-irrigated fields in eastern Colorado. Furrow irrigation is a method of applying water at a specific rate of flow into shallow, evenly spaced channels (Burguete et al., 2014). Water is conveyed by these channels down the slope in the field, and plants can be planted either in the channels or on the beds between the channels depending on the agricultural practice in the region (Gonçalves et al., 2011). This method differs from flood irrigation in that only part of the ground surface is covered with water (Ebrahimian et al., 2013). The water moves through the soil both vertically and horizontally (Siyal et al. 2012). The furrow stream is applied until the desired application depth and lateral penetration are obtained (Ali, 2011). How long water must be applied in the furrows depends on the volume of water required to fill the soil to the desired depth, the intake rate of the soil, and the spacing of the furrows and length of the field (Kelly et al., 2011). A uniform slope is preferred because this allows application of irrigation water with higher efficiency (Latif et al., 2013). Number of irrigation sets should be determined in the field, and the farm should be divided by set for irrigation. Also, time of application is the duration for which water is applied to the furrows in each set. The duration is the irrigation time period for each set to apply the required amount of water through each furrow at an acceptable irrigation efficiency (Reddy et al., 2013).

The objectives of this study were to:

1- Compare seasonal trends of daily ET_r from the ASCE-SPM equation and the PK equation along a climatic gradient in Colorado.
2- Verify the agreement between calculated ET_r from the ASCE-SPM equation and measured ET_r from a lysimeter during the 2010 season for the Arkansas Valley of Colorado and correct the lysimeter ET_r for alfalfa overgrowth.
3- Test the ASCE-SPM ETr along with a locally adapted Kcr curve for corn in an irrigation scheduling spreadsheet tool for simulating the daily soil water deficit of furrow irrigated corn in northeast Colorado.

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CHAPTER TWO: COMPARISON OF REFERENCE EVAPOTRANSPIRATION USING THE AMERICAN SOCIETY OF CIVIL ENGINEERS (ASCE) STANDARDIZED PENMAN-MONTEITH AND PENMAN-KIMBERLY EQUATIONS ACROSS A CLIMATIC GRADIENT IN COLORADO

Overview

Reference evapotranspiration (ET) is used to represent atmospheric demand for water. The Colorado Agricultural Meteorological Network (CoAgMet) provides weather data used for calculating alfalfa reference crop ET (ET_r) using the Penman Kimberly (PK) equation. Recently, CoAgMet has also started to provide alfalfa reference ET using the ASCE Standardized Penman-Monteith equation (ASCE-SPM). The objectives of this study were (1) to compare the alfalfa reference crop ET using the ACSE-SPM and the PK equations along a climatic gradient in Colorado and (2) to evaluate the effects of weather factors on the reference ET values from these two equations. Hourly weather data was collected and obtained from CoAgMet from seven weather stations located in Fort Collins, Greeley, Iliff, Fruita, Rogers Mesa, Rocky Ford, and Yellow Jacket during the years 2008 to 2011. This data was then used to calculate hourly reference ET using the two equations. The two reference ET equations were compared using R^2, Root-Mean-Square Error (RMSE), Relative Error (RE), and index of agreement (d). The R^2 values ranged from 0.93 to 0.99; d ranged from 0.98 to 0.99, RMSE ranged from 0.29 to 0.75 mm/d, and RE ranged from -6.35 to 1.91 %. The seasonal cumulative ET_r calculated values using the PK equation were lower than the ASCE-SPM values on average. For 2011, the highest mean value of relative humidity and lowest mean value of solar radiation were observed at the southernmost site (CSU Rogers Mesa) where the lowest mean ET_r values were calculated among the seven sites. In a comparison of the ASCE-SPM and PK equations at the Fort Collins and Rogers Mesa sites in 2011, differences were observed between the energy balance and aerodynamic terms of each equation. The energy budget calculated by the ASCE-SPM was generally 28% lower than the energy budget calculated by the PK equation at both locations for 2011. On the other hand, the aerodynamic term calculated by the ASCE-SPM equation was from 27 – 28 % higher than the aerodynamic term calculated from PK during most of 2011 at both locations.

Introduction

Evapotranspiration can be determined directly using lysimeters or can be calculated using reference ET equations. The 1982 Penman-Kimberly (PK) and the American Society of Civil Engineers standardized Penman-Monteith (ASCE-SPM; ASCE-EWRI, 2005) equations for alfalfa (tall reference) are two of the most commonly utilized equations to calculate reference ET (Itenfisu et al., 2003). Crop evapotranspiration (ET_c) can be determined by multiplying the reference ET by a crop coefficient. However, the relative performance of these two equations has not been widely tested in irrigated regions of Colorado.

Many studies have been conducted which compare the results between different reference ET equations, such as the 1982 Penman-Kimberly (PK) and ASCE-SPM approaches (Itenfisu et al., 2003). These studies have concluded that both of those equations are sufficiently accurate to recommend their use for calculation of reference ET. This study compares ET_r values calculated using the ASCE-SPM and PK equations under local weather conditions in Colorado because crop coefficient (K_c) values in CoAgMet were developed for use with PK ET_r. The question is; are major adjustments to the K_c curves required for use with ASCE-SPM ET_r? This can only be verified by comparing the ET_r values from the ASCE-SPM and PK equations throughout the growing season.

The ASCE-SPM and the PK equations are used to calculate crop water requirements under local climate and soil conditions (Irmak et al., 2008). Using these equations with inaccurate or average data for weather, soil, and crop conditions will result in inaccurate ET calculations. This can lead to wrong estimates for crop water requirements (Yoder et al., 2005). However, using the standardized information on crop ET rates combined with knowledge of the local weather, soil, and crop conditions can help to determine more efficient irrigation amounts and scheduling (Amir and Martin, 2001). In Colorado, the Colorado Agriculture Meteorological Network (CoAgMet) (http://ccc.atmos.colostate.edu/~coagmet) provides local weather data (Gent and Schwartz, 2003). It provides hourly and daily climate data and calculated reference ET rates and uses both the PK and the ASCE SPM equations (Taghvaeian et al., 2012).

In 2010, Liu et al. (2010) published results from their comparison of the FAO PM and PK methods using climatic data from 1951 to 2007 in the Beijing area. Statistical analyses showed that the PK method had high correlation with the PM method and the lowest values of Root-Mean-Square Error (RMSE).

A study by the Agricultural and Food Engineering Department at the Indian Institute of Technology was done at the experimental farm, Kharagpur, India and found from comparisons of the equations with lysimeter data that the Penman-Monteith equation (1965) gave the best result followed by 1982-PK, and the RMSE in all cases varied between 0.08 and 0.76 mm/d (Kashyap and Panda, 2001).

A comparison study can determine the impacts of using two different reference ET equations for estimating crop ET for the semi-arid conditions of Colorado. The objectives of this study were to:

1- Compare the seasonal behaviors of the ET_r values from ACSE-SPM and PK equations across a climatic gradient in Colorado from 2008 to 2011.
2- Determine and evaluate the effects of climatic factors on ET_r and explain the differences between ASCE-SPM and PK ET_r values.

Materials and Methods

Locations

The weather stations from the Colorado Agriculture Meteorological Network (CoAgMet) used in the study includes seven field sites in Colorado (Table 2-1). The locations of these sites represent a climatic gradient from west to east of Colorado. The hourly data which was used to calculate the ASCE-SPM reference and the PK ET were provided by CoAgMet from 2008 to 2011 (http://ccc.atmos.colostate.edu/~coagmet/station_description.php).

Climatic data collection

Complete automatic weather stations present at the seven sites were used to obtain the factors needed in the ET_r equations. Climatic data was recorded automatically every minute using a data logger and then processed as hourly and daily output. The sensor used to measure rainfall was a TE525 tipping bucket rain-gauge located >1 m above the ground. A R.M. Young Wind Sentry (prop-anemometer) placed 2 m above the ground was used to measure wind speed and wind direction. A Vaisala HMP45C Probe placed 1.5 m above the ground was used to measure temperature and relative humidity. A Licor LI-200X Pyranometer placed ~2 m above the ground was used to measure solar radiation. CSI Model 107 Soil Temp Probe (thermistor) sensors were installed at 0.05 m and 0.15 m depths below the soil surface where two sensors were used; or at 0.1 m depth where only one sensor was used (http://ccc.atmos.colostate.edu/~coagmet/station_description.php).

ET_r calculated by the American Society of Civil Engineers (ASCE) standardized Penman-Monteith Equation

The standardized reference ET can be calculated for (1) a short crop (similar to grass) or (2) a tall crop (similar to alfalfa). ET_{os} is the reference for a short crop that has a height of 12 cm whereas ET_{rs} is the reference for a tall crop that has a height of 50 cm. In addition, this equation can work with both hourly and daily reference ET equations.

The ASCE-SPM equation for tall reference is given:

$$ET_{rs} = \frac{0.408\,\Delta\,(R_n - G) + \gamma \frac{C_n}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \qquad \text{Eq. (1)}$$

where the units for the factor 0.408 coefficient is m^2 mm/MJ. ET_{rs} is the standardized reference crop ET for tall surfaces (mm/h); Δ is the slope of the saturation vapor pressure-temperature curve (kPa/°C); R_n is the calculated net radiation at the crop surface (MJ/m^2/h); G is the soil heat flux density at the soil surface (MJ/m^2/h); γ is a psychrometric constant (kPa/°C); C_n is the numerator values that changes with reference type and calculation time step (K mm s^3/Mg/h or K mm s^3/Mg/d); T is the mean hourly air temperature in °C at 1.5 to 2.5-m height; u_2 is the mean hourly wind speed at 2 m height (m/s); e_s is the saturation vapor pressure at 1.5 to 2.5 m height (kPa); e_a is the mean actual vapor pressure at 1.5 to 2.5 m height (kPa); C_d is a denominator value that changes with reference type and calculation time step (s/m) (Allen et al., 2007). For this study, the ASCE-SPM was used to calculate hourly tall (alfalfa) reference ET_{rs}. The standardized C_n and C_d values were C_n= 66 (K mm s^3/Mg/h) at daytime and nighttime and C_d = 0.25 (s/m) at daytime and C_d = 1.7 (s/m) at nighttime.

ET_r calculated by the Penman-Kimberly Equation

The following equation was used for hourly time steps:

$$\lambda \mathrm{ET_r} = \frac{\Delta}{\Delta+\gamma}(R_n - G) + \frac{\gamma}{\Delta+\gamma} 0.268(e_s - e_a)W_f \qquad \text{Eq. (2)}$$

where ET_r is the reference ET (mm h^{-1}), λ is latent heat of vaporization (MJ kg^{-1}) and W_f is the wind function. The wind function was calibrated for the Kimberly, Idaho locale, and the wind function coefficients vary with the time of year. Net radiation coefficients in the 1982 Penman-Kimberly also depend on the time of year. The Penman-Kimberly 1996 ET_r values were calculated using the wind function (Wright et al., 2000).

The dimensionless wind function is calculated as follows:

$$W_f = a_w + b_w U_2 \qquad \text{Eq. (3)}$$

where: a_w and b_w are empirical coefficients that lessen the effect of the wind function and they are calculated as follows with x representing the day number in the calendar year (Wright, 2000):

$$a_w = 0.4 + 1.4 * e^{\left[-\left(\frac{x-173}{58}\right)^2\right]} \qquad \text{Eq. (4)}$$

$$bw = 0.007 + 0.004 * e^{\left[-\left(\frac{x-243}{80}\right)^2\right]} \qquad \text{Eq. (5)}$$

U_2 is the wind speed at 2 m height in kilometers per day.

Terms of the ASCE-SPM and PK equations

The Ref-ET program (Allen, 2000) is software used for calculating the reference ET rates from weather data and includes 15 methods, including the ASCE-SPM and the PK equations (http://www.kimberly.uidaho.edu/ref-et/).

Ref-ET provides output of some terms of each equation that were used to calculate ET_r. The aerodynamic term includes some weather data and canopy characteristics such as temperature, wind speed, vapor pressure, plant height, LAI, surface resistance and stomata resistance. The energy budget term includes net radiation and soil heat flux density at the soil surface (equations 1 and 2). Daily aerodynamic and energy budget terms were calculated separately from the ASCE-SPM and PK equations and then compared for the CSU ARDEC and Rogers Mesa Sites in 2011 to study the differences between the terms of both equations (ASCE-EWRI, 2005).

Data processing

The REF-ET computer program can calculate reference ET using 15 different equations, two of which are the ASCE-SPM and PK. This program was used to calculate reference ET for a tall crop (similar to alfalfa) that has a height of 50 cm. The calculations were based on the climate data that are available on CoAgMet. The hourly climatic data included Mean Temperature (^oC), Vapor Pressure (kPa), Solar Radiation (MJ/m^2), mean wind speed (m/s), and Mean of Relative Humidity (%). Four years of data (2008 - 2011) obtained from CoAgMet were transferred into Excel and then used by the Ref-ET program to calculate hourly reference evapotranspiration using ASCE-SPM and PK.

The comparisons between the two equations were made using the daily reference ET which was calculated in a 2 step process; hourly weather data were used to calculate hourly $ET_{r,}$ and then hourly ET_r were summed for each 24-hour period to get daily ET_r. This two-step process is deemed more accurate than using daily climate data in calculating the ET_r directly (Allen, 2000).

Evaluation and statistical analysis

The calculated data were analyzed using Microsoft Office Excel. The regression lines of daily ET_r calculated with the two equations were statistically analyzed for the seven locations and four years. The comparisons between the two equations were made using the daily readings to show the correlation and relationship between the ET_r values.

Several statistics were used to compare the two ET_r equations including Sum, Average, Minimum (Min), Maximum (Max), Standard Deviation (STDEV), and R^2. In addition, Root-Mean-Square Error (RMSE) is a statistic used in environmental estimation models (Jacovides and Kontoyiannis, 1995; Wallach, 2006). Small RMSE values indicate good agreement. However, RMSE values are not a good indication of over or under estimation of a model (Jacovides and Kontoyiannis, 1995). Relative Error (RE) was used to present the percentage difference between ET_r from the two equations (Willmott et al., 1985). The index of agreement (d) is another indicator used to measure performance of a model (Harmel and Smith, 2007). It has a domain between one and zero. A 1 value means an excellent agreement, while a 0 value means a poor agreement. Alternatively, R squared (R^2) shows how well data points fit a line or curve. An R^2 value of 1 means an excellent fitting line, while a 0 value means a poor fitting line (Cameron and Windmeijer, 1997).

Root-Mean-Square Error (RMSE) was calculated as follows:

$$\mathrm{RMSE} = \left(1/\mathrm{N}\sum_{i=1}^{\mathrm{N}}(\mathrm{y_i} - \mathrm{x_i})^2\right)^{1/2} \qquad \text{Eq. (4)}$$

where N is the total number of observations, y_i is the calculated SPM ET_r, and x_i is the calculated PK ET_r (Willmott et al., 1985).

Relative Error (RE) was calculated as follows:

$$\mathrm{RE} = \left(\frac{\mathrm{y_i} - \mathrm{x_i}}{\mathrm{x_i}}\right) \times 100 \qquad \text{Eq. (5)}$$

where RE is relative error used to indicate the percentage difference. It can be positive or negative. Positive values mean the percentage of over-estimation, and negative values mean the percentage of under-estimation (Willmott et al., 1985). y_i is mean ET_r from PK equation and x_i is mean ET_r from ASCE-SPM equation.

Index of agreement (d) was calculated as follows:

$$d = 1 - \left(\frac{\sum_{i=1}^{N} (y_i - x_i)^2}{\sum_{i=1}^{N} (|y_i'| - |x_i'|)^2} \right) \qquad \text{Eq. (6)}$$

where: d is between one and zero, $y_i' = y_i - \bar{x}$ and $x_i' = x_i - \bar{x}$, y_i and $\bar{x}$ is the mean measured value (Willmott et al., 1985). y'_i is the ASCE-SPM values and x'_i is the PK values.

Results and Discussion

Annual comparisons

For each year, mean ET_r values using the PK equation were always lower than the values obtained from the ASCE-SPM equation for all locations except the CSU Rogers Mesa site (Table 2-2). The values in the Index of Agreement were close to one (Table 2-2). The negative values for the Relative Error of Mean (%) indicate that the PK ET_r is lower than the ASCE-SPM ET_r on an annual basis. The R^2 values (0.93 - 0.99) indicate that the ET_r from the two equations were strongly correlated in each of the four years in all seven locations. The difference at CSU Expt Rocky Ford for 2011 was the highest compared to other years and other stations, where RE was at -6.4% and RMSE was at 0.72 mm/d (Table 2-2). The two equations have some differences in the way the energy balance and aerodynamic terms are calculated, but the weather data used in both equations are the same, and they calculate daily ET_r under similar conditions. The calculated ET_r from the two equations showed that the PK equation generally resulted in lower annual or seasonal ET_r values than the ASCE-SPM equation which illustrates an important difference between the equations. Based only on mean ET_r values from ASCE-SPM equation and the most complete year of record (2011), the highest mean daily ET_r was observed at Rocky Ford (5.26 mm/d) while the lowest was at Rogers Mesa (3.66 mm/d) (Table 2-3).

To show the cumulative differences throughout a season, daily cumulative plots are shown for all locations in 2011 (Figures 2-5 and 2-6). The cumulative daily ET_r based on the ASCE-SPM and PK equations for 2011 in each of the seven locations was ideal in 2011 in terms of having a full weather data set. The cumulative reference ET data showed the correlation between the total readings of daily ET_r based on the two equations for the years studied at the seven stations, but the cumulative reference ET_r data from the two equations did not match during the year. The cumulative figures show that the PK values were generally lower than the ASCE-SPM. The CSU Rogers Mesa site showed the cumulative daily ET_r based on the PK equation was very close to the cumulative daily ET_r based on the ASCE-SPM equation.

Daily differences by time of year

The differences between the calculated PK ET rates and the ASCE-SPM ET rates were least in the summer months (May - October) at the majority of the stations (Figures 2-7 to 2-13). The differences were greater in late winter and early spring months for all locations. Figures 2-7 to 2-13, for the years 2008, 2010, and 2011, show differences in the daily ET_r values calculated using the ASCE-SPM and PK equations for the seven locations. Note that the daily PK ET_r was generally lower than the daily ASCE-SPM ET_r during the spring, fall, and winter periods. The greatest differences were during spring months followed by the fall months at most locations. Figures 2-10 to 2-12 shows the largest differences in the daily ET_r at the CSU Expt. Rocky station for winter 2011 while the lowest differences during this same period were at the CSU Rogers Mesa station. During the months May through October, the ET_r for the two equations had a smaller difference than the months November through April (ASCE-EWRI, 2005).

Differences in energy budget terms and aerodynamic terms

Figure 2-14 shows a comparison of the daily energy budget terms (mm/d) as calculated by the ASCE-SPM and PK equations at CSU ARDEC Station and CSU Rogers Mesa station for 2011. At the ARDEC station the daily energy budget terms of the PK equation was higher than the daily energy budget terms of the ASCE-SPM equation during 2011. The ET_r can be affected directly by net radiation and soil heat flux because they are the main factors in energy budget terms. Also, Figure 2-15 shows the difference between the aerodynamic part of calculating ET_r from ASCE-SPM and PK equations. Aerodynamic term can be affected too by the weather and plant factors such as temperature, wind speed, humidity, vapor pressure, plant height, LAI, surfaces resistance of plant and stomata resistance. Therefore, at the CSU ARDEC Station and CSU Rogers Mesa station for 2011 show clear differences from calculating aerodynamic term by the two equations. The aerodynamic term calculated by the PK equation was generally lower than the aerodynamic term calculated by ASCE-SPM equation during the year. The differences in the energy budget term and aerodynamic term between the two equations explain why the

ASCE-SPM equation gave relatively higher ET_r values than PK equation during the four years in most locations in Colorado.

Figure 2-16 shows greater variability in net radiation (R_n) differences between the two equations during winter, spring and fall periods; and the PK R_n values to be more consistently lower than ASCE-SPM R_n values from DOY 120 to 230 (mid-year). The differences between the PK and ASCE-SPM ET_r appear to be correlated to the differences in net radiation when looking at these differences at the CSU ARDEC Station and CSU Rogers Mesa Station during 2011 (Figure 2-16; Figures 2-7 and 2-12). A small difference between net radiation as calculated by the two equations correlates to a small difference in ET_r between the two equations. Likewise, a large difference between net radiation correlates to larger differences in ET_r values from the two equations.

Effects of weather

The effects of weather parameters on ET_r differences between the two equations are shown in Figures 2-17 to 2-20. There was no obvious trend in the differences versus R_n (Figure 2-17). However, the difference between PK and ASCE-SPM ET_r became generally more negative when wind speeds were above 2 m/s (Figure 2-18).

The difference between PK and ASCE-SPM ET_r was also affected by humidity (actual vapor pressure or relative humidity). The PK equation tended to give lower ET_r values than the ASCE-SPM equation as vapor pressure or relative humidity decreased (Figures 2-19 and 2-20).

Differences in ET_r were generally less than 0.5 mm/d when mean actual vapor pressure was higher than 1.5 kPa (Figure 2-19).

Implications on crop coefficient curves

Crop evapotranspiration (ET_c) comprises most of the consumptive water use of plants. ET_c can be calculated by multiplying ET_r from ASCE-SPM equation or PK equation with a crop coefficient (K_c) that varies with growth stage. The K_c represents the characteristics of plants such as canopy cover, growth stage, leaf area index, and crop type that affect the amount of ET_c. The length of each growth stage depends on the climate, latitude, elevation, planting date, and crop type, maturity group of different varieties or cultivars, and management practices.

Early in the growing season during the crop germination and establishment stage, most ET_c occurs as evaporation from the soil surface. As the crop canopy develops and covers the soil surface, evaporation from the soil surface decreases and transpiration increases. Early in the season when the plant is small, the water use rate and K_c value also are small (K_c initial stage). As the plant develops, the crop ET rate increases. For agronomic plants, the crop ET rate is at the maximum level when the plant is fully developed (K_c mid-season). The ET rate decreases again toward the end of the season when the plant reaches physiological maturity (K_c end season).

Mean K_c values can be calculated by taking the ratio of measured ET_c and calculated ET_r from a reference ET equation, such as the PK or ASCE-SPM equation. In most locations in this study, the comparison between ET_r values from the ASCE-SPM and PK equations showed generally lower ET_r values from the PK equation. Thus, the lower ET_r values from the PK equation would result in higher calculated K_c values compared to using the ASCE-SPM equation. Given that the K_c values currently used in CoAgMet were developed for use with PK ET_r values, those K_c values would generally have to be decreased in the spring and fall periods and increased during summer, before they can be used with the ASCE-SPM ET_r values. Therefore, the development of new seasonal K_c curves for use with the ASCE-SPM ET_r values is recommended for Colorado conditions.

Conclusion

The current analysis is a comprehensive comparison of the daily ET_r values from the ASCE-SPM and PK equations. This analysis used hourly weather data gathered from seven different locations in Colorado. In general, the PK equation tended to give lower ET_r values during spring and fall periods, and slightly higher values during summer months compared to the ASCE-SPM equation. Comparisons of the seasonal cumulative ET_r showed that the PK equation values were consistently lower than the ASCE-SPM equation. The aerodynamic term calculated by the ASCE-SPM equation was generally higher than the aerodynamic term calculated by the PK equation, and the energy budget term calculated by the PK was generally higher than the energy budget term calculated by the ASCE-SPM equation. The behaviors of the daily energy budget and aerodynamic terms explain the reason why the ASCE-SPM ET_r is relatively higher than PK ET_r.

The difference between PK and ASCE-SPM ET_r became generally more negative when wind speeds were above 2 m/s. The difference between PK and ASCE-SPM ET_r was also affected by humidity (actual vapor pressure or relative humidity). The PK equation tended to give lower ET_r values than the ASCE-SPM equation as vapor pressure or relative humidity decreased. Differences in ET_r were generally less than 0.5 mm/d when mean actual vapor pressure was higher than 1.5 kPa.

Given the differences in ET_r values from the PK and the ASCE-SPM equations and the move towards adopting the ASCE-SPM equation in Colorado, it is recommended that new K_c curves for calculating ET_c be developed for use with ASCE-SPM ET_r values.

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Table 2-1: The locations of the weather stations in Colorado which were used for comparison of ET_r calculated by the ASCE-SPM and PK equations.

Station	Location	Longitude & Latitude
CSU Agricultural Research Development and Education Center (CSUARDEC)	6 miles northeast of Fort Collins	105^o West, 40.6525^o North
Greeley 4	1.5 miles North of Greeley Airport	104.638^o West, 40.4487^o North
Iliff	1.5 miles East of Iliff	103.045^o West, 40.7678^o North
CSU Fruita Experiment	2 miles north east of Fruita	108.7^o West, 39.1803^o North
CSU Rogers Mesa Experiment	4 miles west of Hotchkiss	38.7917^o West, 107.792^o North
CSU Experiment Station Rocky Ford	2.5 miles south east of Rocky Ford	38.0385^o West, 103.695^o North
CSU Yellow Jacket	2.5 miles north west of Yellow Jacket	37.5289^o West, 108.724^o North

Table 2-2: Statistical evaluation of the agreement of the two ETr calculations using the ASCE-SPM and PK equations at seven Colorado weather stations over four years. RE is Relative Error (%),RMSE is Root-Mean-Square Error (mm/d), d is Index of Agreement and R^2 is R squared.

Year	RE (y_i =PK and x_i =ASCE-SPM) (%)	RMSE (mm/d)	Index of Agreement (d)	R^2
		ARDEC		
2008	-4.96	0.75	0.98	0.93
2009	-5.92	0.49	0.99	0.97
2010	-8.12	0.43	0.99	0.98
2011	-5.99	0.47	0.99	0.98
		Greeley		
2008	-0.76	0.34	0.99	0.99
2009	-1.03	0.33	0.99	0.98
2010	-3.27	0.36	0.99	0.99
2011	-4.94	0.44	0.99	0.98
		Iliff		
2008	-3.58	0.52	0.99	0.97
2009	-0.59	0.29	0.99	0.99
2010	-3.93	0.38	0.99	0.98
2011	-4.93	0.43	0.99	0.98

Table 2-2: Statistical evaluation of the agreement of the two ETr calculations using the standardized ASCE- PM ET and the PK at seven Colorado weather stations over four years. RE is Relative Error (%),RMSE is Root-Mean-Square Error (mm/d), d is Index of Agreement and R^2 is R squared. (Continued)

Year	Relative Error of Mean (%)	RMSE (mm/d)	Index of Agreement (d)	R^2
		CSU Rocky Ford		
2008	-5.3	0.56	0.99	0.98
2009	-6.35	0.63	0.99	0.98
2010	-5.31	0.54	0.99	0.98
2011	-6.40	0.72	0.99	0.99
		CSU Fruita		
2008	-3.27	0.45	0.99	0.98
2009	-3.32	0.44	0.99	0.98
2010	-2.44	0.41	1.00	0.98
2011	-4.85	0.4	1.00	0.98
		CSU Rogers Mesa		
2008	1.73	0.42	0.99	0.97
2009	2.49	0.42	0.99	0.96
2010	1.91	0.4	0.99	0.98
2011	0.20	0.4	0.99	0.97
		Yellow Jaket		
2008	-1.54	0.37	1.00	0.98
2009	-2.08	0.37	0.99	0.98
2010	-0.73	0.33	1.00	0.99
2011	-1.81	0.37	1.00	0.99

Table 2-3: Statistical summary of the climate input data and the daily ET_r for the seven locations 2008 – 2011.The correlation (R^2) indicates the strength of relationship between the daily ET values calculated by the standardized ASCE Penman Monteith and the Penman Kimberly equations. CSU is Colorado State University, and ARDEC is Agricultural Research Development and Education Center.

Variable	ARDEC	Greeley	Illif	CSU Fruita	CSU Rocky Ford	CSU Rogers Mesa	CSU Yellow Jacket
				2008			
Mean Temperature (Celsius)	8.71	11.71	10.29	9.46	11.06	9.21	8.14
Vapor Pressure (kPa)	0.65	0.85	0.79	0.64	0.76	0.63	0.49
Solar Radiation ($MJ/m^2/d$)	15.32	17.11	17.53	17.70	17.49	17.51	18.28
Sum Precipitation (millimeters)	224	218	436	139	234	174	289
Mean daily wind speed (m/s)	3.03	2.00	1.39	1.52	2.40	0.90	1.85
Mean of Relative Humidity (Fraction)	0.56	0.58	0.87	0.45	0.57	0.54	0.47
Mean ASCE-PM ETrs (mm/d)	4.39	4.34	4.62	4.38	4.91	3.60	4.22
Mean PK ETrs (mm/d)	4.17	4.31	4.45	4.23	4.65	3.66	4.15
R^2	0.93	0.99	0.97	0.98	0.97	0.98	0.98
				2009			
Mean Temperature (Celsius)	9.87	10.49	12.12	9.68	10.77	9.63	8.68
Vapor Pressure (kPa)	0.75	0.91	1.06	0.66	0.78	0.63	0.50
Solar Radiation ($MJ/m^2/d$)	15.96	16.43	15.90	17.35	17.50	16.89	17.32
Sum Precipitation (millimeters)	285	339	223	141	262	160	194
Mean daily wind speed (m/s)	2.67	2.19	1.82	1.42	2.37	0.78	1.76
Mean of Relative Humidity (Fraction)	0.58	0.63	0.64	0.46	0.58	0.53	0.46
Mean ASCE-PM ETrs (mm/d)	3.93	4.07	4.02	4.23	4.75	3.43	4.12
Mean PK ETr (mm/d)	3.70	4.03	3.99	4.09	4.45	3.52	4.03
R^2	0.97	0.98	0.99	0.98	0.96	0.98	0.98

Table 2-3: Statistical summary of the climate input data and the daily ET_r for the seven locations 2008 – 2011.The correlation (R^2) indicates the strength of relationship between the daily ET values calculated by the standardized ASCE Penman Monteith and the Penman Kimberly equations. CSU is Colorado State University, and ARDEC is Agricultural Research Development and Education Center. (Continued)

Variable	ARDEC	Greeley	Illif	CSU Fruita	CSU Rocky Ford	CSU Rogers Mesa	CSU Yellow Jacket
				2010			
Mean Temperature (Celsius)	13.20	9.20	9.79	10.03	11.61	9.95	8.24
Vapor Pressure (kPa)	0.71	0.75	0.84	0.72	0.80	0.64	0.58
Solar Radiation (MJ/m^2/d)	16.03	16.49	15.49	17.53	18.17	17.07	17.80
Sum Precipitation (millimeters)	316	235	379	206	346	309	293
Mean daily wind speed (m/s)	1.5	2.12	2.14	1.43	2.27	0.85	1.73
Mean of Relative Humidity (Fraction)	0.52	0.60	0.62	0.48	0.57	0.53	0.53
Mean ASCE-PM ETrs (mm/d)	3.65	4.03	4.00	4.19	4.96	3.63	3.95
Mean PK ETr (mm/d)	3.35	3.89	3.84	4.09	4.69	3.70	3.92
R^2	0.98	0.99	0.98	0.98	0.98	0.98	0.99
				2011			
Mean Temperature (Celsius)	8.86	8.77	8.89	9.71	9.55	9.31	8.40
Vapor Pressure (kPa)	0.69	0.73	0.82	0.71	0.68	0.61	0.54
Solar Radiation (MJ/m^2/d)	16.01	16.32	15.20	17.40	18.41	17.08	18.74
Sum Precipitation (millimeters)	312	280	492	214	153	267	312
Mean daily wind speed (m/s)	2.68	2.25	2.23	1.66	12.91	0.94	1.77
Mean of Relative Humidity (Fraction)	0.57	0.59	0.62	0.46	0.59	0.51	0.49
Mean ASCE-PM ETrs (mm/d)	4.35	4.13	3.90	4.30	5.26	3.66	4.24
Mean PK ETr (mm/d)	4.09	3.93	3.71	4.09	4.93	3.66	4.16
R^2	0.98	0.98	0.98	0.99	0.97	0.98	0.99

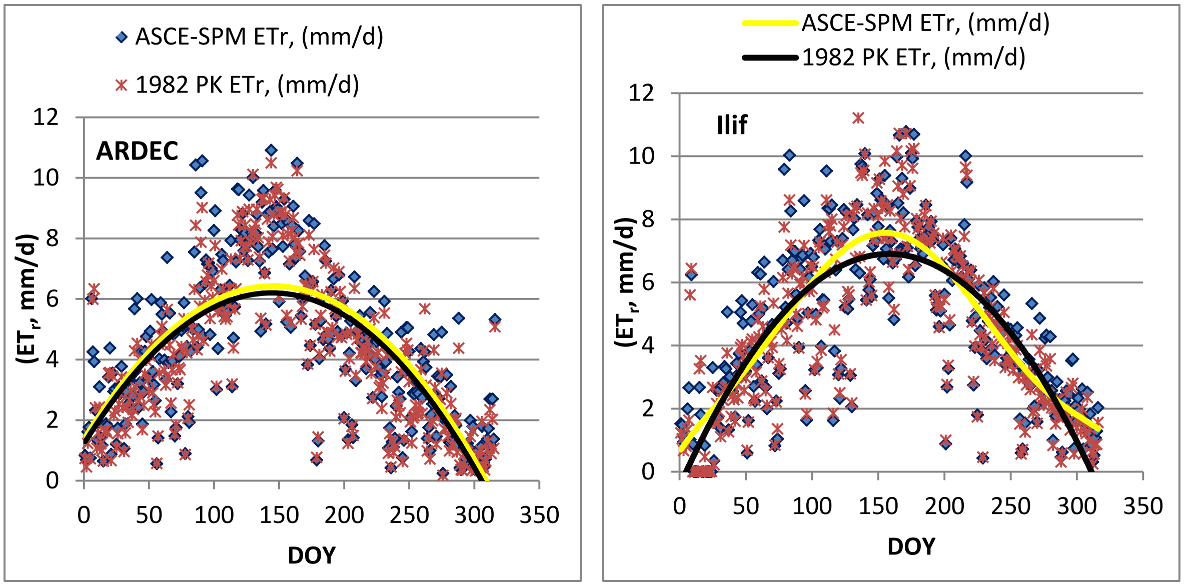


Figure 2-1: Daily reference ET (mm/d) as calculated by the American Society of Civil Engineers Standardized Penman-Monteith (ASCE-SPM) and Penman-Kimberly (PK) equations at Agricultural Research Development and Education Center (ARDEC) and Iliff locations for 2008. DOY is day of year.

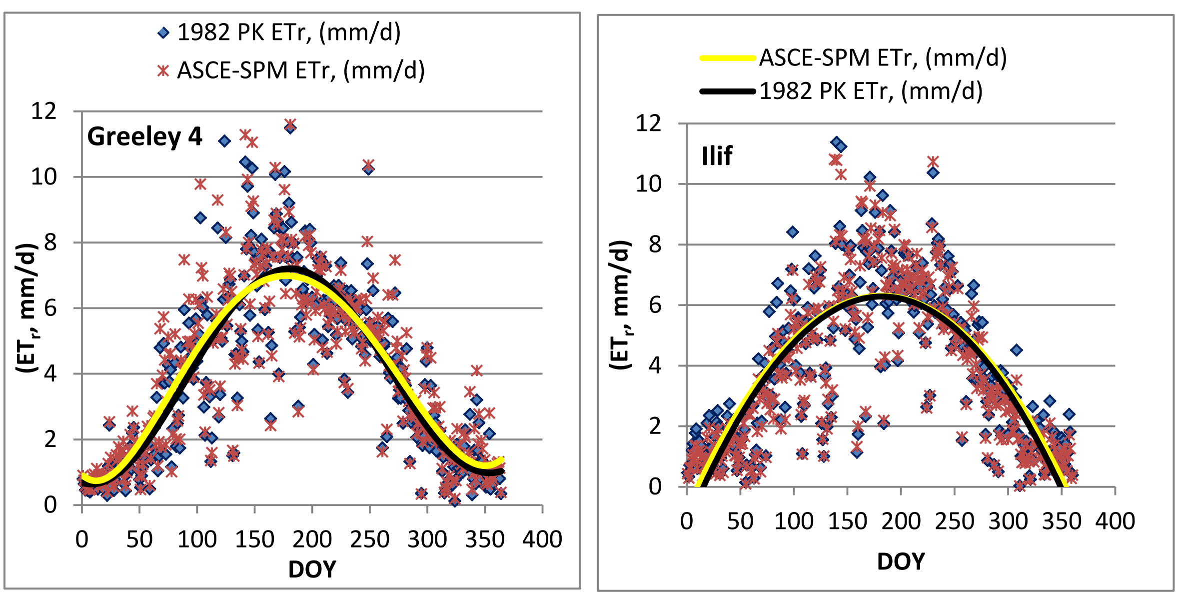


Figure 2-2: A comparison of the daily reference evapotranspiration (ET_r, mm/d) as calculated by the American Society of Civil Engineers Standardized Penman-Monteith (ASCE-SPM) and Penman-Kimberly (PK) equations at the Greeley4 and Iliff locations for 2010. DOY is day of year.

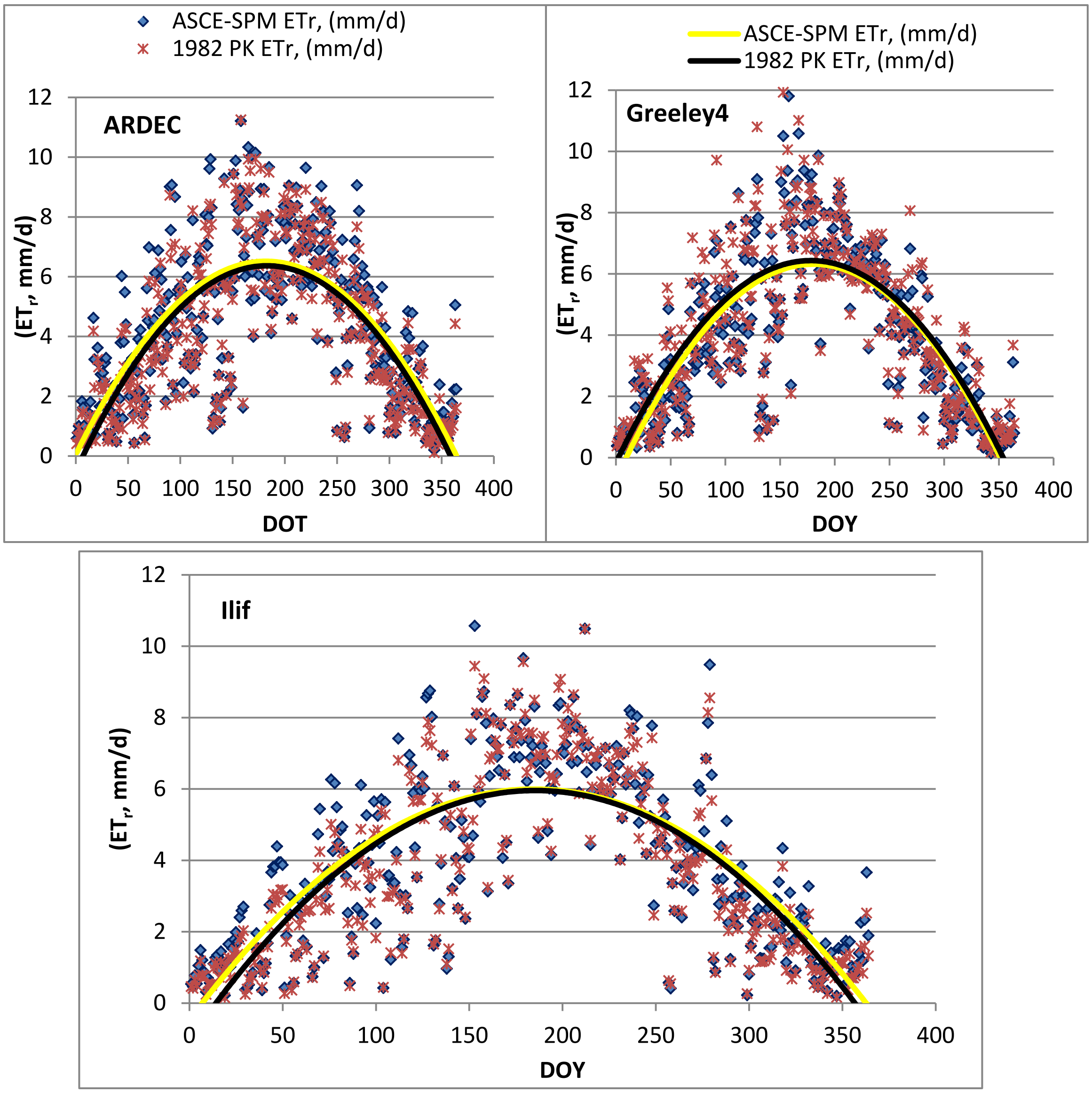


Figure 2-3: A comparison of the daily reference evapotranspiration (ET_r, mm/d) as calculated by the American Society of Civil Engineers Standardized Penman-Monteith (ASCE-SPM) and Penman-Kimberly (PK) equations at Agricultural Research Development and Education Center (ARDEC), Greeley, and Iliff locations for 2011. DOY is day of year.

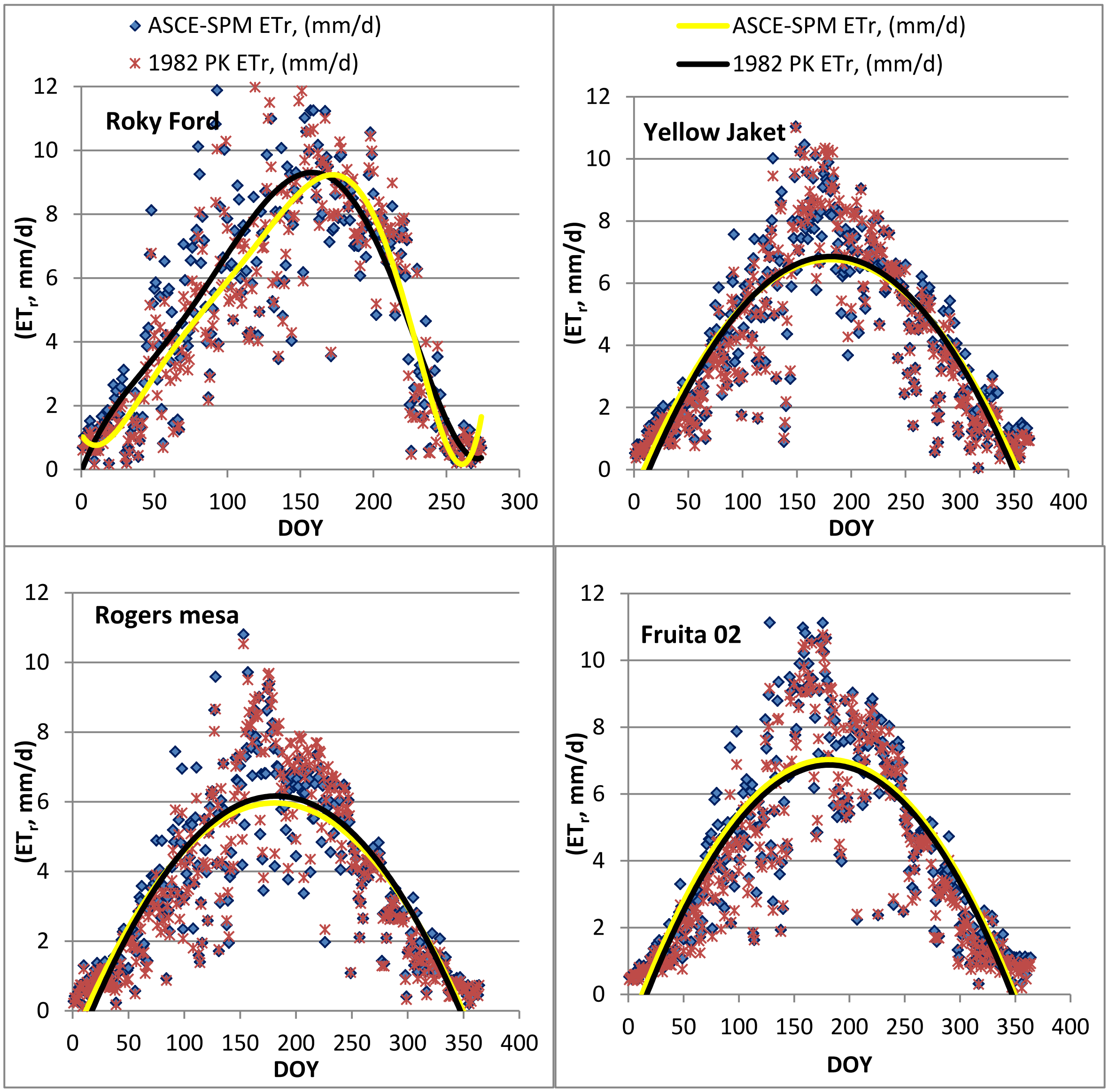


Figure 2-4: A comparison of the daily reference evapotranspiration (ET_r, mm/d) as calculated by the American Society of Civil Engineers Standardized Penman-Monteith (ASCE-SPM) and Penman-Kimberly (PK) equations at Colorado State University Fruita 02, at Colorado State University Rogers Mesa for 2011. DOY is day of year.

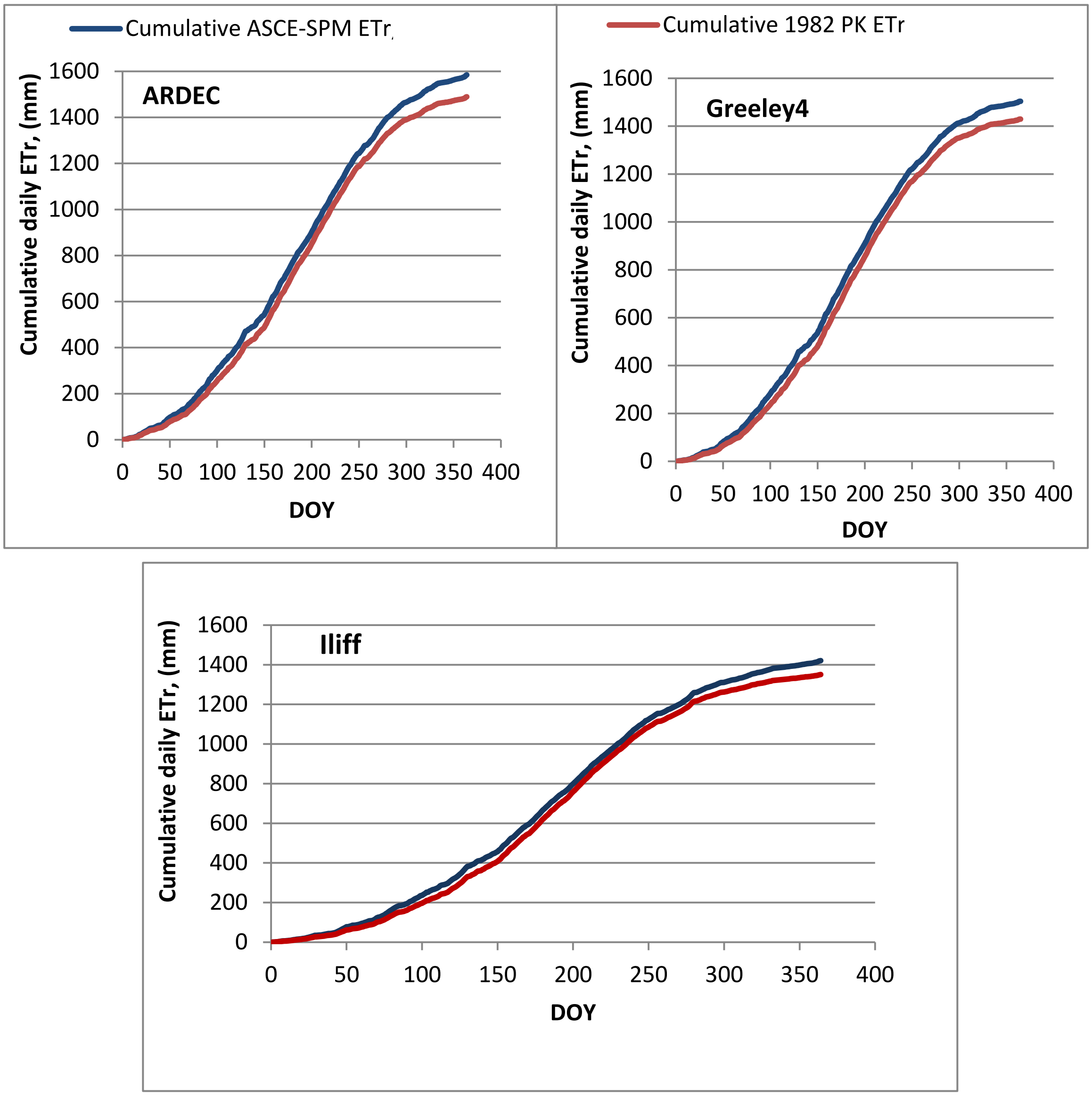


Figure 2-5: Cumulative daily reference evapotranspiration (ET_r, mm) calculated based on the American Society of Civil Engineers Standardized Penman-Monteith (ASCE-SPM) and Penman-Kimberly (PK) equations for 2011 from the Agricultural Research Development and Education Center (ARDEC), Greeley4, and Iliff stations. DOY is day of year.

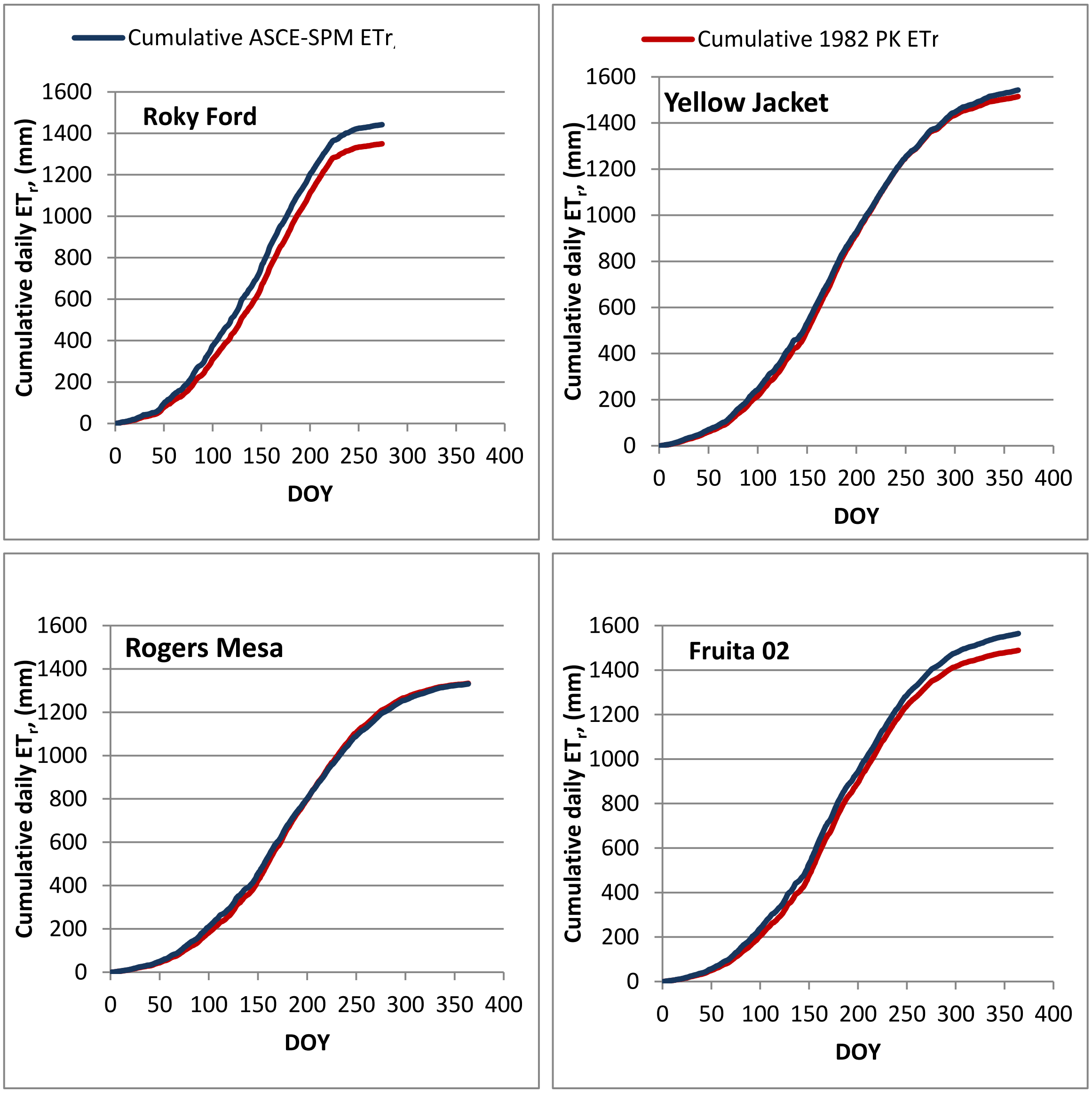


Figure 2-6: Cumulative daily reference evapotranspiration (ET_r, mm) calculated based on the American Society of Civil Engineers Standardized Penman-Monteith (ASCE-SPM) and Penman-Kimberly (PK) equations for 2011 from the Colorado State University (CSU) Experiment Rocky Ford, CSU Fruita 02 Experiment station, CSU Rogers Mesa and Yellow Jacket stations. DOY is day of year.

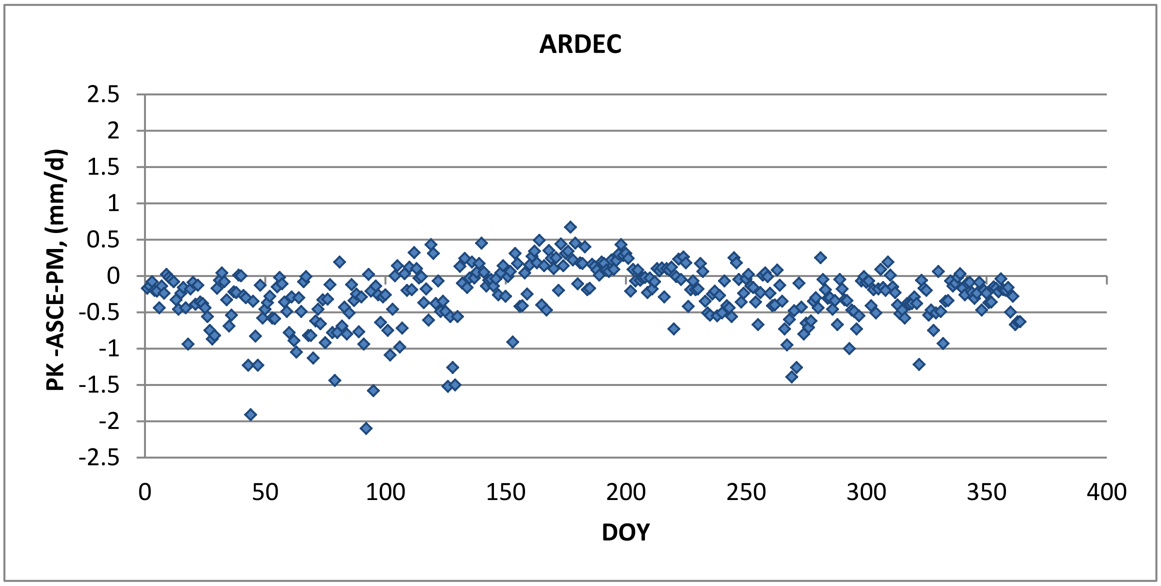


Figure 2-7: The difference in daily reference evapotranspiration (ET_r, mm/d) between the Penman-Kimberly (PK) and the American Society of Civil Engineers Standardized Penman-Monteith (ASCE-SPM) equations from the Agricultural Research Development and Education Center (ARDEC) for 2011. DOY is day of year**.**

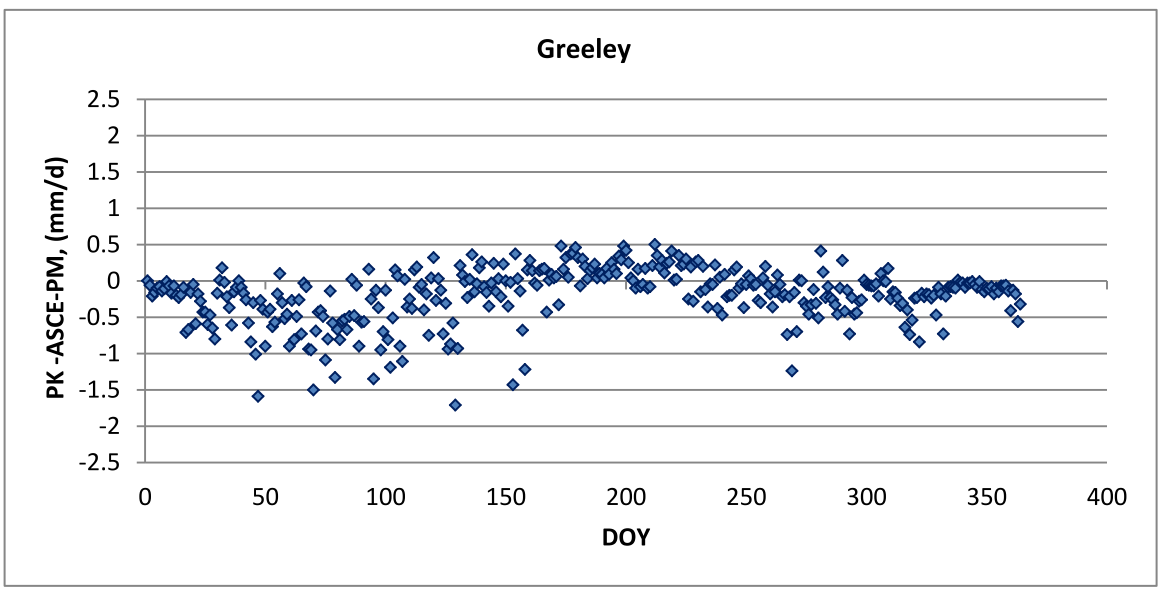


Figure 2-8: The difference in daily reference evapotranspiration (ET_r, mm/d) between the Penman-Kimberly (PK) and the American Society of Civil Engineers Standardized Penman-Monteith (ASCE-SPM) equations from the Greeley4 station for 2011. DOY is day of year.

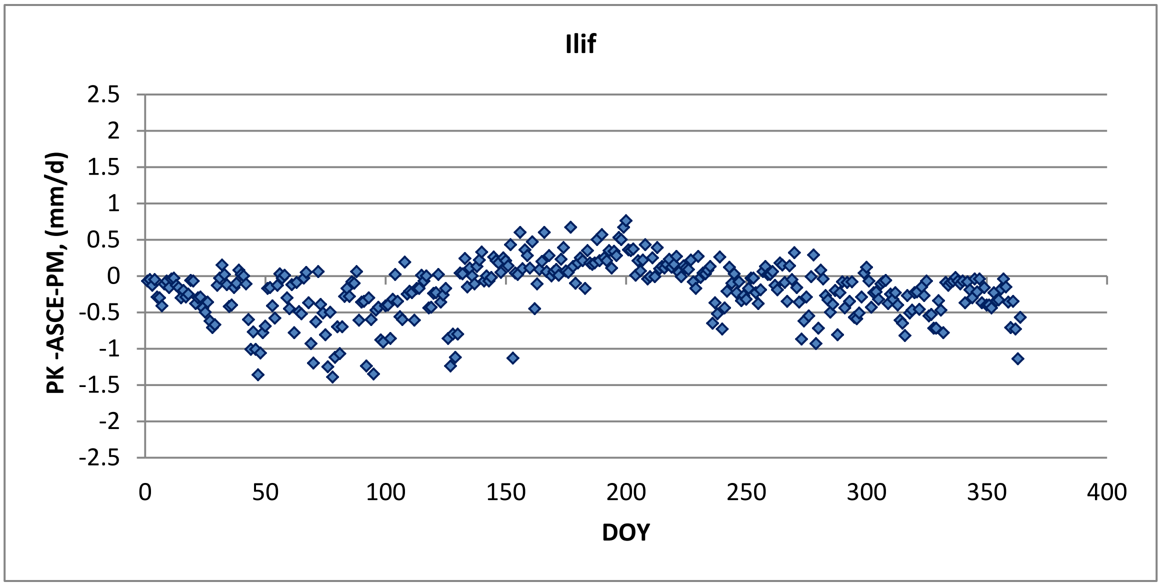


Figure 2-9: The difference in reference evapotranspiration (ET_r, mm/d) between the Penman-Kimberly (PK) and the American Society of Civil Engineers Standardized Penman-Monteith (ASCE-SPM) equations from the Iliff station for 2011. DOY is day of year.

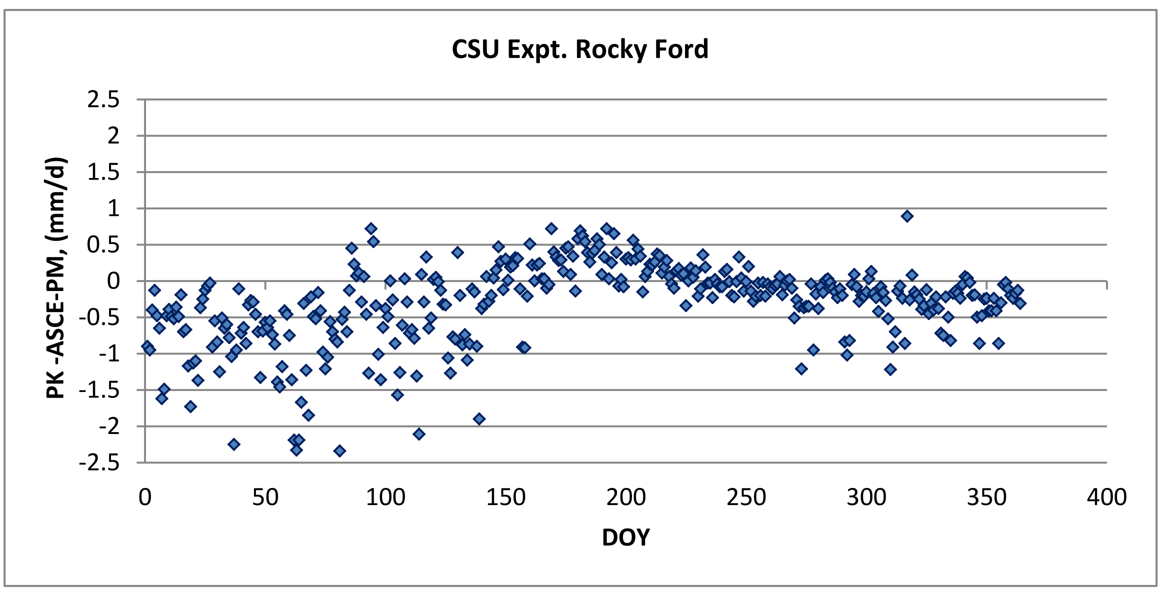


Figure 2-10: The difference in daily reference evapotranspiration (ET_r, mm/d) between the Penman-Kimberly (PK) and the American Society of Civil Engineers Standardized Penman-Monteith (ASCE-SPM) equations from the CSU Experiment Rocky station for 2011. DOY is day of year.

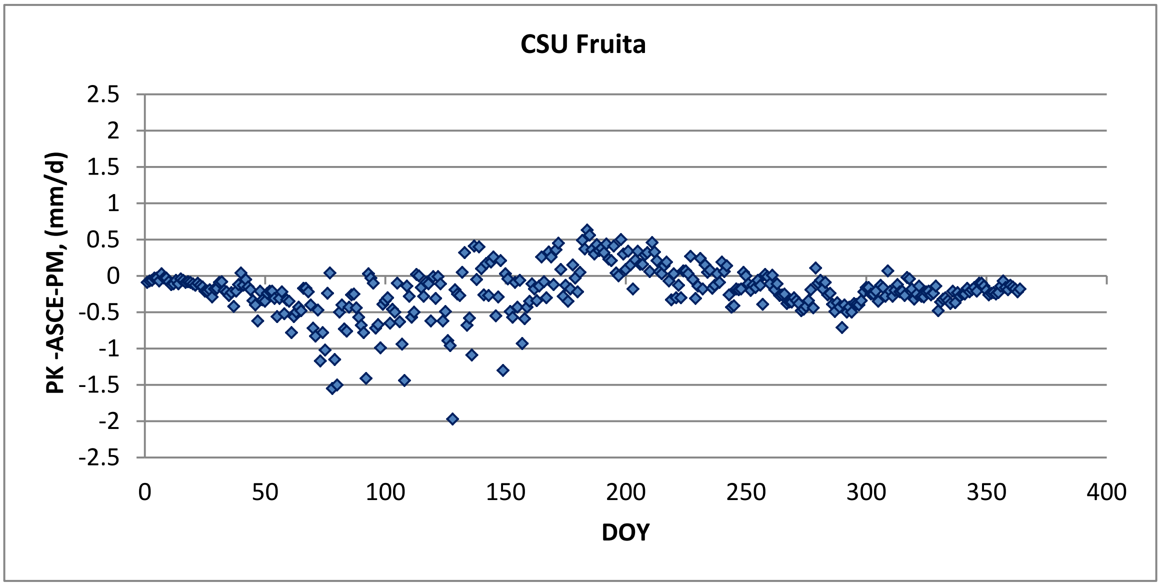


Figure 2-11: The difference in daily reference evapotranspiration (ET_r, mm/d) between the Penman-Kimberly (PK) and the American Society of Civil Engineers Standardized Penman-Monteith (ASCE-SPM) equations from the CSU Fruita Experiment station for 2011. DOY is day of year.

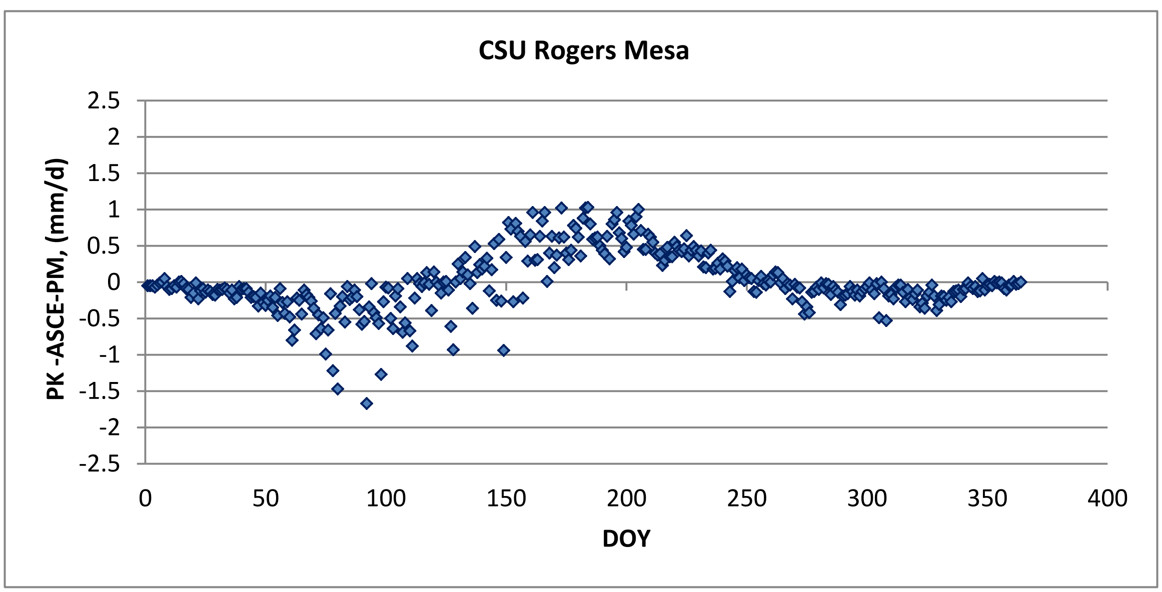


Figure 2-12: The difference in daily reference evapotranspiration (ET_r, mm/d) between the Penman-Kimberly (PK) and the American Society of Civil Engineers Standardized Penman-Monteith (ASCE-SPM) equations from the Colorado State University Rogers Mesa station for 2011. DOY is day of year.

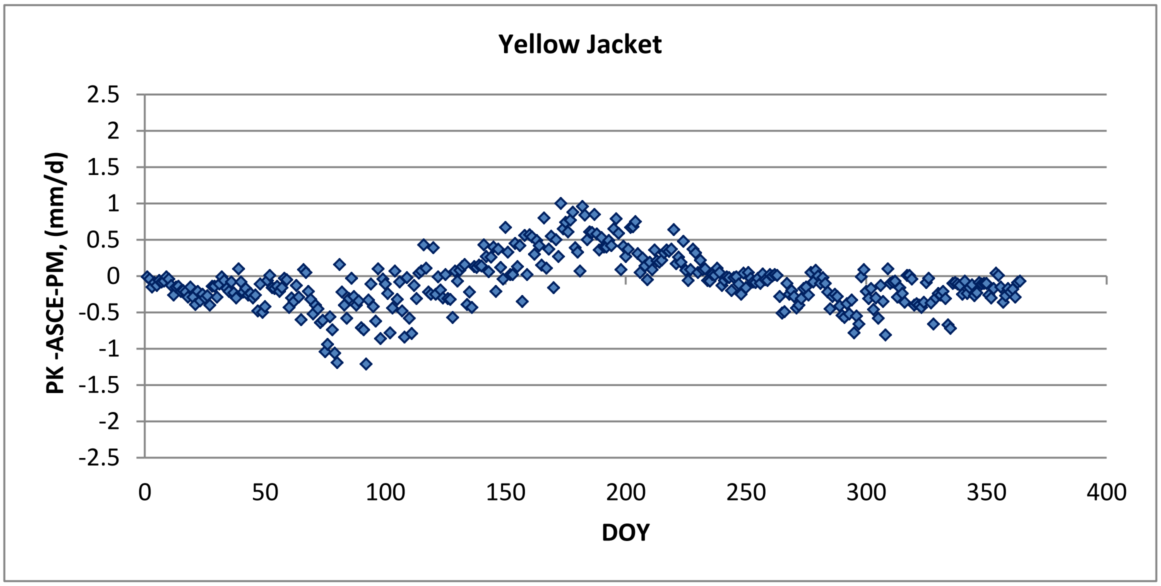


Figure 2-13: The difference in daily reference evapotranspiration (ET_r, mm/d) between the Penman-Kimberly (PK) and the American Society of Civil Engineers Standardized Penman-Monteith (ASCE-SPM) equations from the Yellow Jacket station for 2011. DOY is day of year.

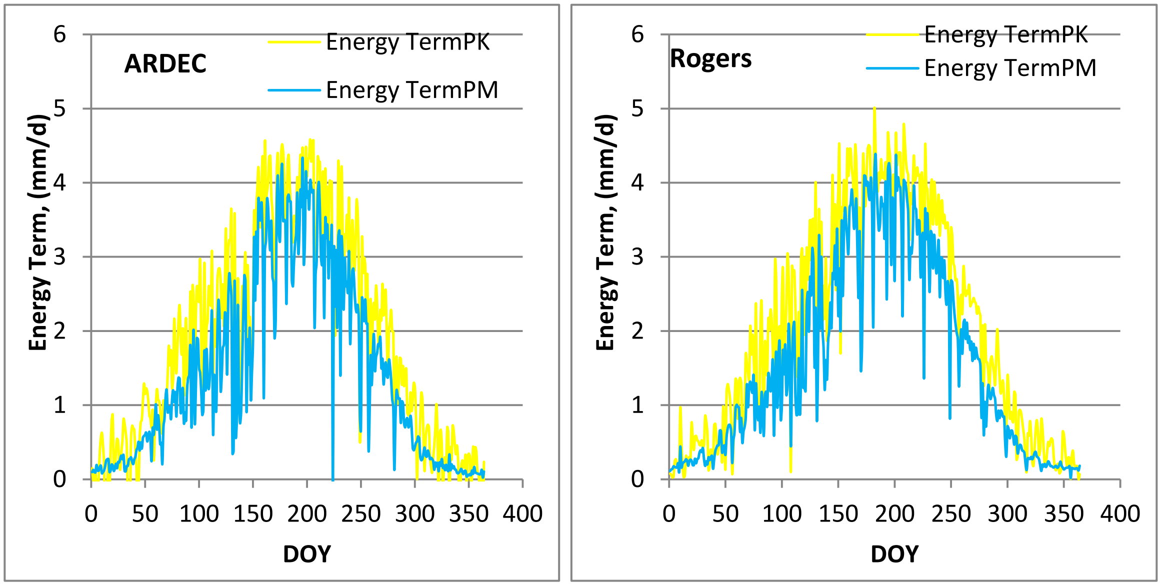


Figure 2-14: A comparison of the daily energy budget term (mm/d) as calculated by the Penman-Kimberly (PK) and the American Society of Civil Engineers Standardized Penman-Monteith (ASCE-SPM) equations at the Agricultural Research Development and Education Center (ARDEC) and Colorado State University Rogers mesa stations for 2011. DOY is day of year.

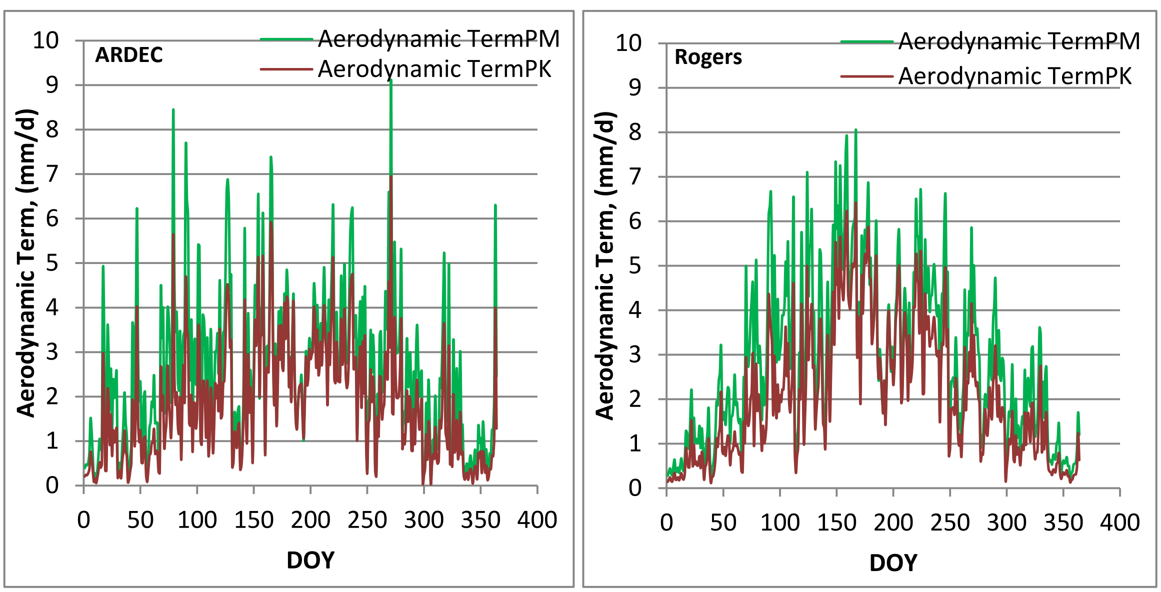


Figure 2-15: A comparison of the daily aerodynamic term (mm/d) as calculated by the Penman-Kimberly (PK) and the American Society of Civil Engineers Standardized Penman-Monteith (ASCE-SPM) equations at the Agricultural Research Development and Education Center (ARDEC) and Colorado State University Rogers mesa stations for 2011. DOY is day of year.

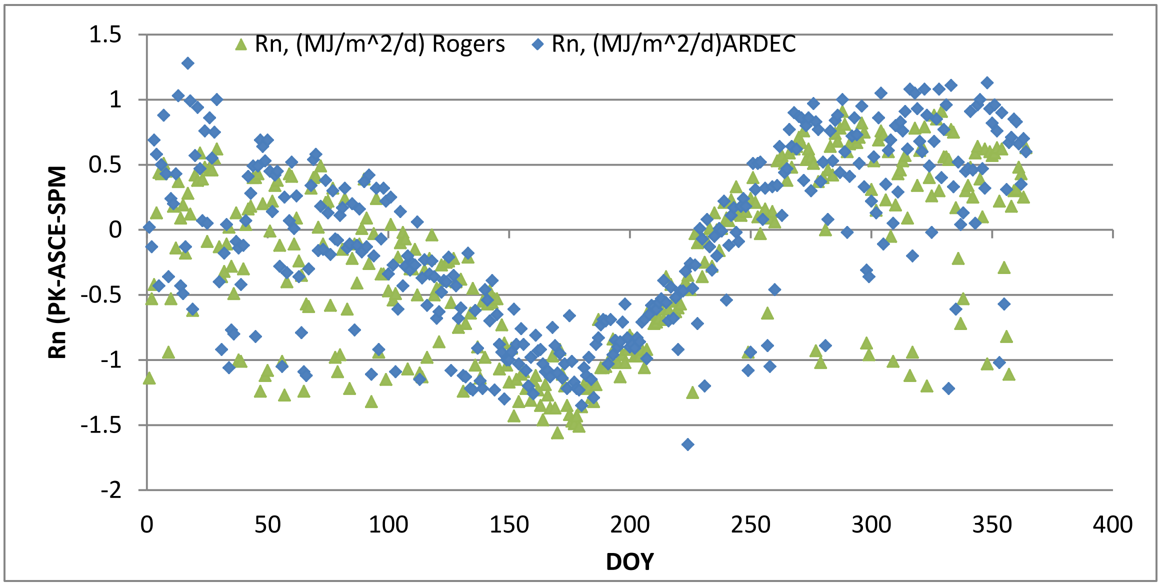
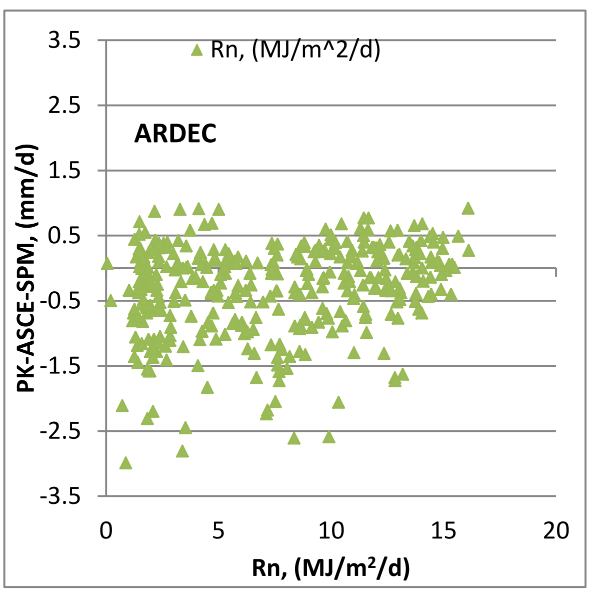


Figure 2-16: The difference in daily net radiation (Rn, MJ/m^2/d) as calculated by the Penman-Kimberly (PK) and the American Society of Civil Engineers Standardized Penman-Monteith (ASCE-SPM) equations at the Agricultural Research Development and Education Center (ARDEC) and Colorado State University Rogers mesa stations for 2011. DOY is day of year.



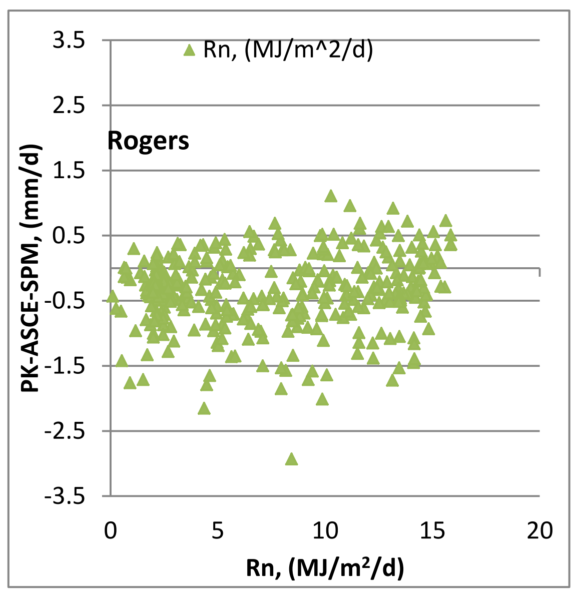


Figure 2-17: A comparison of the difference between daily reference evapotranspiration (ET_r, mm/d) between the Penman-Kimberly (PK) and the American Society of Civil Engineers Standardized Penman-Monteith (ASCE-SPM) equations as affected by net radiation (Rn, Mj/m^2/d) at CSU ARDEC and CSU Rogers mesa Stations for 2011.

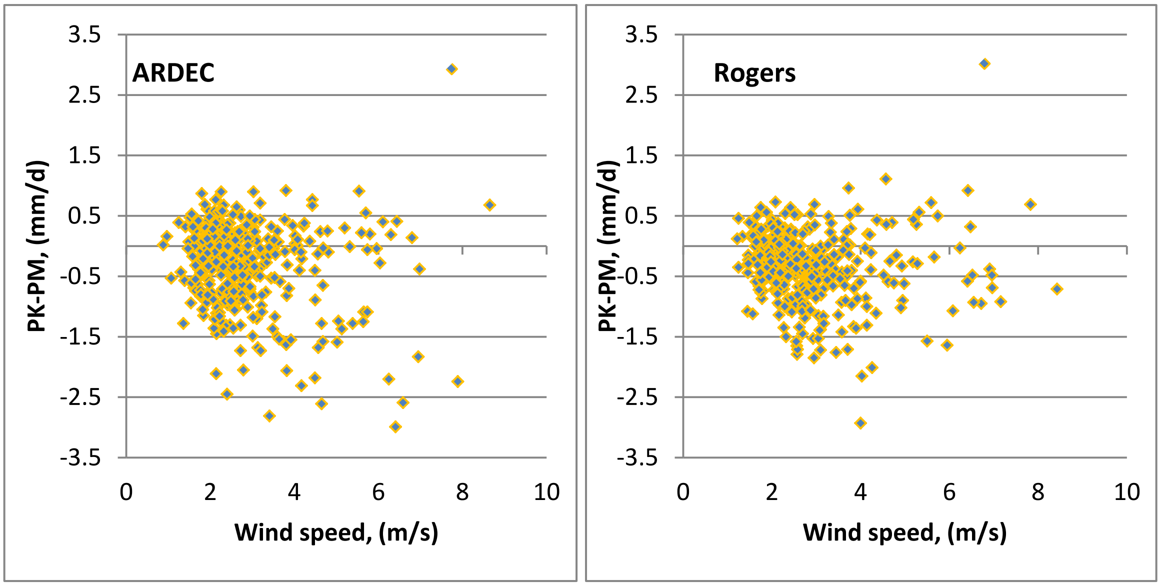


Figure 2-18: A comparison of the difference between daily reference evapotranspiration (ET_r, mm/d) between the Penman-Kimberly (PK) and the American Society of Civil Engineers Standardized Penman-Monteith (ASCE-SPM) equations as affected by mean wind speed (u_2, m/s) at CSU ARDEC and CSU Rogers mesa Stations for 2011.

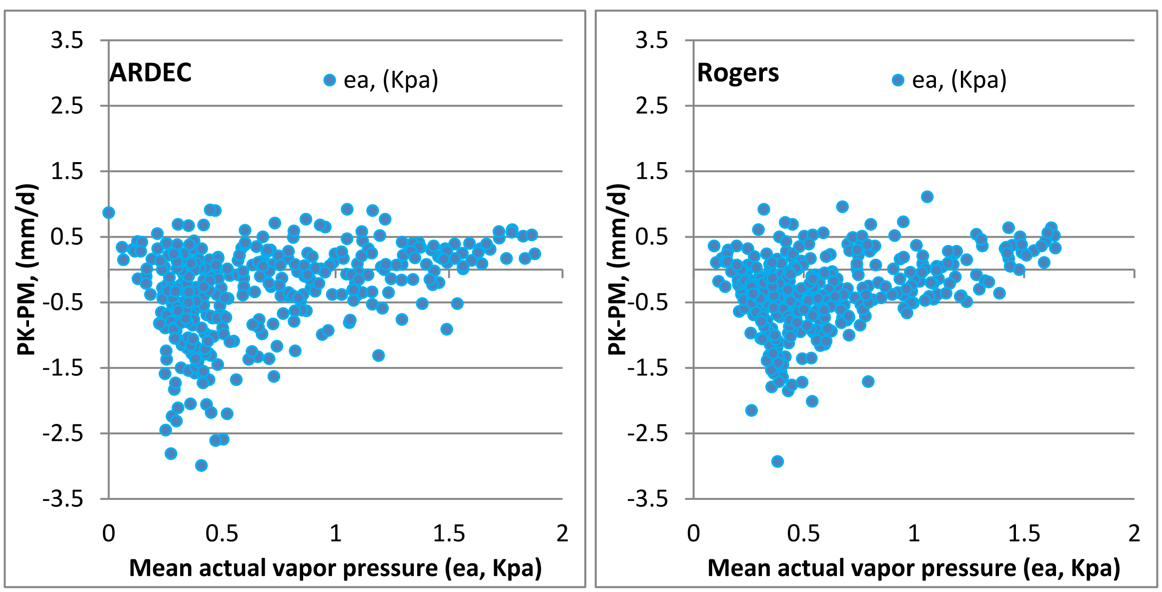


Figure 2-19: A comparison of the difference between daily reference evapotranspiration (ETr, mm/d) between the Penman-Kimberly (PK) and the American Society of Civil Engineers Standardized Penman-Monteith (ASCE-SPM) equations as affected by mean actual vapor pressure (ea, kpa) at CSU ARDEC and CSU Rogers mesa Stations for 2011.

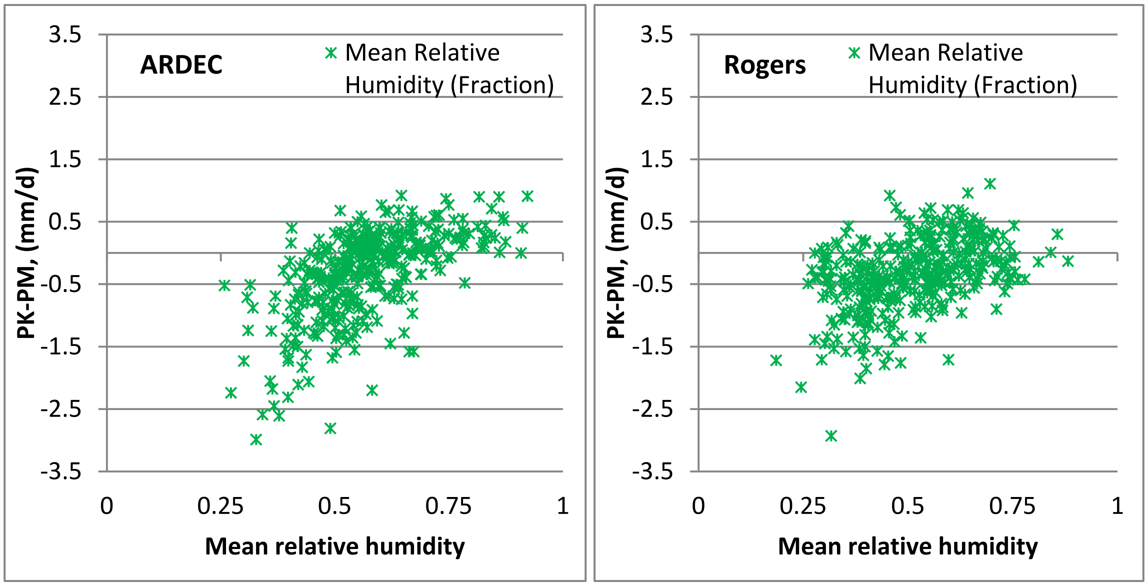


Figure 2-20: A comparison of the difference between daily reference evapotranspiration (ET_r, mm/d) between the Penman-Kimberly (PK) and the American Society of Civil Engineers Standardized Penman-Monteith (ASCE-SPM) equations as affected by mean relative humidity at CSU ARDEC and CSU Rogers mesa Stations for 2011.

CHAPTER THREE: EFFECTIVE SURFACE AREA CORRECTIONS FOR ALFALFA REFERENCE EVAPOTRANSPIRATION FROM A WEIGHING LYSIMETER

Overview

Evapotranspiration (ET) can be measured in the field using a lysimeter, which measures the actual ET through the changes in mass of a soil monolith supporting an actively growing crop. Alfalfa reference (ET_r) can be calculated using the American Society of Civil Engineers (ASCE) standardized Penman-Monteith equation (Allen et al., 2005) and climate data from a local weather station. This study compared alfalfa ET measured by a lysimeter (nominal 3 m × 3 m x 2.4 m) in the center of a 4.06 ha furrow-irrigated field at the Arkansas Valley Research Center in Rocky Ford, CO to the calculated values from the ASCE standardized Penman-Monteith equation in periods of reference conditions. Four days were selected when alfalfa in the lysimeter was 50 – 55 cm tall, unstressed, completely covering the ground, but with its canopy extending beyond the outer walls of the lysimeter. Climate data from CoAgMet was used to calculate ET_r by the ASCE standardized Penman-Monteith equation. Comparisons of hourly ET between the calculated ET_r using the ASCE standardized Penman-Monteith equation and ET_r measured by the lysimeter were performed. The first comparison was without any adjustments in the lysimeter ET_r where the Root-Mean-Square Error (RMSE, mm/h) was 0.08 on 9/16/2010, 0.11 on 9/23/2010, 0.10 on 10/1/2010 and on 0.08 on 10/12/2010. The Index of Agreement (d) between lysimeter and ASCE standardized ET_r was 0.98 on 9/16/2010 and 9/23/2010, 0.97 on 10/1/2010, and 0.96 on 10/12/2010. This same comparison was done using lysimeter ET_r corrected for the effective canopy area to account for overgrowth of the alfalfa beyond the lysimeter's 3.03 m x 3.03 m surface dimensions; the evaporative area increased from 9.181 m^2 up 12.461 m^2 on 10/12/2010. The RMSE (mm) between the hourly corrected lysimeter ET_r and the ASCE standardized ET was reduced to 0.05 in 9/16/2010, 0.04 on 9/23/2010, 0.05 on 10/1/2010 and 0.03 on 10/12/2010. The d values for this comparison were improved to 0.99 on 9/16/2010, 1.00 on 9/23/2010 and 0.99 on both 10/1/2010 and 10/12/2010. These results showed that it is important to use the correct effective canopy area when computing ET_r from a weighing lysimeter.

Introduction

Evapotranspiration (ET) represents the amount of water that evaporates from the soil and plant surfaces and the transpiration from plants (Zhang et al., 2001). Calculating ET plays an important role in estimating crop water requirements. Consumption of water increases with increasing ET in plants (Zhang and Oweis, 1999). Evapotranspiration is affected by climate factors such as solar radiation, wind speed, vapor pressure, relative humidity and temperature (Ephrath et al., 1996). Because these climate factors cannot be controlled in the field, irrigation scheduling is used to apply the amount of water that is needed and helps to regulate ET in the field (Burt et al., 1997). Therefore, the goal of irrigation scheduling is to supply the amount of water that plants need for physiological processing and optimal growth (Majumdar, 2004). Evapotranspiration can be measured in the field by using a water balance equation, but this approach requires data that is difficult to measure such as deep percolation and runoff (Duan and Fedler, 2009). The water balance equation is as follows:

$$ET_c = Irr + P - D - RO \pm \Delta\ SWC \qquad \textbf{(1)}$$

where ET_c is crop ET (mm), Irr is irrigation (mm), P is precipitation (mm), D is deep percolation (mm), RO is runoff (mm), and ΔSWC is the change in soil water content as measured by mass changes in soil samples from the field (mm) (Sudheer et al., 2003).

Evapotranspiration can also be measured in the field using a lysimeter which measures the actual ET_c through the difference in mass of a lysimeter over time (Sudheer et al., 2003). Specifically, it measures how much water has been lost since the previous measurement.

A lysimeter can have various shapes and selecting the appropriate one depends on which plants are to be evaluated for ET (Allen et al., 1992). For example, two lysimeters have been installed at Rocky Ford, Colorado. The size of the larger lysimeter is 3 m × 3 m x 2.4 m, and the size of the smaller lysimeter is 1.5 m x 1.5 m x 2.4 m (Al Wahaibi, 2011). The lysimeter tanks were filled using undisturbed soil from the site where they were installed, and then alfalfa was planted in the lysimeters (Andales et al., 2010). Evapotranspiration can be measured by scale-load cell (mV/V output; 0.02% standard deviation). One unit of load cell output (1 mV/V) is equivalent to 74.58 mm of water (Andales, personal communication). Thus, the changes in load cell output are multiplied by 74.58 to calculate the amount of water that is lost via drainage or ET and the amounts of water that are added through precipitation or irrigation (Hickman, 2011). Two drainage tanks were placed under the scale to measure drainage from the lysimeter (Andales et al., 2010).

Alfalfa reference crop ET_r can be calculated using available climate data from a weather station in the field or the closest station to the field within a 100 square kilometer area that would normally be covered by a weather station (Smith, 2000). Many equations can be used to calculate the ET_r based on climate data (Allen et al., 2005). In Colorado the two equations used for calculating ET_r in the Colorado Agriculture Meteorological Network (CoAgMet;

www.coagmet.com) are the ASCE standardized Penman-Monteith and Penman-Kimberly equations (Al Wahaibi, 2011). CoAgMet is the Colorado agricultural meteorological network. It provides hourly and daily weather data and calculated reference ET online every day for more than 60 automated weather stations located throughout Colorado (Andales et al., 2009a).

In 1999 the American Society of Civil Engineers (ASCE) and Environmental and Water Resources Institute (EWRI) suggested one standardized equation at the request of the Irrigation Association in Virginia (Walter et al., 2000). They worked from the FAO-56 Penman-Monteith (Allen et al., 2005) until they reached the final form that can calculate hourly and daily reference ET for a short crop like grass and a tall crop like alfalfa (Allen et al. 2005). This new equation was named the ASCE standardized reference ET equation. Use of this equation to calculate reference ET depends on the availability of weather data (Temesgen et al., 2005).

Alfalfa was recommended as a reference crop because it has a leaf area and height similar to most crops and has larger aerodynamic and surface conductance values than grass (Pereira et al., 1999). If using alfalfa as the reference crop, it should be grown under ideal well watered conditions and have 30 to 50 cm of top growth and no exposure to any kind of stress (Yoder et al., 2005). In Colorado, alfalfa has historically been used as the reference crop for estimating crop ET.

Al Wahaibi (2011) found that daily measured ET_r from a lysimeter and calculated ET_r from the ASCE standardized equation showed good agreement with the Index of Agreement ranging from 0.82 to 0.97 from a 2008 to 2010 study using 50 cm tall alfalfa under no stress. There was good correlation between ET measured with a weighing lysimeter and ET from the FAO−56 Penman−Monteith equation, while ET from the FAO−24 Penman, Hargreaves−Samani, and Priestly−Taylor equations overestimated ET (Yoder et al., 2005). In addition, a study performed by Lopez-Urrea et al. (2006) showed that the mean ET from the ASCE Penman–Monteith equation was 4% higher than the mean ET from a measured lysimeter. Also, the calculated hourly ET from the FAO-56 Penman–Monteith equation was more accurate than the ASCE Penman–Monteith method under Albacete, Spain weather conditions. Andales et al. (2009b) reported that for the 2008 season the daily calculated ET_r from the ASCE standardized Penman-Monteith equation was less than the measured ET_r from a lysimeter in the Arkansas Valley of Colorado (Andales et al., 2009b).

Using the correct surface area is important when the plant canopy extends beyond the boundaries of the lysimeter. Extension beyond lysimeter boundaries increases evaporation energy via solar radiation interception, and then consumption of water increases. In addition, the problem was observed in Rocky Ford that alfalfa extended outside the lysimeter boundary, which affected the accuracy of ET measurement by the lysimeter. In other words, the problem occurred where the alfalfa canopy inside the lysimeter was leaning outward due to the "bloom effect" (Allen et al., 2011). Allen et al. (2011) defined the bloom effect as "the area of exposed plant canopy has exceeded the assumed effective area of the lysimeter."

The objectives of this study were:

1- To quantify the effects of alfalfa overgrowth on measured reference ET from a precision weighing lysimeter during the 2010 season in the Arkansas Valley of Colorado (Rocky Ford, Colorado).
2- To correct the measured alfalfa ET from the lysimeter to account for effects of overgrowth.

Materials and Methods

Location of lysimeter

A weighing lysimeter was installed in 2006 at the Arkansas Valley Research Center in Rocky Ford which is in southeast Colorado (latitude 38^o 2' 17.30", longitude 103^o 41' 17.60", altitude 1,274 m above sea level). The location of the lysimeter was in the center of a field (159 m x 256 m), and this field was surrounded by 22 ha of irrigated land and planted with different crops such as corn, canola, oats and vegetables. The field in which the lysimeter is installed is surrounded by 7 m wide dirt roads on three sides. The CSU Rocky Ford Experiment Station is located at the CSU Arkansas Valley Research Center which is 4 km south east of Rocky Ford, Colorado.

Lysimeter design

The lysimeter is composed of an inner tank (container box) with dimensions of 3m x 3m x 2.4m deep and an outer tank in which the inner tank is placed. The enclosed space between the two tanks houses the weighing mechanism, drainage system, load cells, data logger and standing room for about 6 people. The weighing mechanism consists of a mechanical lever scale-load cell combination with a 100:1 mechanical advantage. The lysimeter installation and calibration was finished in 2006 (Andales et al., 2009b). The alfalfa grown on the lysimeter was irrigated by furrow irrigation. The scheduling of irrigation was dependent on the soil water content, determined volumetrically. The soil water content was measured weekly by neutron probe and gravimetrically to know the availability of water for plants to meet the total water requirement. Both methods were used to get soil water content measurements. The neutron probe was used to measure soil water content at 10 depths from 10 cm to 190 cm, at 20 cm increments. Irrigations were applied when soil water depletions approached 50% of the available water content between field capacity and wilting point.

Measured evapotranspiration from lysimeter

This study focused on alfalfa ET only at the reference stage (50 – 55 cm canopy height) for each cutting cycle when the canopy was observed to extend beyond the walls of the lysimeter and when there were no precipitation, irrigation, or drainage events. Four days during the 2010 season were identified that met these criteria: 9/16/2010, 9/23/2010, 10/1/2010 and 10/12/2010. For each date, canopy extension beyond the walls of the lysimeter was measured by taking the average horizontal measurement of alfalfa extending from the four sides of the lysimeter (Al Wahaibi, 2011).

The load cell readings of the lysimeter were taken every 2 seconds and were averaged in 15-minute intervals (450 readings per 15 minutes) to filter out the noise that may be caused by wind. This was consistent with recommendations of Howell et al. (1995). The difference between average load cell readings (mV/V) centered around the beginning and end of each 15-minute increment were multiplied by 74.58 mm/(mV/V). The 74.58 coefficient to convert load cell readings to equivalent mm of water was based on the 2011 calibration using Colorado State certified weights assuming a water density of 1000 kg/m3 (Andales, personal communication). Hourly ET was then obtained by summing the four 15-minute ET values for each hour.

The ASCE standardized reference ET equation

The ASCE standardized Penman-Monteith (ASCE-SPM) equation was used to calculate theoretical alfalfa reference ET, symbolized by $ET_{rs.}$ The ET_{rs} values on the four selected dates were deemed as good baselines for comparison with the lysimeter ET_r, since they represented potential alfalfa ET rates under the given weather conditions.

The ASCE-SPM reference ET equation is:

$$ET_{rs} = \frac{0.408\,\Delta\,(R_n - G) + \gamma \frac{C_n}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \qquad \text{Eq. (2)}$$

where ET_{rs} is the standardized reference crop ET for tall surfaces with a height of 50 cm such as alfalfa (mm/h); the units for the 0.408 coefficient are m^2 mm/MJ; Δ is the slope of the saturation vapor pressure temperature curve (kPa/°C); R_n is the calculated net radiation at the crop surface ($MJ/m^2/h$); G is the soil heat flux density at the soil surface ($MJ/m^2/h$); γ is a psychrometric constant (kPa/°C); C_n is the numerator constant that changes with reference type and calculation time step (K mm s^3 /Mg/h or K mm s^3 /Mg/d); T is the mean hourly air temperature in °C at 1.5 to 2.5m height; u_2 is the mean hourly wind speed at 2-m height (m/s); e_s is the saturation vapor pressure at 1.5 to 2.5-m height (kPa); e_a is the mean actual vapor pressure at 1.5 to 2.5-m height (kPa); and C_d is a denominator constant that changes with reference type and calculation time step (s/m). Hourly daytime and nighttime C_n = 66 (K mm s^3 /Mg/h), and hourly daytime C_d = 0.25 (s/m) and hourly nighttime C_d = 1.7 (s/m).

Hourly weather data from CoAgMet's Rocky Ford, Colorado weather station was used in the Ref-ET computer program (Allen, 2000). The hourly weather data included mean temperature (^{o}C), vapor pressure (kPa), solar radiation (MJm^{-2}), mean wind speed (m/s), and mean relative humidity (%). The Ref-ET program includes 15 methods of calculating ET_r including the ASCE-SPM equation. Hourly calculated ET_{rs} from the ACSE-SPM equation was then compared to the hourly measured ET_r from the lysimeter on the 4 selected dates to quantify the effect of alfalfa overgrowth on lysimeter ET_r.

Lysimeter evapotranspiration corrections

Comparisons between lysimeter ET_r and calculated ET_{rs} indicated that the ET_r from the lysimeter was affected by the alfalfa canopy extension beyond the lysimeter's 3.03 m x 3.03 m effective surface dimensions, extending at times up to 3.53 m x 3.53 m. For example, the average evaporative area increased from 9.181 m^2 to 12.461 m^2 on 10/12/2010 (Table 3-1).

The theoretical effective surface area of the lysimeter was measured up to the midpoint of the rubber seals separating the monolith interior wall from the external retainer wall (i.e. middle of the gap). That is because the canopy inside the monolith intersected with the canopy outside the monolith at the mid-point of the gap, assuming crop growth was the same inside and outside of the lysimeter. The distance between the interior wall and mid-point of the gap was 0.015 m. Therefore, the effective surface area is

$$\left[3.0m + 0.015\frac{m}{side} * 2\ sides\right]^2 = 9.181\ \mathrm{m}^2 \qquad \text{Eq. (3)}$$

To correct for the alfalfa overgrowth, the measured lysimeter ET_r values were divided by the correction ratio (Corrected lysimeter ET= uncorrected ET/ correction ratio) that came from dividing the effective canopy surface area by the lysimeter area (Table 3-1). The lysimeter surface area is always 9.181 m^2 because there is no change in the actual area of the lysimeter, but alfalfa extension outside the actual area was measured on each date so that the correction ratio could be specifically calculated for each date.

Statistical analysis

Microsoft Office Excel was used to compare ASCE-SPM ET_{rs} and lysimeter ET_r values. Hourly reference ET using the ASCE-SPM equation was calculated by the Ref-ET program. The hourly climatic data obtained from CoAgMet for four days were transferred into Excel and then used by the Ref-ET program.

The sum, average, minimum, maximum, standard deviation, and R^2 were used to compare the ASCE-SPM equation to the lysimeter results. In addition, the results were evaluated with the Root-Mean-Square Error (RMSE), where a small RMSE value indicates good performance (Jacovides and Kontoyiannis, 1995; Wallach, 2006). However, RMSE is not a good indication for over or under estimation of a model (Jacovides and Kontoyiannis, 1995). Another indicator used to measure the performance of a model is the index of agreement (d) (Harmel and Smith, 2007). It ranges between one and zero, where 1 represents an excellent agreement and 0 represents a poor agreement. For evaluation of the agreement between ASCE-SPM equation compared to the lysimeter, ET values and its R^2 were determined at the CSU Experiment Station at Rocky Ford for the four days. Additional statistics used for evaluating agreement were

Relative Error (RE) and the Nash-Sutcliffe Efficiency Index (E). The statistics were calculated using the following formulas:

Root-Mean-Square Error (RMSE) was calculated as follows:

$$\mathrm{RMSE} = \left(1/\mathrm{N}\sum_{i=1}^{\mathrm{N}}(\mathrm{y_i} - \mathrm{x_i})^2\right)^{1/2} \qquad \text{Eq. (4)}$$

where N is the total number of observations, y_i is the calculated ASCE-SPM ET_{rs}, and x_i is the measured lysimeter ET_r (Willmott and Matsuura, 2005).

Relative Error (RE) values can be positive or negative values and represent a percentage of the errors relative to the observed mean, where a positive value expresses the percentage of over-estimation and a negative value expresses the percentage of under-estimation. Relative Error (RE) was calculated as follows:

$$\mathrm{RE} = \left(\frac{\mathrm{Y} - \mathrm{X}}{X}\right) \times 100 \qquad \text{Eq. (5)}$$

where y is the mean calculated ASCE-SPM ET_{rS} and x is the mean measured lysimeter ET_r (Al Wahaibi, 2011).

Index of Agreement (d) is a value between one and zero, where 1 indicates a perfect agreement and 0 indicates a poor agreement. The Index of Agreement (d) represents how strong the relationships between two factors are by matching the points of the data from the two factors (Legates and McCabe, 1999). This was calculated as follows:

$$d = 1 - \left(\frac{\sum_{i=1}^{N} (y_i - x_i)^2}{\sum_{i=1}^{N} (|y_i'| - |x_i'|)^2} \right) \qquad \text{Eq. (6)}$$

where:

$y_i' = y_i - \bar{x}$ and $x_i' = x_i - \bar{x}$, y_i is the calculated ASCE-SPM ET_{rS}; x_i is the measured lysimeter ET_r, and $\bar{x}$ is the mean measured value (Willmott, 1981).

Nash and Sutcliffe (**E**) is often referred to as the efficiency index. The efficiency index can be positive or negative and is a value between -∞ and +1, where 1 indicates a perfect agreement and negative values indicate a poor agreement and nonlinear relationships.

$$E = 1 - \left(\frac{\sum_{i=1}^{N} (\breve{Y}_i - Y_i)^2}{\sum_{i=1}^{N} (y_i - \bar{Y})^2} \right) \qquad \text{Eq. (7)}$$

where $\breve{Y}_i$ and Y_i are predicted (ASCE-SPM) and measured (lysimeter) values of the criterion dependent variable Y (i.e., ET_r). $\bar{Y}$ is the mean of the measured values of Y, N= is sample size, and y_i = is the observed lysimeter ET_r.

Results and Discussion

The calculated hourly ET_{rs} from the ASCE-SPM equation was compared with both the uncorrected and corrected hourly measured ET_r from the weighing lysimeter located in the Arkansas Valley of Colorado in Rocky Ford, Colorado for the season 2010. Table 3-2 shows the average weather conditions for the four specific observation days of alfalfa as reference plant.

The comparison between hourly ET_r from the lysimeter and ASCE-SPM ET_{rs} was specific for the four days when there was alfalfa overgrowth beyond the lysimeter area and after effective canopy area was corrected. The other days were ignored because alfalfa height was either below 50 cm or above 55 cm, and the field measurements of overgrowth were not made.

Table 3-3 shows the relation between hourly ET_{rs} from the ASCE-SPM equation and hourly ET_r from the lysimeter for the same four days. The hourly ET_r values from the lysimeter were found to be significantly higher than ET_{rs}, because alfalfa grew beyond the lysimeter area. Alfalfa extended beyond the edge of the lysimeter due to soil compaction around the outside edge of the lysimeter leading to stunted alfalfa. The soil compaction was a result of soil settling after construction and possibly foot traffic during data collection, lysimeter maintenance and harvesting events. The subsequent correction considered the effective surface area including the alfalfa extending beyond the lysimeter boundary.

Before the correction, the Relative Error of Mean was showing an over-estimation of the lysimeter ET_r compared to the ASCE-SPM equation. After the adjustment for the effective canopy area, the Relative Error of Mean was reduced significantly on all four days. Also, the RMSE was higher before the adjustment than after the adjustment which means there was an improvement due to the adjustment. The d values showed nearly perfect agreement between lysimeter ET_r and ASCE-SPM ET_{rs} after the adjustment in all four days. The efficiency index (E) also showed an improvement after the adjustment. Overall, the area adjustment reduced RE and RMSE and increased d and E on all four dates.

Figures 3-1 to 3-4 show the comparisons between the hourly measured ET_r from the lysimeter to ET_r values calculated from the ASCE-SPM equation for the four selected days. In each figure, the first graph (a) shows a clear difference between the time series of hourly ET_r measured from the lysimeter before and after making the corrections in effective canopy surface area. The ET_r values from the lysimeter before the adjustment were always higher due to the increased area of the alfalfa extending beyond the dimensions of the lysimeter, whereas the corrected ET shows better agreement with the ASCE-SPM ET_{rs}.

The second graph (b) in each figure shows the linear relationship between uncorrected ET_r from the lysimeter and ASCE-SPM ET_{rs}. The ET_{rs} values were below the 1:1 line and indicated that they were generally lower than the lysimeter ET_r values. The third graph (c) in each figure shows the relation between the corrected ET_r from the lysimeter compared to ET_{rs} from ASCE-SPM equation, with data points closer to the 1:1 line indicating better agreement.

Measuring hourly reference ET was done for alfalfa at 50 cm height on the first day and 55 cm on the next three days (Table 3-3). When measuring reference ET for alfalfa in the field, alfalfa should be at reference stage and not under any sort of stress such as water stress, salt stress or weather stress, which affect an accurate hourly ET_r at this stage of plant life.

These results indicate that the ASCE-SPM equation can be used to identify systematic biases in lysimeter ET_r when the alfalfa crop is at reference conditions. When there is alfalfa overgrowth, disagreement between lysimeter ET_r and ASCE-SPM ET_{rs} could be explained by the additional ET from the canopy that extends beyond the lysimeter boundaries. The accuracy of the measured hourly ET_r from the lysimeter can be improved by making corrections in the effective canopy surface area. It is possible that building barriers or a fence to prevent plants from extending outside the lysimeter boundaries can reduce this source of error.

Conclusion

The study showed differences between ET_r measured from the lysimeter and ET_{rs} calculated from the ASCE-SPM equation. The values of the measured ET_r from the lysimeter were higher than the ASCE-SPM calculated values when there was alfalfa overgrowth beyond the lysimeter boundaries. The canopy surface area adjustments reduced the differences between measured hourly ET_r from the lysimeter and the calculated hourly ET_{rs} values from the ASCE-SPM equation. Over-estimated lysimeter ET_r can affect the crop coefficient (K_{cr}) values derived from this data. K_{cr} would be under-estimated if ET_r was over-estimated. Correcting the measurement of alfalfa ET_r from the lysimeter through accounting for effects of alfalfa overgrowth can lead to improved estimation of ET_r and corresponding K_{cr} values.

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Table 3-1: Lysimeter surface area (m^2), alfalfa effective canopy area (m^2) and correction ratio (Canopy area, m^2/ Lysimeter Area, m^2) used to correct measured lysimeter ET_r values for four days in 2010.

Date	Lysimeter Area, m^2	Canopy area, m^2	Correction ratio
9/16/2010	9.181	11.089	1.208
9/23/2010	9.181	11.765	1.281
10/1/2010	9.181	12.461	1.357
10/12/2010	9.181	12.461	1.357

Table 3-2: Average temperature (Celsius), relative humidity (Fraction), vapor pressure (kPa), total solar radiation (kJ/m^2 * min), and wind speed (m/s) data for four days in 2010.

Date	Average Temperature (Celsius)	Average Relative Humidity (Fraction)	Average Vapor Pressure (kPa)	Total Solar Radiation (kJ/m^2 * min)	Average Wind Speed (m/s)
9/16/2010	20.93	0.51	1.20	366.31	1.78
9/23/2010	20.65	0.60	1.30	343.82	1.63
10/1/2010	17.18	0.50	0.93	307.14	1.41
10/12/2010	9.15	0.69	0.79	219.51	1.97

Table 3-3: Statistical evaluation of the agreement between the ASCE-SPM ET_{rs} and ET_r measured with a lysimeter at the CSU Experiment Station in Rocky Ford for four days in 2010.

	Plant Height	Hourly ET_r before adjustments	Hourly ET_r after adjustments
		9/16/2010	
Relative Error of Mean (%)		27.07	3.14
RMSE		0.08	0.05
Index of Agreement (d)	50cm	0.98	0.99
Nash-Suttcliffe E		0.92	0.97
No. Obs.		24	24
		9/23/2010	
Relative Error of Mean (%)		26.38	-3.32
RMSE		0.11	0.04
Index of Agreement (d)	55cm	0.98	1
Nash-Suttcliffe E		0.90	0.99
No. Obs.		24	24
		10/1/2010	
Relative Error of Mean (%)		43.5	3.64
RMSE		0.10	0.05
Index of Agreement (d)	55cm	0.97	0.99
Nash-Suttcliffe E		0.84	0.96
No. Obs.		24	24
		10/12/2010	
Relative Error of Mean (%)		43.62	3.73
RMSE		0.08	0.03
Index of Agreement (d)	55cm	0.96	0.99
Nash-Suttcliffe E		0.81	0.98
No. Obs.		24	24

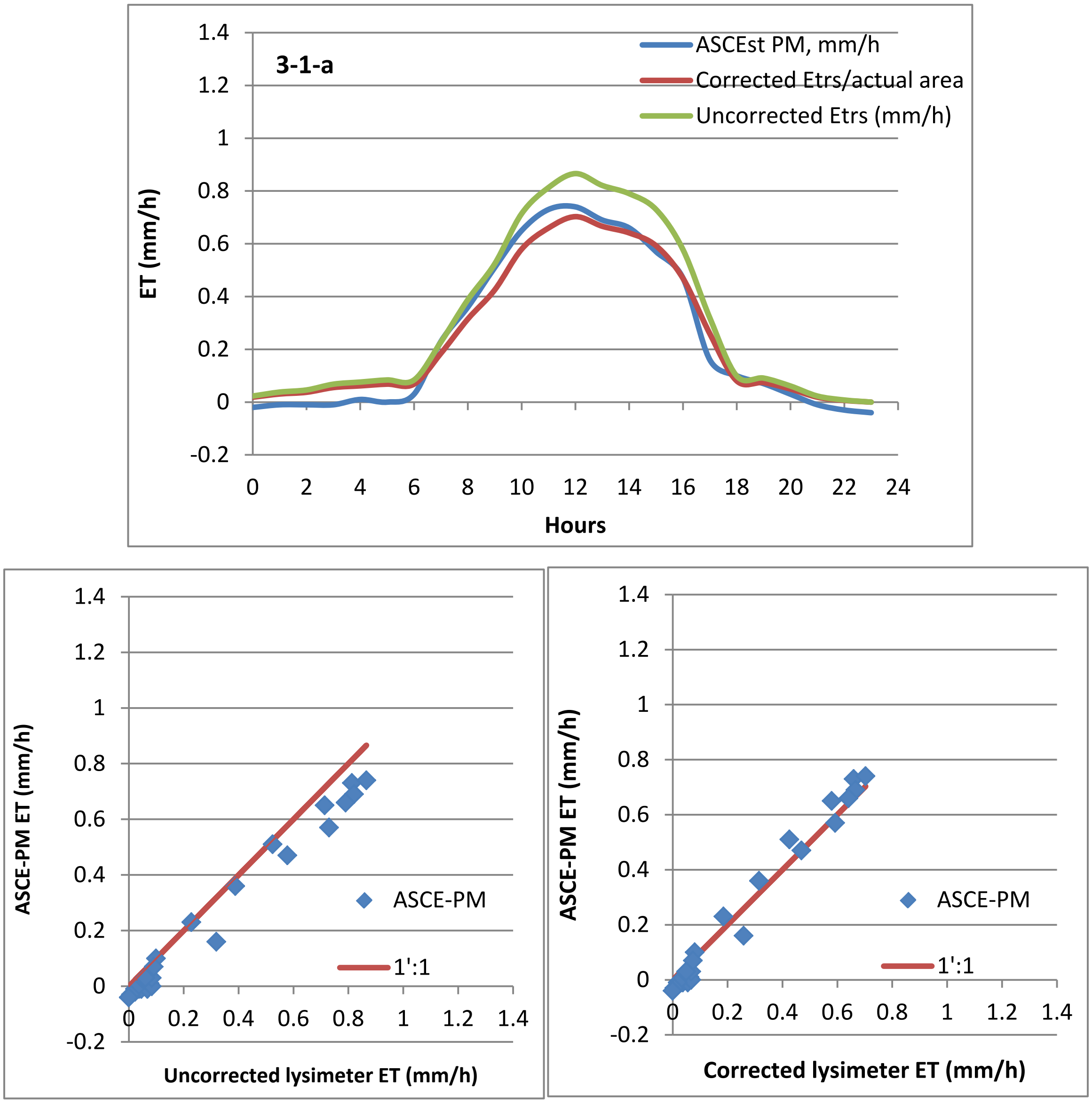

Figure 3-1: 3-1-a shows the difference between hourly calculated ET_{rs} from the standardized ASCE Penman-Monteith equation compared with measured ET_r from the lysimeter for 9/16/2010 before and after correcting for canopy area. 3-1-b and 3-1-c show the agreement between ET_r from ASCE-SPM compared with measured ET_r from the lysimeter before and after correcting for effective canopy area.

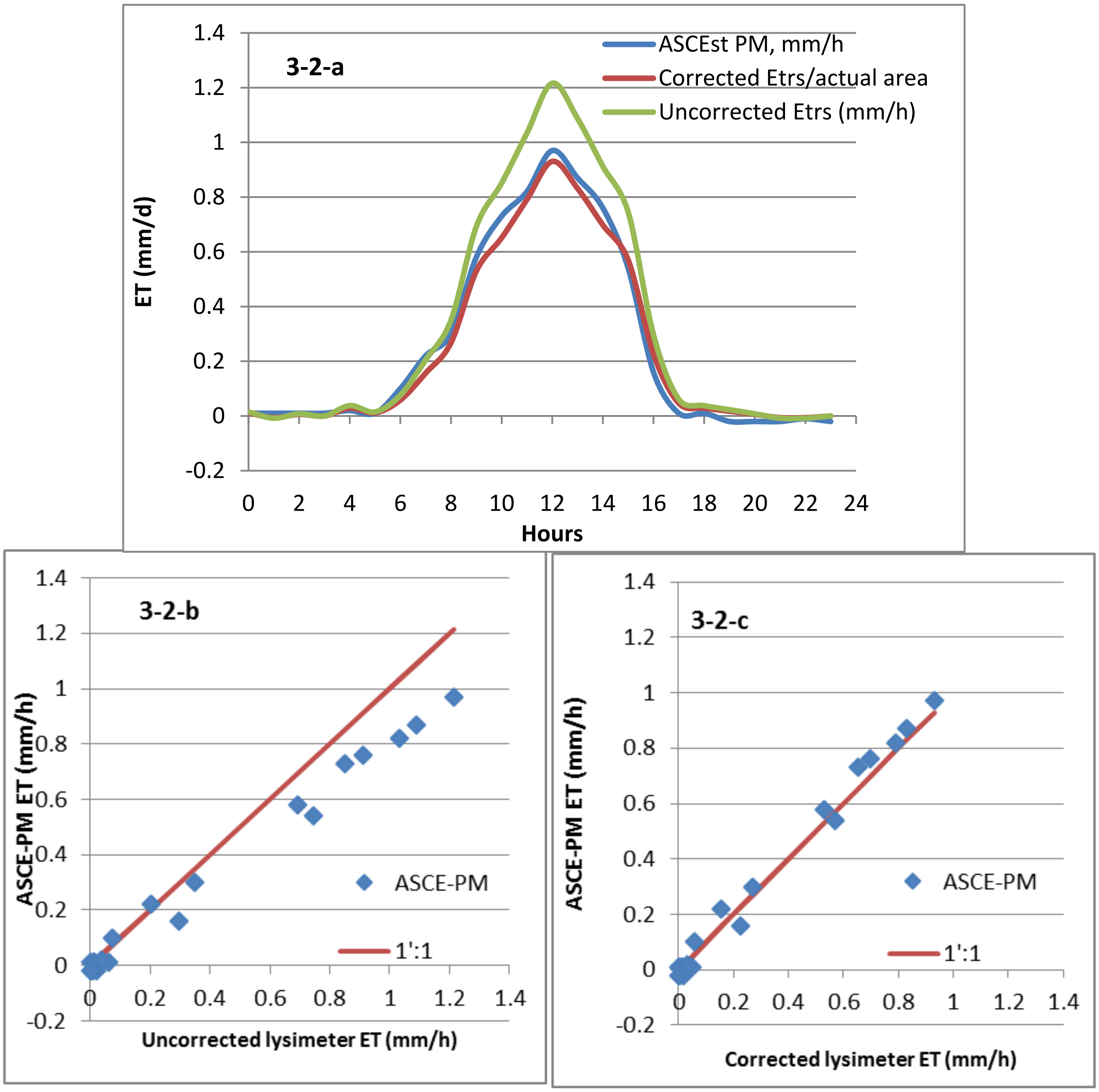

Figure 3-2: 3-2-a shows the difference between calculated ET_{rs} from the standardized ASCE Penman-Monteith equation compared with measured ET_r from the lysimeter for 9/23/2010 before and after correcting for canopy area. 3-2-b and 3-2-c show the difference between ET_r from ASCE-SPM compared with measured ET_r from the lysimeter before and after correcting for canopy area.

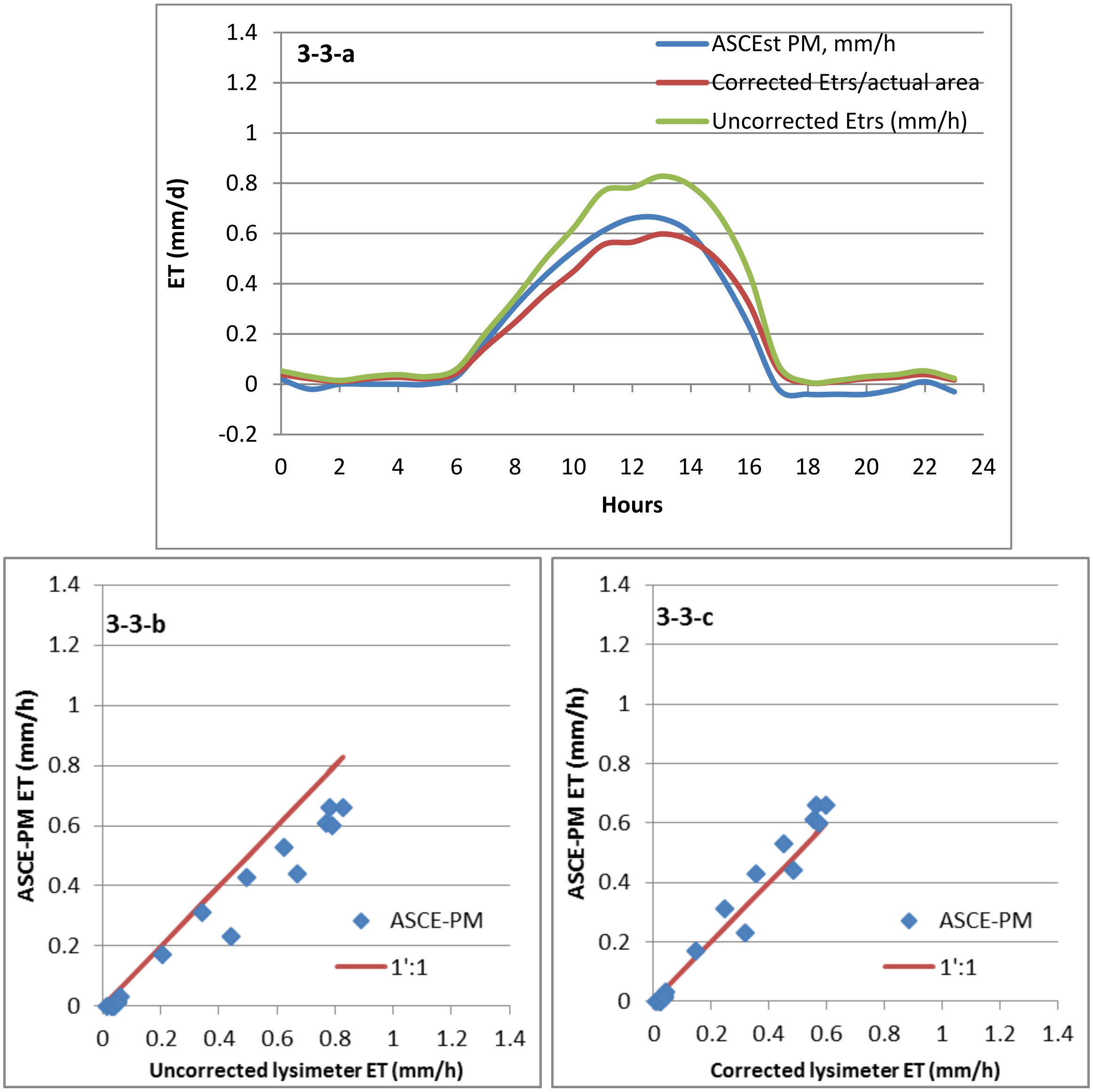

Figure 3-3: 3-3-a shows the difference between calculated ET_{rs} from the standardized ASCE Penman-Monteith equation compared with measured ET_r from the lysimeter for 10/1/2010 before and after correcting for canopy area. 3-3-b and 3-3-c show the difference between ET_r from ASCE-PM compared with measured ET_r from the lysimeter before and after correcting for canopy area.

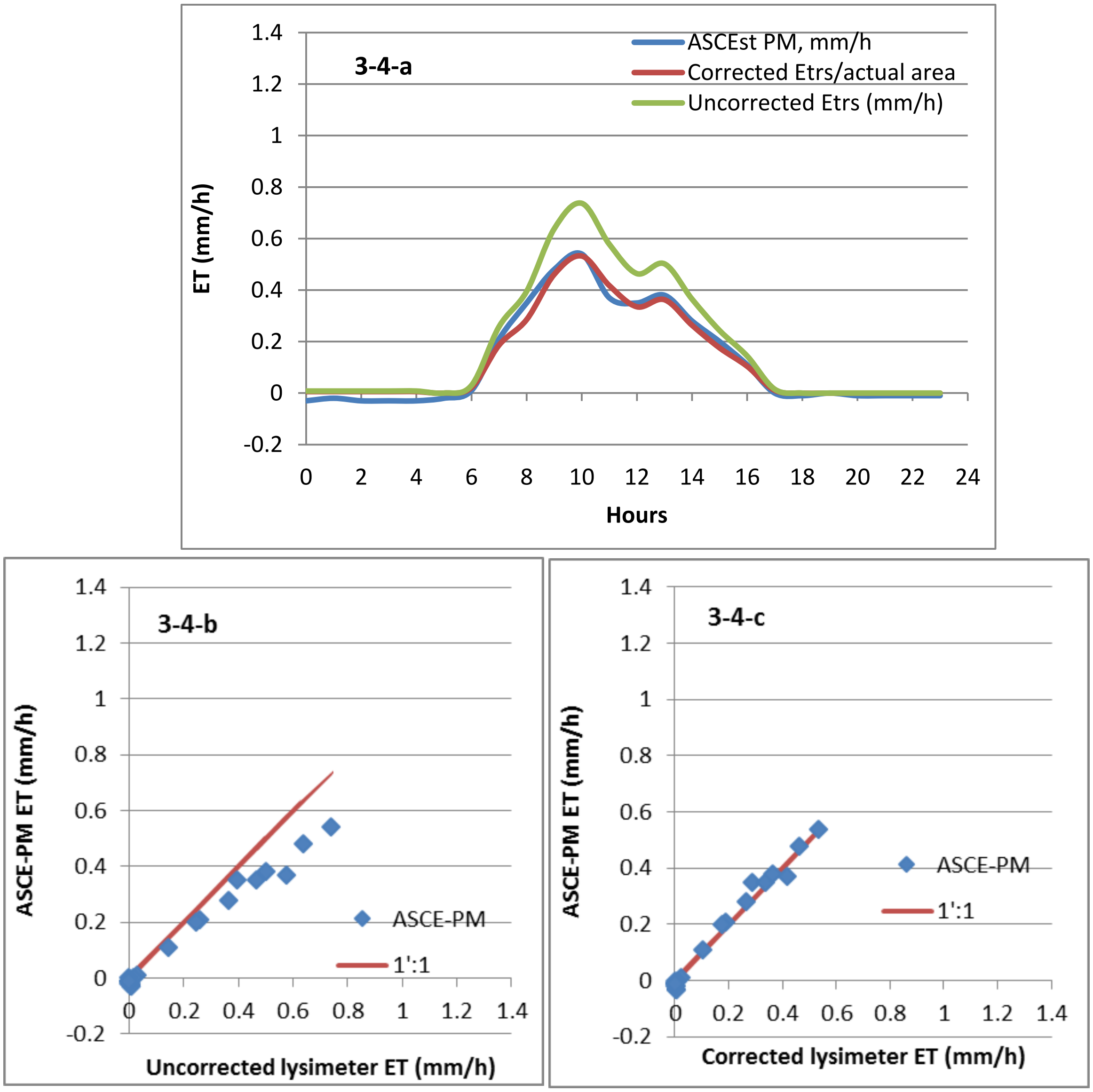

Figure 3-4: 3-4-a shows the difference between calculated ET_{rs} from the standardized ASCE Penman-Monteith equation compared with measured ET_r from the lysimeter for 10/12/2010 before and after correcting for canopy area. 3-4-b and 3-4-c show the difference between ET_r from ASCE-PM compared with measured ET_r from the lysimeter before and after correcting for canopy area.

CHAPTER FOUR: EVALUATION OF COLORADO IRRIGATION SCHEDULER (CIS) FOR FURROW IRRIGATED CORN IN NORTHEAST COLORADO

Overview

Improved irrigation application efficiency depends on irrigation scheduling that specifies when and how much to irrigate. Efficient irrigation entails applying only enough water to meet the crop's evapotranspiration (ET) requirement. Crop water requirements are the foundation of irrigation scheduling. Excessive irrigation could lead to negative impacts on soil, crops and the environment. A local irrigation scheduling tool that keeps track of the soil water balance and required irrigation amounts throughout the growing season can help irrigators keep track of water requirements and make more efficient use of their limited water supplies. The objectives of this study were to: (1) field test and evaluate the accuracy of an irrigation scheduling spreadsheet tool for calculating soil water deficits (D_c) in a furrow-irrigated corn (*Zea mays* L) field located near Greeley, Colorado and (2) determine the effect of frequency of mid-season corrections of D_c on the accuracy of the irrigation scheduler. A corn crop was grown for three seasons (2010 - 2012) in rows spaced 76 cm apart. Daily weather data from an automatic weather station located 143.9 m from the field were used to calculate ET and effective precipitation in the irrigation scheduler. Root zone soil water status was monitored using gravimetric and volumetric measurements. The irrigation scheduling spreadsheet tool developed in Visual Basic for Applications was designed to calculate daily D_c by water balance of the managed root zone. The results showed good agreement between calculated and measured deficits where index of agreement (d) was near 0.5 or above for most years of this study, specifically when measurements of soil water content (SWC) were inserted bi-weekly or monthly. Root-Mean-Square Error (RMSE) did not exceed 2.54 mm when using SWC once per season in 2011, while inputting bi-weekly measurements resulted in d values of 0.96 in 2010, 0.99 in 2011 and 0.70 in 2012. Also, the CIS showed that amounts of irrigation water used during the years of study could be reduced by 30 to 50% through use of CIS.

Introduction

Irrigation management tools provide information to irrigators in readily usable form for making appropriate decisions on timing and amounts of irrigation (Callan et al., 2004). Irrigation scheduling depends on answering the two main questions of when and how much water to apply to the crops. Irrigation scheduling is an important management tool because it is used to increase the efficiency of water usage and reduce runoff and deep percolation during the irrigation season (Pereira et al., 2002). Knowledge of crop water requirements is fundamental to irrigation scheduling. Excessive irrigation which exceeds crop water requirement can lead to negative impacts on soil, crops and the environment (Stockle, 2001). Over irrigation can have a negative effect on root respiration (Maier and Kress, 2000), and it also contributes to rising water tables, which ascend to the surface by capillary action (Sophocleous, 2002). This is one of the main causes of soil salinity (Rengasamy, 2006). Deep percolation is the result of heavy irrigation and can lead to groundwater pollution by leaching chemical nutrients beyond the root zone (Mmolawa and Or, 2000). In addition to that, excessive irrigation can lead to an increase in the amount of runoff, and this has a significant impact on soil erosion, which also has a negative effect on the soil environment (Pimentel, 2006).

On the other hand, reducing irrigation below the crop requirements subjects plants to water stress which has a negative impact on plant productivity (Ko and Piccinni, 2009). If the stress continues for a certain period, and depending on the type of plant and its resistance to drought, the type of soil and its ability to retain water, the plants eventually reach a permanent wilting point (Ehlers and Goss, 2003).

To achieve an efficient balance between over watering and under watering plants in the field, the following two questions must be answered: how much and how often should the field be irrigated (Pereira et al., 2002). Crop water requirement is defined as the amount of water that needs to be added to meet ET needs (English et al., 2002). ET includes both the evaporation from the soil and plant surfaces and the transpiration from the plant (FAO, 2009). ET can be measured using lysimeters or indirect methods or calculated using reference ET equations. The FAO Penman Monteith equation for short grass and the ASCE standardized Penman Monteith equation (ASCE-SPM) (Allen et al., 2005) for tall alfalfa are the most recommended equations to calculate reference ET (FAO, 2009). Crop ET can be determined by multiplying reference ET by the crop coefficient (Ko and Piccinni, 2009).

Water requirements depend on the ET rate (Allen et al., 1998). The quantity of water used for the synthesis of plant tissue is less than 1% of the water absorbed, and the rest is lost by ET and is not included in the processes of growth (Jensen, 1968). When considering the total amount of water needed by plants, it is very important to estimate the amount of irrigation water which is required for the different roles in plant life, especially the critical ones (Oweis et al., 1999).

Crop ET is the consumption of water by plants as a result of their physiological traits. The amount of water plants need depends on the growth stage of the plants. ET increases through the growth stages, and some of this water can be kept in plant cells, while other water goes to the atmosphere through the plant (Cattivelli et al., 2008).

Before using a reference ET equation to calculate crop water requirements, it has been recommended that the equation be tested under the local climate and soil conditions (Gavilán et al., 2006). Using an untested American Society of Civil Engineers Penman Monteith (ASCE-SPM) equation under Colorado conditions could lead to an inaccurate estimation of crop water requirement.

Agricultural products rank high in importance in the state of Colorado. The South Platte River provides around 12 percent of the state's supply (Thorvaldsen and Pritchett, 2005), and is one of the water resources used most intensively in Colorado (Watson et al., 2011). Needless to say, agricultural land needs a lot of water for irrigation. Since water is one of the production inputs, reducing irrigation costs will increase the profitability of farming operations (FAO, 1993).

In Colorado, the ASCE-SPM equation of the American Society of Civil Engineers (ASCE) is being adopted to determine reference ET (Al Wahaibi, 2011). For example, the United States Supreme Court recommended the use of the ASCE-SPM equation to calculate ET for subsequent resolutions for compliance with the Arkansas River compact between Colorado and Kansas (Berrada et al., 2008). However, this equation has not been tested in agricultural sites in Colorado, and the crop coefficients have been measured in different locations outside Colorado. Using a tested ASCE standardized reference ET equation with local crop coefficients could help farmers in Colorado make better ET-based irrigation scheduling decisions (Al Wahaibi, 2011).

Furrow irrigation is a method of applying water at a specific rate of flow into shallow, evenly spaced channels (Howell, 2003). These small channels convey the water down or across the slope of the field to the vicinity of plants growing in the furrows or on the beds between the furrows (Kang et al., 2000). This method differs from flood irrigation in that only part of the ground surface is covered with water. The water infiltrates the soil both vertically and horizontally. The furrow stream is applied until the desired application depth and lateral penetration are obtained. How long water must be applied to the furrows depends on the volume of water required to fill the soil to the desired depth, the intake rate of the soil, and the spacing of the furrows (Benjamin et al., 1997). Land grading to provide uniform slopes is essential to permit uniform water application and efficient irrigation. Furrows are particularly suitable for irrigating crops subject to injury if water covers the crown or stems of the plants (Brouwer et al., 1988).

Corn is widely grown throughout the USA, including Colorado. Fertile soil provides a good environment for corn growing in healthy conditions (Kucharik, 2006). Corn is usually planted in May of each year in Northern Colorado when the air temperature reaches at least 50 degrees Fahrenheit (Sacks et al., 2010). Corn is one of the most irrigated crops in Colorado. Corn is typically planted by sowing seeds at a depth of 30-38 millimeters, in rows 75 centimeters apart at 2.8 centimeters interval. Providing the ideal amount of water through irrigation scheduling during the growing season would offer higher production with less cost (Schneider and Pendery, 1983).

Using information on crop ET rates combined with knowledge of local weather, soil, and crop conditions, one can determine irrigation amounts and scheduling. This information must be provided to irrigators in readily usable form for making appropriate decisions on timing and amounts of irrigation. A locally-developed irrigation scheduling tool that keeps track of the soil water balance and required irrigation amounts throughout the growing season can help irrigators keep track of water requirements and make more efficient use of their limited water supplies. The Colorado Irrigation Scheduler (CIS; Gleason, 2013) is such a tool, but has not been evaluated for furrow irrigation.

The objectives of this study were to:

(1) Field test and evaluate the accuracy of an irrigation scheduling spreadsheet tool for calculating soil water deficits (D_c) in a furrow-irrigated corn field located near Greeley, Colorado during years 2010, 2011 and 2012.

(2) Determine the effect of frequency of mid-season corrections of D_c on the accuracy of the irrigation scheduler.

Materials and Methods

Field study

The field site was in northeast Colorado and was irrigated using furrow irrigation. The exact locations of measurement points were determined by a Global Positioning System (GPS). In 2010 the coordinates were Latitude: 40° 26’ 42.93” North, Longitude: 104° 38’ 4.76” West; in 2011 the coordinates were Latitude: 40° 26' 43.48" North, Longitude: 104° 38' 3.61" West; and in 2012 the coordinates were Latitude: 40° 44’ 41.52” North, Longitude: 104° 63’ 9.74” West.

A corn crop (DKC52-59) was planted May 25, 2010, and the planting density was 32,000 seeds/acre. In 2011, corn (DKC52-59) was planted May 3rd and the planting density was 34,000 seeds/acre. In 2012, corn (DKC 52-04) was planted May 2nd, and the population of plants was

34,400 plants/acre. The corn was grown on ridges, and furrows in between the ridges were spaced 76.2 cm apart with furrow irrigation by gated pipe. Irrigation water applied in the furrows was measured by Seametrics1 AG2000 magnetic flow meters, and values were recorded using a data-logger (CR200, Campbell Scientific, Inc., Logan, UT) (Chavez et al., 2012), where the flow meter was installed after the pump outlet, just before the water flowed into the gated pipe.

Soil water and crop measurement

The corn field test involved using weekly root zone gravimetric soil water measurements at six depths 15, 30, 45, 60, 90 and 105 cm, and soil moisture was also monitored weekly using a neutron probe at seven depths 15, 30, 45, 60, 75, 90 and 105 cm. In addition, since crop coefficients change with crop development, weekly recordings of corn developmental growth stages, height and leaf area index (LAI) were done to evaluate how well the seasonal crop coefficient curves of the corn represented actual crop development.

The basic measurement of soil water is the difference between the mass of soil samples before and after putting them in an oven at 105^{o}C for one or two days. Samples were obtained from different depths in the field using a JMC backsaver soil probe (Clements Associates Inc., Newton. IA). These samples were immediately put in covered cans (known mass) to prevent evaporation of water. The cans were brought to the lab and weighed directly to get fresh mass, and then they were placed in an oven for one or two days to get dry mass.

Soil water content (SWC) was calculated using these equations:

$$\theta_g = \frac{FM - ODM}{ODM} \qquad \text{(Eq. 1)}$$

$$\theta_v = \theta_g * \left(\frac{\rho_b}{\rho_w}\right) \quad \text{(Eq. 2)}$$

where θ_g is SWC by mass (g/g), FM is fresh mass of the soil sample (g), ODM is oven dry mass of the soil sample (g), θ_v is SWC by volume (cm^3/cm^3), ρ_b is soil bulk density (g/cm^3), and ρ_w is density of water (1.0 g/cm^3).

Evapotranspiration estimation

The Colorado Agricultural Meteorological Network (CoAgMet) includes 69 automatic weather stations that provide internet access to daily weather data. The weather stations have sensors used to measure the factors needed in the ET equations. Climatic data was recorded automatically every minute by a data logger and used to calculate hourly and daily output. The sensor used to measure rainfall was a TE525 tipping bucket rain-gauge located 2 m above the ground. The RM Young 03101 Wind Sentry cup anemometer and RM Young Wind Monitor (prop-anemometer) were placed 2 m above the ground to measure wind speed and direction, respectively. The Vaisala HMP45 was placed 1.5 m above the ground to measure temperature and relative humidity. The Vaisala PTB101B was used to measure barometric pressure. The REBS Q7 net radiometer placed 1.5 m above the ground was used to measure net radiation. The Licor LI-200X Pyranometer placed 2 m high was used to measure incoming and reflected radiation. The Vaisala HMP45C Probe sensor was placed 1.5 meters above the soil surface and was used to measure crop canopy temperature. Soil temperature sensors (CSI Model 107 Soil Temp Probe) were installed at depths of 5 cm and 15 cm where two sensors were used, and 10 cm where only one was used (CoAgMet) (http://ccc.atmos.colostate.edu/~coagmet/station_description.php).

The ASCE-SPM equation was used to calculate reference ET for a tall crop (similar to alfalfa). ET_{rs} is the symbol used for a tall reference crop that has a height of 50 cm. In addition, this equation can work with both hourly and daily reference ET data.

The ASCE-SPM reference ET equation is given as (Allen et al., 2005):

$$ET_{rs} = \frac{0.408\,\Delta\,(R_n - G) + \gamma \frac{C_n}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \qquad \text{Eq. (3)}$$

where the units for the 0.408 coefficient are m^2 mm/MJ; ET_{rs} is the standardized reference crop ET for tall surfaces (mm/h); Δ is the slope of the saturation vapor pressure-temperature curve (kPa/°C); R_n is the calculated net radiation at the crop surface ($MJ/m^2/h$); G is the soil heat flux density at the soil surface ($MJ/m^2/h$); $\boldsymbol{\gamma}$ is a psychrometric constant (kPa/°C), C_n is the numerator constant that changes with reference type and calculation time step (K mm s^3 /Mg/h or K mm s^3 /Mg/d); T is the mean hourly air temperature in °C at 1.5 to 2.5-m height; u_2 is the mean hourly wind speed at 2-m height (m/s); e_s is the saturation vapor pressure at 1.5 to 2.5-m height (kPa); e_a is the mean actual vapor pressure at 1.5 to 2.5-m height (kPa); and C_d is a denominator constant that changes with reference type and calculation time step (s/m). Hourly daytime and nighttime C_n=66 (K mm s^3 /Mg/h), and hourly daytime C_d=0.25 (s/m) and hourly nighttime C_d= 1.7 (s/m) (Allen et al., 2005).

Ref-ET (http://extension.uidaho.edu/kimberly/) is an electronic program used to calculate reference ET from many equations. Ref-ET was used to calculate alfalfa reference ET using the ASCE-SPM equation (Allen et al., 2005). Corn ET_c was calculated by using the following equation (Gleason, 2013):

$$ET_c = ET_{rs} \times K_{cr} \qquad \text{Eq-(4)}$$

Where ET_c is actual crop ET (mm), ET_{rs} is reference ET for a tall crop (similar to alfalfa) (mm), and K_{cr} is an alfalfa-based crop coefficient.

Allen et al. (1998) described the methods of converting crop coefficient (K_{co}) based on grass to crop coefficient (K_{cr}) based on alfalfa. Gleason (2013) developed the K_{cr} curve to use in CIS following the FAO style curve, and Allen et al. (2007) explained the K curve based on the FAO style curve.

The total growing degree days (GDD, °C) was used to convert K_c from K_{co} to K_{cr}. The GDD was used to calculate the four crop development stages after emergence to maturation, and then the number of days after planting can be used in tracking corn development to predict the harvest time (Allen et al., 2007). GDD was calculated by using the following equation

$$\mathrm{GDD} = \sum_{i=m}^{n}[(\mathrm{Tmax} + \mathrm{Tmin})/2 - \mathrm{Tbase}\ ] \qquad \text{Eq-(5)}$$

where, m is the first day of the season, n is the last day of the season, T_{max} is maximum daily air temperature °C, T_{min} is minimum daily air temperature °C, and T_{base} is base air temperature set at 10 °C for corn. Gleason (2013) calculated the total GDD °C for corn from emergence to reach maturity, and it was set at 1370.23 °C·d during 2010, at 1453.9 °C·d during 2011 and at 1579.2°C·d during 2012.

There is another way to calculate ETc when plants are exposed to stress using water stress coefficient (K_s; Allen et al., 1998).

$ET_c = ET_{rs} \times K_{cr} \times K_s$ Eq-(6)

The Ks is used to calculate the transpiration by a plant under water stressed conditions when the soil water deficit around the root zone exceeds management allowed depletion (MAD) before applying water by irrigation or precipitation. The Ks is calculated using the following equation:

$$K_s = \frac{TAW - Dp}{(1 - MAD)TAW} \quad \text{for } D_p > d_{MAD} \qquad \text{Eq. (7)}$$

($K_s = 1$ if $D_p < d_{MAD}$)

where TAW is total plant available water (mm), D_p is the previous day's soil water deficit (mm), MAD is management allowed depletion (decimal fraction), and d_{MAD} the depth of management allowed depletion (Gleason, 2013).

Irrigation water was applied to the field before plants reached MAD. MAD is the percentage of total available water (TAW) that is readily available water (RAW). Depth of d_{MAD} (which is the amount of water added to the field) was determined as follows:

$$d_{MAD} = (MAD/100) * AWC * D_{rz} \qquad \text{Eq. (8)}$$

AWC is available water capacity of the root zone (depth of available water per unit depth of soil), and D_{rz} is depth of root zone (cm). The d_{MAD} can be used to determine when and how much to irrigate. When the soil water deficit (D_i) reaches d_{MAD}, when $D_i \geq d_{MAD}$, water should be applied to reduce water stress.

Colorado Irrigation Scheduler (CIS)

Focusing on when and how much water should be applied to the field before plants reach Management Allowed Depletion (MAD) is the best way to keep plants from water stress. To avoid plant water stress, water should be available to plants before they reach MAD. On a daily basis, the following equation was used to estimate the soil water deficit (D_i) in the root zone:

$$D_i = D_{(i-1)} + ET_c - P - Irr - G + Roff + Dp \qquad \text{Eq. (9)}$$

where D_i is the soil water deficit in the root zone on day i (mm), D_{i-1} is the soil water deficit on the previous day (mm), ET_c is the crop ET rate for the current day (mm), P is the gross precipitation for the current day (mm), Irr is the net irrigation amount infiltrated into the soil for the current day (mm), G is upflux of shallow ground water into the root zone (mm), Roff is surface runoff (mm), and Dp is deep percolation or drainage (mm). In the CIS, Irr is calculated by multiplying gross irrigation amount with the irrigation application efficiency (Ea). The gross irrigation (GI) is the amount of water that must be pumped to the field; it is greater than net irrigation (NI) by a factor which depends on the irrigation application efficiency (Ea). Ea is defined as the percentage of amount of water stored in the root zone after water loss via surface runoff and/or deep percolation (Gleason, 2013). The Ea value in the simulations for furrow-irrigated corn was 55%, and it agreed with Irmak et al.'s (2011) estimation of 55%. Also, Saseendran et al. (2014) cited Irmak et al. (2011) in stating that Ea is 55% in Greeley, Weld County, Colorado.

Crops uptake water from the soil to grow and meet their ET_c requirement, and soil water content added to reach field capacity is called the net irrigation requirement. The soil water deficit (D) is the soil water content at which water should be added to keep plants out of stress. Also, irrigation management prevents water content from decreasing below MAD soil water deficits, which means it is important to apply the net irrigation requirement at the right time. Due to the difficulty in calculating current days upflux and the surface runoff each day (Andales et al., 2011), and the ground water table being below the root zone for most crops, Andales et al. (2011) simplified the equation to be:

$$D_i = Dp + ET_c - P - Irr \qquad \text{Eq. (10)}$$

Andales et al. (2011) assumed that runoff will occur if (P + Irr) exceeds (Dp + ET_c). Through this assumption D_i becomes negative and can be set to zero.

The site in Greeley was used for field testing because the site was an existing, fully instrumented site for making precise crop ET and soil water balance measurements with soil moisture monitors, soil temperature probes and precipitation gauges. The site was near an existing CoAgMet weather station (Greeley 4). The daily weather data was provided by CoAgMet and used to calculate ET via the ASCE-SPM equation through Ref-ET, and then the ET was multiplied by the appropriate crop coefficient to estimate daily crop ET. The estimated crop ET was used in an irrigation scheduling spreadsheet that performs simple soil water balance calculations to estimate daily soil water deficits. The soil water deficit is also the net amount of water (e.g., net irrigation) required to refill the root zone back to field capacity. Irrigation is recommended to the producers whenever the soil water deficit approached a pre-set MAD level, which was determined as a function of crop type and developmental stage. The ET-based irrigation scheduling tool was evaluated by comparing the calculated daily soil water deficits to actual deficits measured using gravimetric sampling.

The CIS for annual crops was developed in Microsoft Excel using Visual Basic for Applications (Gleason, 2013). It was used to calculate the deficit using soil moisture content and weather data from CoAgMet for the years 2010, 2011 and 2012. This data included soil water content, local crop and reference ET, field capacity, available water, precipitation, maximum and minimum temperature, emergence date, end date of season and gross irrigation. The result from running the CIS curve shows the deficit situation during the season. The curve shows the MAD that should not be reached by soil water content to prevent plants from undergoing water stress. Also, the movement of the MAD line shows when soil water content was increased by irrigation or precipitation. Deep percolation and runoff were shown in some cases when application water (irrigation and precipitation) was in excess of what the plants needed.

CIS evaluation

The climatic data obtained from CoAgMet was transferred to an Excel spreadsheet. The calculations of water balance were determined in the furrow irrigation system using CIS. The comparison and the regression lines between different soil moisture measurements and the difference between the original crop coefficient and adjusted ones were also analyzed.

The performance of the measured and calculated deficit was examined by the Root-Mean-Square Error (RMSE) and index of agreement (d) using the following formulas:

Root-Mean-Square Error (RMSE) was calculated as follows:

$$\mathrm{RMSE} = \left(1/\mathrm{N}\sum_{i=1}^{\mathrm{N}}(\mathrm{y_i} - \mathrm{x_i})^2\right)^{1/2} \qquad \text{Eq. (11)}$$

where y_i is the calculated water deficit; x_i is the actual water deficit; and N is the total number of observations.

Index of agreement (d) was calculated as follows:

$$d = 1 - \left(\frac{\sum_{i=1}^{N} (y_i - x_i)^2}{\sum_{i=1}^{N} (|y_i'| - |x_i'|)^2} \right) \qquad \text{Eq. (12)}$$

Where:

d is between one and zero. A value of 1 represents a perfect agreement, while a value of 0 means a poor agreement, $y_i' = y_i - \bar{x}$ and $x_i' = x_i - \bar{x}$, y_i is the calculated water deficit; x_i is the actual water deficit, and $\bar{x}$ is the mean measured value.

Results and Discussion

Field water balance and corn growth

Water balance is the difference between inputs and outputs of water from a field. Measured water balance from the field showed that the amount of water that was applied to the field through irrigation and precipitation (P) was highest in 2010 which resulted in high values in ET_c, deep percolation (DP) and runoff (Roff) (Table 4-1). Also, in 2011 the applied water was higher than 2012, and losing water by ET_c was higher than other years (Table 4-1). In 2012 the field received 574 mm irrigation, which was low compared to 2010 and 2011 because according to the 2012 Annual Report by Trout and Baker (2013), the field infiltration rate was much lower than in 2010 and 2011 and applied water reached the tail end of the furrow without increasing gross irrigation. In other words, due to the low infiltration rate, water flowed to reach the end of the furrow with less water applied. Reduced infiltration was assumed due to changes in tillage, field preparation, and furrow packing (Trout and Baker, 2013). In addition, Table 4-1 shows that the amounts of irrigation varied among years, although there was not a big change in soil water content in each season. Comparing measured water balance from the field and calculated water balance from CIS showed percentage of error in Dp and Roff for each season. Percentage error ranged from 19.4 % to 34.2 %.

The calculated water balance equation using CIS resulted in different outputs in Dp and Roff. The irrigation, precipitation, ET_c and soil water content (SWC) were the same because they were measured values inserted into CIS as inputs. The primary objective in using CIS was to understand the deficit situation during the growing season because it is a good indicator of plant stress. The CIS did not predict the exact amount of water that was lost from the field through deep percolation and runoff.

Plant height measurements showed that plants grew normally without water stress or other damage during the three seasons (Figure 4-1). Measured maximum plant heights were between 200 and 250 cm for most plants. Also, maize leaf number in 2010 and 2011 showed similar values during both seasons (Figure 4-2). Plant height and leaf number were used as indicators of plant growth. The soil water deficit experienced by plants throughout the season seemed to have had no impact on plant growth and showed normal Leaf Area Index (LAI) development, as well (Figures 4-3 and 4-4). In addition, measured LAI showed good correspondence with the plant stages of maize based on field measurements during the seasons of 2010, 2011 and 2012 (Figure 4-3) as it relates to Kcr for 2011 (Figure 4-4).

CIS evaluation

Comparing calculated to actual deficit showed how well the CIS was working. Soil water content was considered a good guide to estimate how much and when plants should be irrigated. In 2010 full irrigation was used, and the amount of water applied to the field was 1285 mm. The predicted total of Dp and Roff was 482 mm showing that too much water was applied (Table 4-1); irrigation exceeded water demand which resulted in increased Dp and Roff losses. The CIS calculation of Dp + Roff depends greatly on the value of application efficiency (Ea) that was used in the CIS. The Ea value was 55%, and other studies at this location have used 55% for furrow-irrigated corn (Saseendran et al., 2014). Also, in 2012 the total gross irrigation was 574 mm, and precipitation was low at only 131 mm (Table 4-1). As stated in the 2012 Annual Report by Trout and Baker (2013), furrows were compacted by driving a tractor wheel down each row to reduce infiltration rate. Infiltration was determined using three infiltrometer measurements during the season and compared reasonably well with an aggregated infiltration rate measured with furrow flume data (Trout and Baker, 2013). The results in Table 4-1 show how well the CIS model simulated the field. Also, the Roff and Dp calculated by CIS was 283 mm in 2011 using actual gross irrigations, but using CIS recommended (simulated) irrigation, the Roff and Dp was reduced to 84 mm (Table 4-1). In other words, the simulation by the model corrected the amounts of water that should have been applied instead of what was actually applied. The model showed a potential for simultaneous reductions in both the amount of irrigation and the Roff and Dp losses, and it is not easy to replicate this in the field, but it has been done in the best way using this model. The results for 2011 confirm the CIS model because it was supplied with actual data from the field and resulted in a good simulation. In addition, in 2012 the total actual Roff and Dp was recorded to be 266 mm (Trout and Baker, 2013), but CIS simulation reduced irrigation amounts, thus predicting the Roff and Dp amounts could have been only 15 mm, which was much lower compared to using actual irrigation in CIS calculations (Table 4-1).

Table 4-2 shows the differences between actual soil water deficit from field measurements and the CIS calculated deficit. CIS showed good performance based on the index of agreement (d) in the case of correcting (inputting) CIS deficits using measured bi-weekly or monthly soil water deficits, and in contrast, weaker results when inserting only one measurement of soil water deficit in the beginning of the season into CIS. Using one soil water measurement per season in CIS showed bigger differences between calculated and actual D_c, and suggests that more frequent corrections to simulated D_c are recommended to avoid water stress in the field. Calculating water deficit is useful to remind farmers when the next irrigation should be without losing water through over-irrigation. Furrow irrigation uses significantly more water than sprinkler irrigation because water cannot reach the lower end of the field until the upper end is almost saturated. Therefore, much water is lost to excessive runoff and deep percolation. The irrigation scheduling spreadsheet showed that there was no water stress because the D_c did not exceed MAD during the whole season, which kept plants in a healthy situation and avoided stress. This model worked very well when corrected twice per month (once every two weeks) using measured soil profile water content.

Figure 4-5 shows the exact weekly deficit point in 2011 through inserting weekly volumetric soil water content and deficit measurements and daily climate data into CIS. Measuring soil water content in the field twice each month resulted in higher index of agreement values compared to having this same data measured less often (Table 4-2) (Figure 4-6). In this comparison in 2011, the index of agreement (d) was 0.99, which is very high. The CIS provided good results when using bi-weekly per season soil water and deficit measurements compared to monthly and once seasonally for the years 2010, 2011 and 2012. These results show that the CIS is running well, and it can be used as a reminder to farmers about the next irrigation. On the other hand, running CIS in 2011 using the monthly soil water content data reduced the index of agreement (d) to 0.43 and increased the RMSE value to 2.80 mm. In 2011, there was a weak relationship between monthly measured and calculated deficits (Figure 4-7). Moreover, using a onetime soil water content measurement for the whole season showed a poor relationship between the actual deficit and calculated deficit. The weak relation was evidenced by an index of agreement (d) of 0.43 and an RMSE value of 2.65 mm in 2011 (Table 4-2). Therefore, the relationship was weaker when soil water deficit was measured seasonally compared to monthly (Figure 4-8). Figure 4-8 shows the deficit in the beginning of the season almost two weeks after planting and before first irrigation (recorded Jun 30, 2011). The SWC in the root zone should be above the MAD line at each irrigation, which means there was only a deficit in the field in the beginning of the growing season. The results show how important soil water deficit is in developing a good irrigation schedule.

Plant growth was normal in all three years because there was no stress during the season because the deficit did not reach the MAD depth. First irrigation in 2010 season was in the beginning of July, and the field was irrigated six times during the whole season (Table 4-3). In 2011, the amount of gross irrigation was lower at 1096 mm compared to 2010 when 1286 mm of irrigation were applied (Table 4-3). In 2012, although the gross irrigation started earlier compared to other years, this year had low gross irrigation compared to other years because the furrow infiltration rate was much lower and it took less time for water to reach the end of the field (Trout and Baker, 2013) (Table 4-3). The results in Table 4-3 show how the CIS model could simulate irrigation and reduce water use. The total gross irrigation in 2011 was 1096 mm, and simulation of the gross irrigation would have been only 635 mm (Table 4-3).

The model showed that optimal irrigation of the field could have reduced the amount of irrigation water substantially in all three years (Table 4-4). The data presented good results and confirmed the potential for CIS in furrow irrigated systems. Figure 4-9 shows the simulation of net irrigation distributed over the season based on calculated soil water content measurements, daily climate data and gross irrigation in CIS. The CIS predicted daily soil water deficits to guide when and how much the field should be irrigated to prevent plant stress conditions or over-irrigation.

Conclusion

Water use efficiency can be improved by increasing crop production while applying less irrigation water to meet the water needs of plants without wasting water via Dp and Roff. Soil water content plays an important role in documenting and avoiding water deficits. The CIS model provided good results when using bi-weekly soil water measurements and satisfactory results for monthly and seasonal measurements for the years 2010, 2011 and 2012. Most values of agreement between calculated and measured deficits were strong and showed that the model worked well during all seasons. Also, CIS worked well by adjusting the amount of irrigation based on soil water deficit status in the CIS. Thus, CIS could help improve water management by predicting the amount and timing of the next irrigation. In reference to the three years of study and a field simulation, the model was successful in estimating when and how much water should be applied to achieve the main objective of increasing irrigation efficiency. In spite of the different amounts of irrigation in different years and different locations in the corn field, the model gave promising results with high index of agreement values between the actual water deficit and the calculated deficit. However, to make sure this model is working very well, the model should be run in future years as a tactical tool to test its effectiveness. To get satisfactory results from the model, it is recommended to use soil moisture content measured bi-weekly and daily climate data.

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Table 4-1: Total calculated water balance (crop evapotranspiration (ETc), irrigation (Irr), precipitation (P), run off (Roff), deep percolation (Dp), and the change of the soil water content (∆SWC) from Colorado Irrigation Scheduler for each year (2010, 2011, and 2012). The difference indicates the difference between Roff+Dp calculated by water balance and Roff+Dp predicted by CIS. The Roff+Dp simulated by CIS (mm) were values obtained when hypothetical gross irrigations were applied according to CIS recommendations. Percent Error is the difference of the Roff+Dp calculated by water balance and Roff+Dp predicted by CIS ,divided by Roff+Dp calculated by water balance and multiplied by 100.

Year	ET_c, mm/d	Irr, mm	P, mm	Roff + Dp calculated by water balance, mm	Roff + Dp predicted by CIS, mm	∆ SWC, mm	difference	error %	Roff+Dp Simulated by CIS, mm
2010	796	1285	165	683	482	-29	201	29.4	54
2011	973	1096	228	351	283	0	68	19.4	84
2012	438	574	131	266	175	-1	91	34.2	15

Table 4-2: Statistical evaluation of the agreement (Root-Mean-Square Error (RMSE), Index of Agreement (d), and number of observations (No. Obs.)) of bi-weekly, monthly and once per season calculated and actual deficit for the years 2010, 2011, and 2012. The weekly data relationship is expected to show perfect agreement; therefore, it has been excluded from the table.

Times	Bi-weekly			Monthly			Once per Season		
Year	2010	2011	2012	2010	2011	2012	2010	2011	2012
RMSE	0.81	0.27	2.55	3.08	2.80	6.69	3.74	2.65	6.32
d	0.96	0.99	0.70	0.72	0.43	0.63	0.65	0.43	0.32
No. Obs.	8	8	8	12	11	12	16	14	16

Table 4-3: Actual irrigations for the years 2010, 2011 and 2012, and simulated irrigations (Irr.) for 2011.

Actual Irrigation, mm						Simulated Irrigation 2011	
2010		2011		2012		Irr, mm	date
226	3-Jul	103	30-Jun	82	5-Jun	25	8-May
264	13-Jul	103	1-Jul	67	19-Jun	25	6-Jun
214	24-Jul	110	13-Jul	36	26-Jun	25	14-Jun
213	4-Aug	110	14-Jul	58	3-Jul	178	21-Jul
181	17-Aug	165	27-Jul	45	15-Jul	152	8-Aug
188	1-Sep	159	9-Aug	81	22-Jul	127	24-Aug
1286	Total	196	23-Aug	45	31-Jul	25	12-Sep
		75	6-Sep	70	11-Aug	50	23-Sep
		75	7-Sep	42	21-Aug	25	4-Oct
		1096	Total	48	2-Sep	635	Total
				574	Total		

Table 4-4: Actual total gross irrigation, precipitation (P), simulated irrigation (Irr.) without inserting soil water content to Colorado Irrigation Scheduler (CIS) , actual total application of irrigation and precipitation, total simulated application of irrigation and precipitation, and the difference between actual and simulated applications for years 2010, 2011 and 2012.

Year	Actual Total Gross Irrigation, mm	Precipitation, mm	Simulated Irr., mm	Actual total Irr.+P., mm	Total simulated application Irr. + P., mm	Difference between actual and simulated applications, mm
2010	1285	166	571	1451	738	713
2011	1095	228	635	1323	863	460
2012	573	130	127	704	207	497

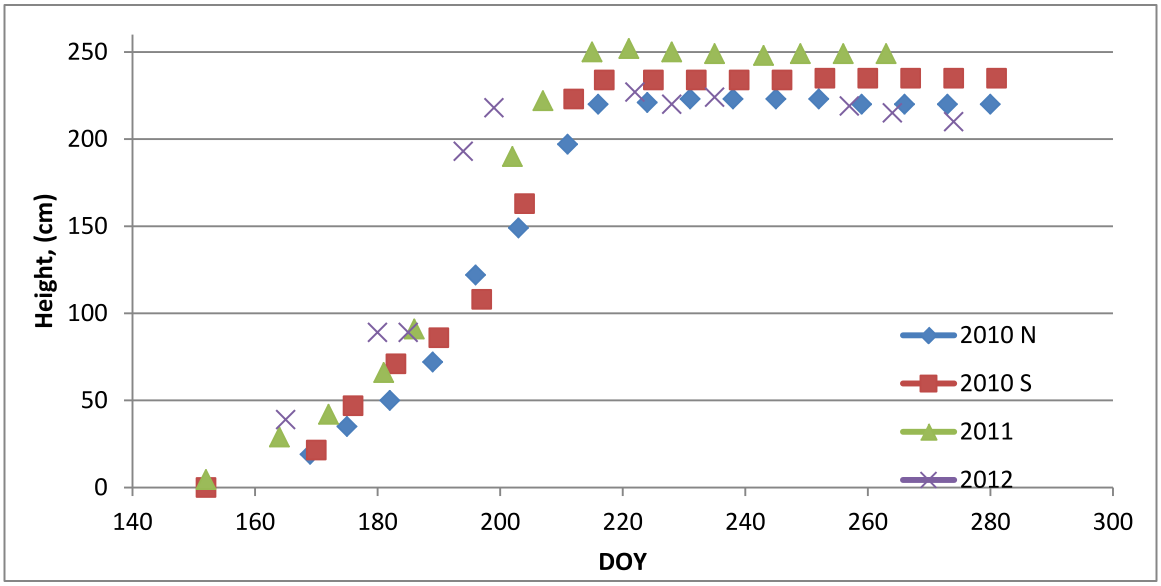

Figure 4-1: Figure 4-1: Maize height near Greeley, CO for 2010, 2011 and 2012 seasons. DOY is day of year, 2010 N was in the north side of the field, and 2010 S was in the south in 2010.

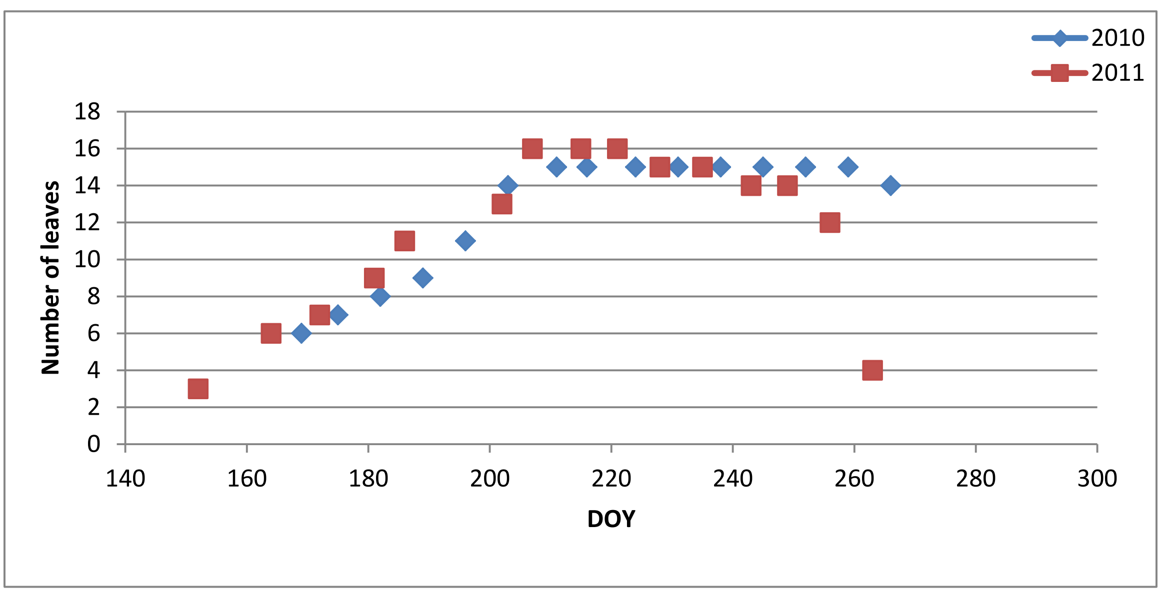

Figure 4-2: The average green leaf number per plant (n=2) of maize grown near Greeley, CO in 2010 and 2011. Data from 2012 has been excluded because most of the leaves were exposed to hail damage. DOY is day of year.

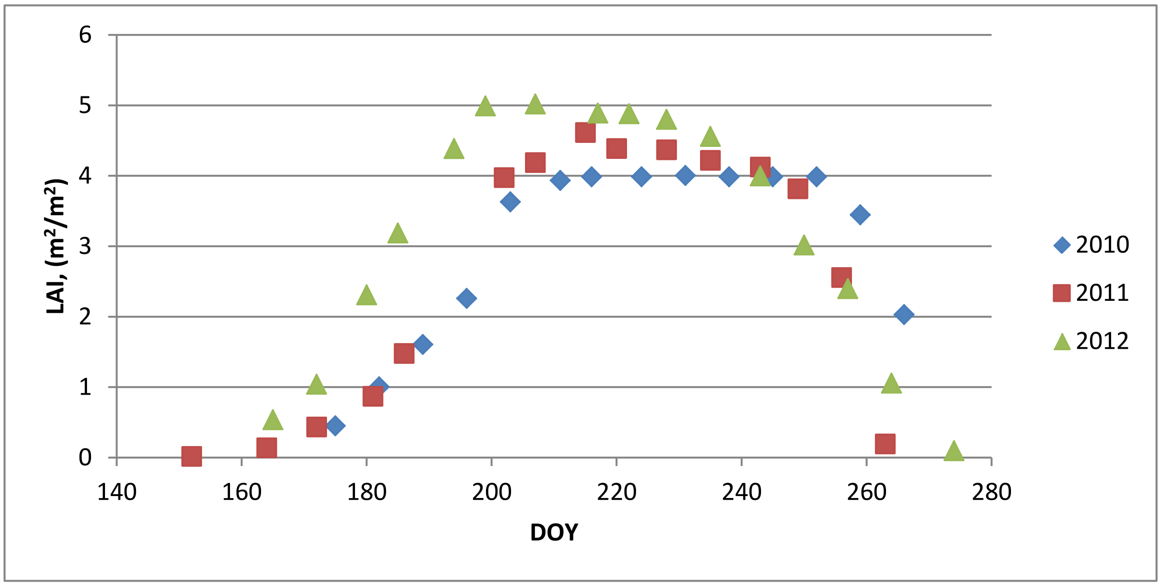

Figure 4-3: Maize leaf area index (LAI) near Greeley, CO for 2010, 2011 and 2012 seasons. DOY is day of year.

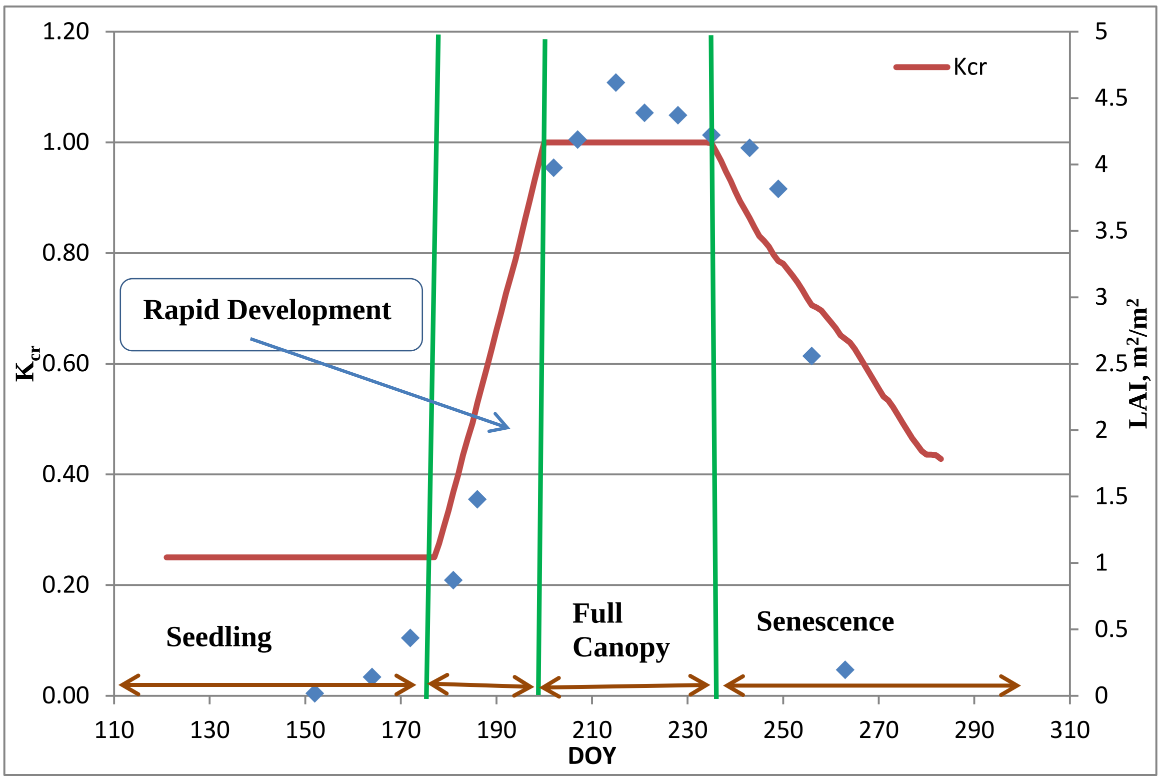

Figure 4-4: Leaf Area Index (LAI) and Kcr (crop coefficient) of maize grown near Greeley, CO in 2011. DOY is day of year.

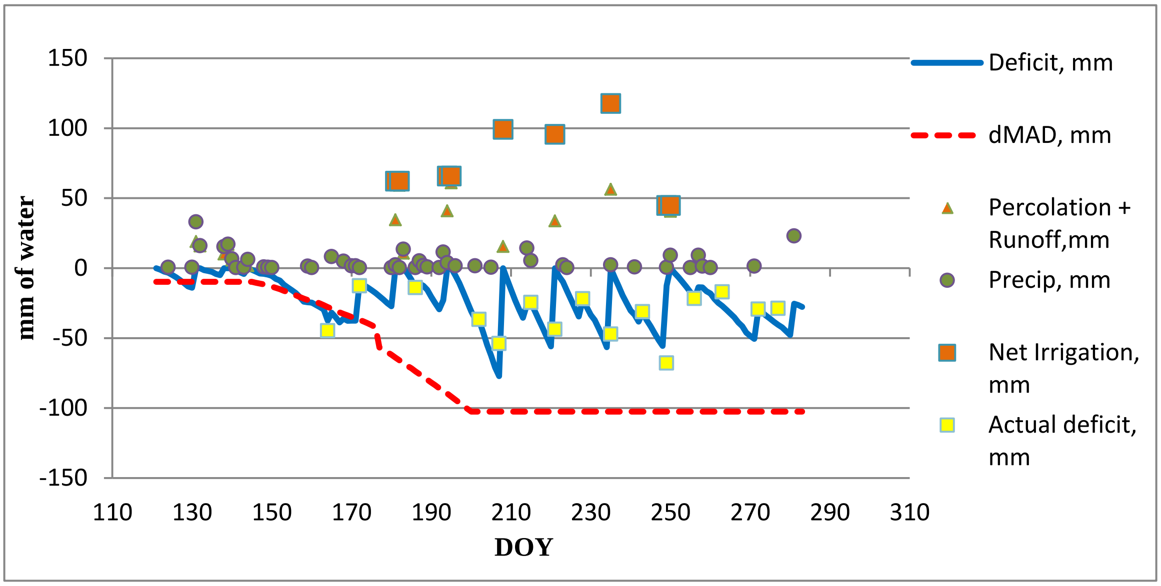

Figure 4-5: Irrigation scheduling for a corn field near Greeley, CO using weekly volumetric soil water content measurements and daily climate data in 2011. DOY is day of year, and d_{MAD} is the depth of management allowed depletion.

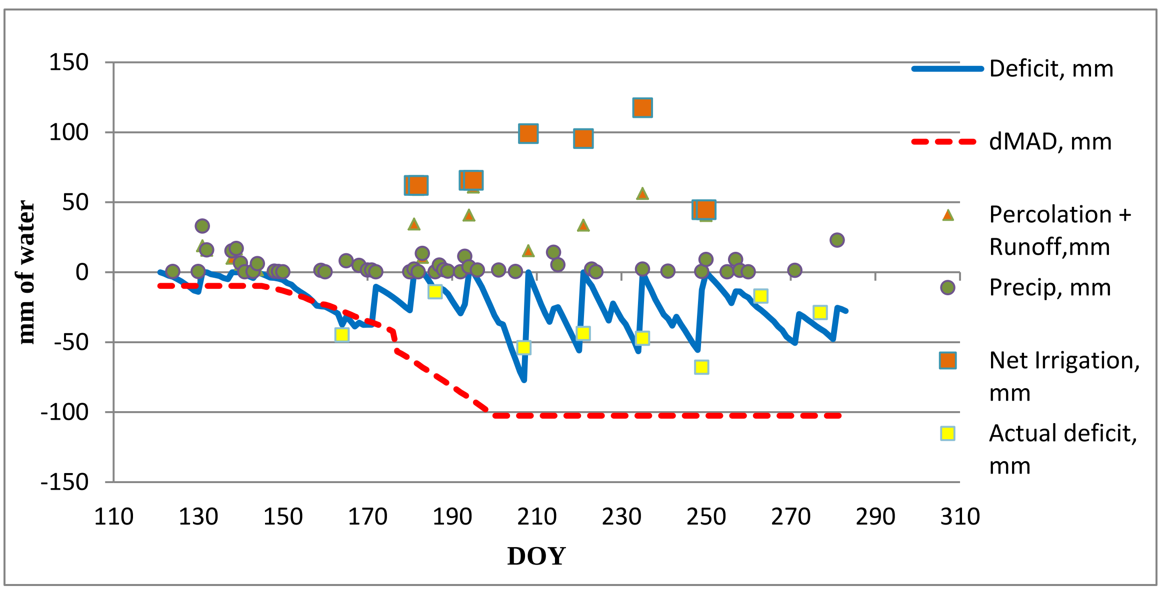

Figure 4-6: Irrigation scheduling for a corn field near Greeley, CO using bi-weekly volumetric soil water content measurements and daily climate data in 2011. DOY is day of year, and d_{MAD} is the depth of management allowed depletion.

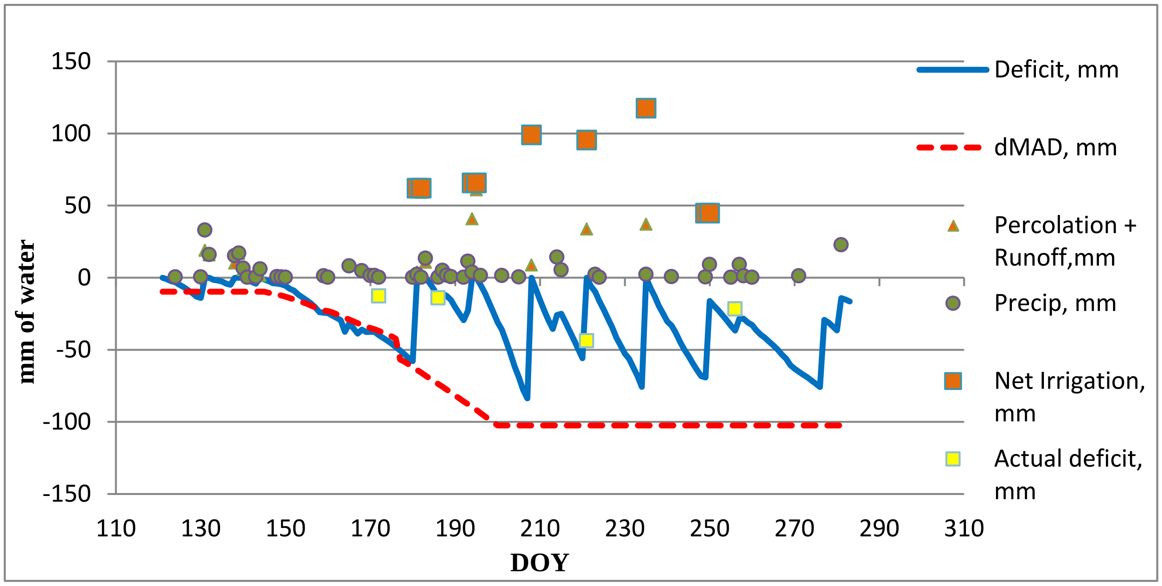

Figure 4-7: Irrigation scheduling for a corn field near Greeley, CO using monthly volumetric soil water content measurements and daily climate data in 2011. DOY is day of year, and d_{MAD} is the depth of management allowed depletion.

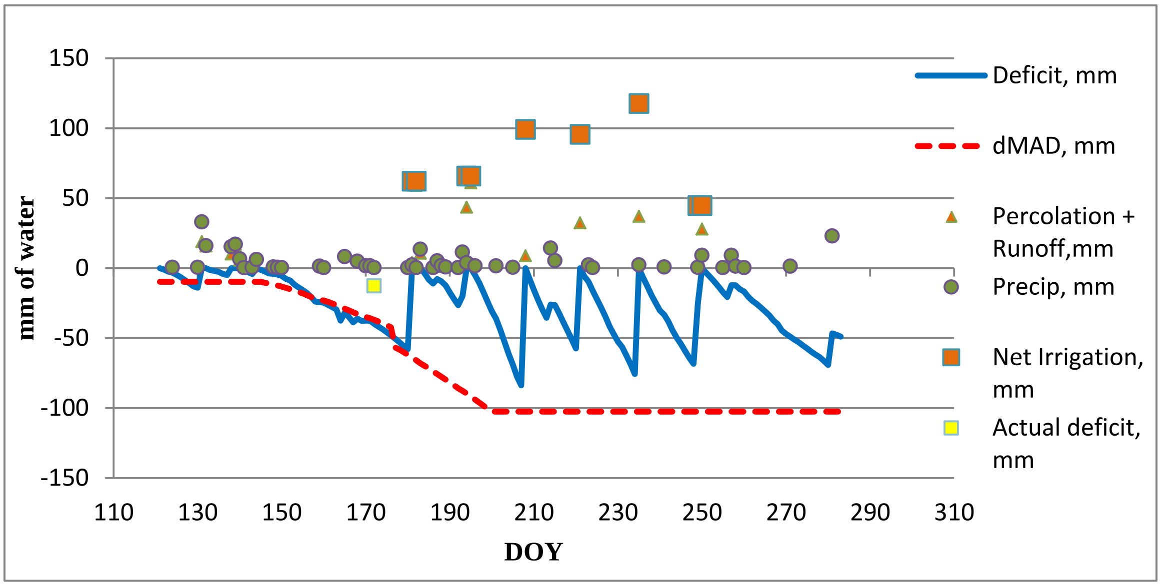

Figure 4-8: Irrigation scheduling for a corn field near Greeley, CO using one time volumetric soil water content measurements and daily climate data in 2011. DOY is day of year, and d_{MAD} is the depth of management allowed depletion.

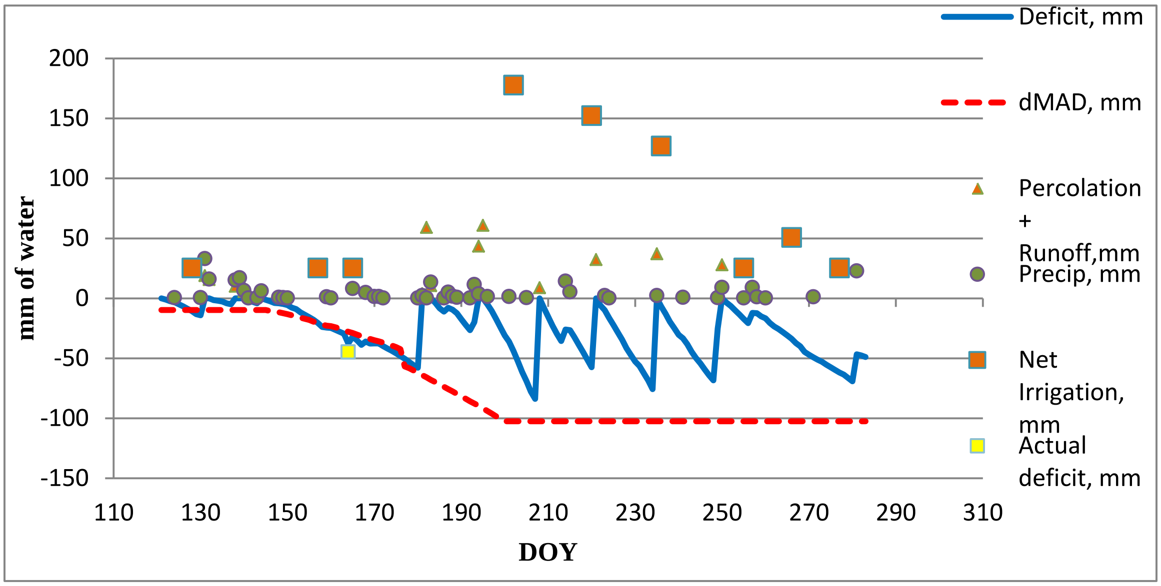

Figure 4-9: Simulated net irrigation distributed over the season based on soil water content for a corn field near Greeley, CO using one time volumetric soil water content measurements and daily climate data in 2011. The figure shows different amounts and time of net irrigation through calculating gross irrigation in Colorado Irrigation Scheduler (CIS). DOY is day of year, and d_{MAD} is the depth of management allowed depletion.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The ASCE standardized Penman-Monteith (ASCE-SPM) and Penman-Kimberly (PK) equations were compared at seven locations in Colorado for 2008 to 2011. The analysis included a comprehensive comparison of the reference daily ET_r values for the ASCE-SPM and PK equations. There was a clear difference between the daily ET_r using the two equations. The seasonal cumulative values showed the ET_r values calculated with the PK equation were generally lower than those calculated using the ASCE-SPM equation. In general, the PK equation tended to give lower ET_r values during spring and fall periods, and slightly higher values during summer months compared to the ASCE-SPM equation. In 2011, which had the most complete weather record, the highest mean daily ET_r was observed at the CSU Experiment Station in Rocky Ford (Southeast Colorado), and the lowest value was recorded at the CSU Experiment Station in Rogers Mesa (West Slope). As a result of the relatively larger aerodynamic term in the ASCE-SPM equation, ET_r was higher from the ASCE-SPM equation during spring and fall periods, when wind speeds were relatively higher. On the other hand, the energy balance term was a little larger in the PK equation compared to the ASCE-SPM equation.

The difference between PK and ASCE-SPM ET_r became generally more negative when wind speeds were above 2 m/s. The difference between PK and ASCE-SPM ET_r was also affected by humidity (actual vapor pressure or relative humidity). The PK equation tended to give lower ET_r values than the ASCE-SPM equation as vapor pressure or relative humidity decreased. Differences in ET_r were generally less than 0.5 mm/d when mean actual vapor pressure was higher than 1.5 kPa.

Differences were documented between ET_r measured from a lysimeter and ET_{rs} calculated using the ASCE-SPM equation. When alfalfa was at reference conditions (50-55 cm tall, not water-stressed), the values of the measured ET_r from the lysimeter were higher than the ASCE-SPM calculated values due to alfalfa overgrowth beyond the lysimeter boundaries. Canopy surface area adjustments reduced the differences between measured hourly ET_r from the lysimeter and the calculated hourly ET_{rs} values from the ASCE-SPM equation. Over-estimated lysimeter ET_r can affect the crop coefficient (K_{cr}) values derived from this data. K_{cr} would be under-estimated if ET_r was over-estimated. This study showed that the ASCE-SPM ET_r values can be used to detect possible lysimeter ET overestimation caused by crop overgrowth. Correcting the measurement of alfalfa ET_r from the lysimeter through accounting for effects of alfalfa overgrowth can lead to improved estimation of ET_r and corresponding K_{cr} values.

Irrigation scheduling can be based on soil water deficit using soil water content, gross irrigation and ET_r from a field. A model (Colorado Irrigation Scheduler, CIS) was used to evaluate and simulate irrigation in a furrow-irrigated corn field from 2010 to 2012. Irrigation efficiency depends on increasing crop production with less water and reducing water losses via percolation and runoff. The CIS model provided good irrigation recommendations during the years 2010, 2011 and 2012. Most index of agreement (d) values between actual and calculated deficit were high and showed the model was working well during the growing season. CIS can help to schedule irrigation as the season progresses. Referencing the past three years and simulated reality in the field, the model was successful in estimating when and how much water should be applied to the field. In spite of the different amounts of irrigation in different years and different corn planting locations, the CIS model gave promising results as demonstrated by index of agreement values of 0.5 or above for most years of this study. This shows the extent of matching the real deficit with the calculated deficit. However, to make sure this model is working very well, CIS should be utilized in fields close to the study locations that were tested. In addition, one may possibly apply the data from the field day-by-day and let the model make estimations that depend on daily climate data from the field. Correcting the CIS with measured soil moisture content every other week combined with daily climate data showed that the CIS model could effectively estimate daily soil water deficit (d = 0.70 to 0.99).

Recommendations

Based on the findings of this study, the following recommendations are given for future work.

- In place of current crop coefficients that were developed for the PK equation in Colorado, new crop coefficient (K_c) curves for calculating ET_c should be developed for use with ASCE-SPM ET_r values under Colorado conditions.
- Control the over-growth or extension of crop canopies beyond the lysimeter edges to avoid over-estimation of crop ET values from lysimeters.
- If possible, use local lysimeters to develop K_c curves in other locations, such as CSU Rogers Mesa or Iliff, Colorado, since each site has different environmental characteristics. The CSU Rocky Ford Station had the highest ET_r compared to the other six locations in Colorado, and the CSU Rogers Mesa Station had the lowest ET_r.
- Use sprinkler irrigation to insure equal water distribution outside and inside the lysimeter area for uniform crop growth.
- To get optimum results from the CIS, soil water content should be collected bi-weekly. However, the CIS can work adequately with monthly data.
- Test the CIS under other soil and climate conditions and with other crops.