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**INTRASEASONAL MANAGEMENT STRATEGIES
FOR DEFICIT IRRIGATION**

by

Isaac Mortensen

A THESIS

**Presented to the Faculty of
The Graduate College at the University of Nebraska
In Partial Fulfillment of Requirements
For the Degree of Master of Science**

**Majors: Agricultural Economics and
Agricultural and Biological Systems Engineering**

**Under the Supervision of Professors
Raymond J. Supalla and Derrel L. Martin**

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INTRASEASONAL MANAGEMENT STRATEGIES FOR DEFICIT IRRIGATION

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University of Nebraska, 2011

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Reduced availability of irrigation water to producers has led to the need for intraseasonal management strategies that efficiently use the limited supply of irrigation water.

Historical weather data was used to develop a range of conditions experienced at the location. Sound weather data improves the dependability of management strategies.

Data from weather stations on the Automated Weather Data Network and the Colorado AgMet network were evaluated based upon net radiation and dew point temperature observations expected in an irrigated agricultural setting. This weather data was used to create a relationship between the Penman-Montieth evapotranspiration (ET) and

Hargreaves ET and the geographical location of the weather stations. The AquaCrop model was calibrated to data from the Carbon Sequestration Project at Mead, Nebraska.

The model was able to accurately predict canopy cover ($R^2 = 0.96$), biomass production ($R^2 = 0.98$), and yields ($R^2 = 0.84$, $RMSE = 0.72 \text{ Mg ha}^{-1}$). The model was also able to track ET throughout the growing season. The weather data and calibrated model were used to simulate the impact of irrigation timing throughout the growing season and to determine the timing of irrigation events that produced the highest marginal yields for different system capacities and initial soil water contents. Using the optimized irrigation distribution, a management strategy was developed to deficit irrigate corn based upon days after planting, initial soil water content, well-watered ET, and a yield goal. The model predicted yields within 10% of the yield goal for the majority of simulations. It translated geographically and expressed the ability to account for differences in system capacity.

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1. Introduction

Irrigation is an important staple of production agriculture in Nebraska. As is common in semiarid climates, seasonal precipitation is not sufficient to meet the evapotranspiration (ET) demands of many crops. This is especially true for water intensive crops such as corn. Irrigation water is applied to crops to make up for the intraseasonal ET deficits. The High Plains Aquifer has long provided a steady source of irrigation water for the state; however, recent studies have shown that aquifer levels have declined in some areas over the past half a century where water has been removed from the aquifer faster than it was replenished. Simultaneously, the demand for water continues to increase. Several natural resource districts have implemented moratoriums on well drilling and/or expansion of irrigated acres in an effort to balance current water demands and stabilize the long-term availability of the water resource.

In addition to moratoriums, irrigation allocations have been put into effect to reduce total withdrawals. Irrigation allocations potentially leave producers with an insufficient amount of water to fully meet ET requirements. Intentionally under irrigating a crop to increase profitability or conserve water in the long term is known as deficit irrigation (Martin et al., 1985).

Numerous strategies have been developed to improve the productive potential of a deficit irrigated crop (Fereris and Soriano, 2007). Methods have been developed to reduce the plant population and perhaps ET consumption. Other research has focused upon applying a full allotment of irrigation to a reduced irrigated area. The use of a crop rotation that includes crops that use smaller amounts of ET during their growth cycle

have been explored to save water for more water intensive crops. The majority of these strategies have concentrated on seasonal water usage and production.

Intraseasonal management strategies are needed to efficiently take advantage of the production potential of a unit of irrigation water. Reduced levels of irrigation limit the producer's ability to replenish water in the root zone. As volumetric water content in the root zone approaches the permanent wilting point, the crop becomes subjected to increasing levels of stress. Doorenbos and Kassam (1979) proposed that reductions in potential yield can be related to reduction in ET using a yield response factor. The response factor varies with growth stage and emphasizes the importance of timing of stress on crop yield.

Crops have different reactions to stress depending upon the severity and timing of the stress. The reactions can be categorized as reduced growth, closing stomata, or senescing early. The combination and impact of the different reactions influence the crop's production and allocation of its water supply.

The purpose of this research is to investigate intraseasonal deficit irrigation management strategies to maximize the production efficiency of each unit of irrigation water. By varying irrigation throughout the growing season the marginal value of each unit of irrigation can be determined. Irrigation events that produce the greatest marginal value will be combined with subsequent marginal yield maximizing irrigation events to produce a yield maximizing production function. The timing of the most valuable irrigation events can then be used to develop a strategy to allocate irrigation water throughout the growing season.

The AquaCrop model (Raes et al., 2009) was used to simulate the effect of irrigation timing on the marginal value of a unit of irrigation water throughout the growing season. The ability to accurately predict field results is paramount when using a model. The AquaCrop model was calibrated to data collected in the carbon sequestration program at Mead, NE (Suyker and Verma 2009). The sensitivity of the model to changes in various model parameters and inputs is then tested for to ensure model robustness.

Accurate weather data is necessary for the development of an irrigation management strategy. The AquaCrop model requires inputs of temperature, precipitation, and short-crop reference evapotranspiration (ET_o) to simulate the development of a crop. The use of inaccurate weather data affects the quality and reliability of simulated results.

Several sources of historical weather data are available; however, the suitability and completeness of the data is not consistent. Older records are often limited in the scope of data collected. Weather stations that record larger ranges of measurements are less frequently distributed throughout Nebraska, Kansas, and the front range of Colorado. Furthermore, instrumentation is subject to malfunctions and miscalibrations.

Weather stations that record the measurements necessary to calculate ET using the Penman-Monteith method were evaluated based on net radiation and dew point temperature observations that are expected in an irrigated agricultural setting. Daily data that were determined to be sufficiently accurate were used to create a relationship between the Hargreaves ET technique and the Penman-Monteith ET technique based on the geographic location of the weather stations. This relationship was then applied to the

more frequently distributed weather stations that only record temperature and precipitation.

Chapter Two evaluated weather stations and data from Kansas, Nebraska, and eastern Colorado. Several quality control mechanisms were employed to filter quality data points from across the region. The data points were then used to develop a region wide regression model to relate Hargreaves ET to the Penman-Monteith ET and the geographical location of the weather station.

Chapter Three investigated the use of the crop growth model AquaCrop. The AquaCrop model was calibrated using data from the Carbon Sequestration Program near Mead, NE. In Chapter Four the sensitivity of the calibrated model to several parameters was examined.

Finally in Chapter Five, the weather data and the calibrated model were combined to study the marginal returns of corn to an additional unit of net irrigation at different times during the growing season. The combination of irrigation timings that produced the greatest marginal returns were used to develop an intraseasonal irrigation management strategy. The strategy was then validated for different location across southwest and south-central Nebraska as well as for different system capacities.

2. Analysis of Weather Data

Background

Deficit irrigation presents a complex risk management dilemma for agricultural producers. Current crop insurance policies cover either rainfed production or fully irrigated crops. Limited-irrigation allocations have the potential to hamper producer's ability to deliver a full supply of water to their crops. Techniques are needed to mitigate the risk associated with partially irrigated crops.

Water Optimizer is a county-based irrigation management tool designed to deal with less than full water supplies and evaluate the consequences of a change in policy dealing with the seasonal allocation of irrigation water amounts (Martin and Supalla, 2010 and Martin et al., 2010). The program provides optimal annual or multi-year distribution of available irrigation water. The model provides a target for marginal net return and expected crop yields based on producer preferences. The model does not provide guidance for intraseasonal scheduling for deficit irrigation.

Currently, the Water Optimizer program is limited to the 93 counties in Nebraska; however, problems associated with limited irrigation do not stop at the state border. Policy options being considered for the Republican River Basin have implications for Nebraska, but also a large portion of Kansas, and the front range of Colorado. This region is faced with limited water supplies that may require intraseasonal water management for the major irrigated crops grown in the region. To address these issues in the larger region the crop production and water usage data for the larger region must be developed.

Water Optimizer uses the CROPSIM growth model to develop data needed to parameterize the program. Weather data is an important input into crop growth models.

Accurate data is necessary to ensure the reliability of model output and reassure those who depend upon the data for decision making purposes. The weather data inputs required to run the CROPSIM model include minimum and maximum temperature, precipitation, and tall-crop reference ET (ET_r). Similarly the AquaCrop model uses minimum and maximum temperature, precipitation, and short-crop reference ET (ET_o).

Monteith (1965) developed a methodology based on the original work of Penman (1948) to estimate water use from cropped systems. The Penman-Monteith method, which has been adapted for estimating reference crop ET, requires weather data for air temperature, relative humidity, solar radiation and wind speed (Walters et al., 2005). This data is available for the High Plains on two weather networks. Weather data for Nebraska, Kansas and some locations in Colorado are available on the High Plains Regional Climate Center's (HPRCC; hprcc@unl.edu) Automated Weather Data Network (AWDN) at the University of Nebraska. The Colorado Agricultural Meteorological network (CoAgMet) operates across Colorado and measures the same data as the AWDN system; however, some parameters are measured at different heights.

The amount of historical data available from the AWDN and CoAgMet stations is limited. Data from these weather stations begins in the mid-1980s to the early 2000s. Alternatively, the National Weather Service (NWS) and cooperators to the National Oceanic and Atmospheric Association operate weather stations that provide data dating back to the late 1800s in some cases. This extended weather data set allows for simulation of crop production and water usage over a longer period of time. Unfortunately, these stations (referred to as NWS weather stations) record only minimum and maximum temperature and precipitation; they do not measure solar radiation,

humidity, or wind speed. Thus, the Penman-Monteith reference ET estimation method cannot be applied directly to these stations.

Alternatively the Hargreaves method for estimating reference ET requires only minimum and maximum temperature measurements (Hargreaves and Samani, 1985). The Penman-Monteith method has been shown to be more accurate than the Hargreaves method for estimating reference ET (Allen et al., 2005). However, there are relatively fewer weather stations in the region that measure the types of data necessary to calculate Penman-Monteith reference ET. Conversely, there are nearly ten times as many NWS weather stations in the same region. This chapter describes a method to capture a portion of the information lost through the utilization of the Hargreaves equation by developing a relationship to the Penman-Monteith procedure based on the geographical location of the weather stations. A geographical regression eliminates the need to assign AWDN stations to specific NWS station and smooths the effect of individual automated weather station. The process includes the acquisition of weather data, evaluation and exclusion of erroneous weather data, development of regression models, and evaluation of the regression results.

Objectives

1. Examine and evaluate the quality of the AWDN station data from Kansas, Nebraska, and the front range of Colorado.
2. Use the weather data to develop a relationship between the Hargreaves reference ET, Penman-Monteith reference ET, and the geographical location of the weather station for the Kansas, Nebraska, and eastern Colorado region.

Methods

Data Acquisition

Hourly and daily data were downloaded for sixty weather stations across Nebraska, Kansas, and the eastern portion of Colorado. Hourly and daily data were also downloaded from the CoAgMet Network for 13 additional sites on the front range of Colorado. Weather data were acquired for the period from the start of the station until December 31, 2008 for each site. The locations of the weather stations are included in Figure 2.1. Inspection of the weather data files revealed that several formats have been used in logging and delivering the data. The number of weather parameters reported and the order of the data in the dataset varied among sites. Stations were classified according to their format for data processing. The classification of each station was recorded in the

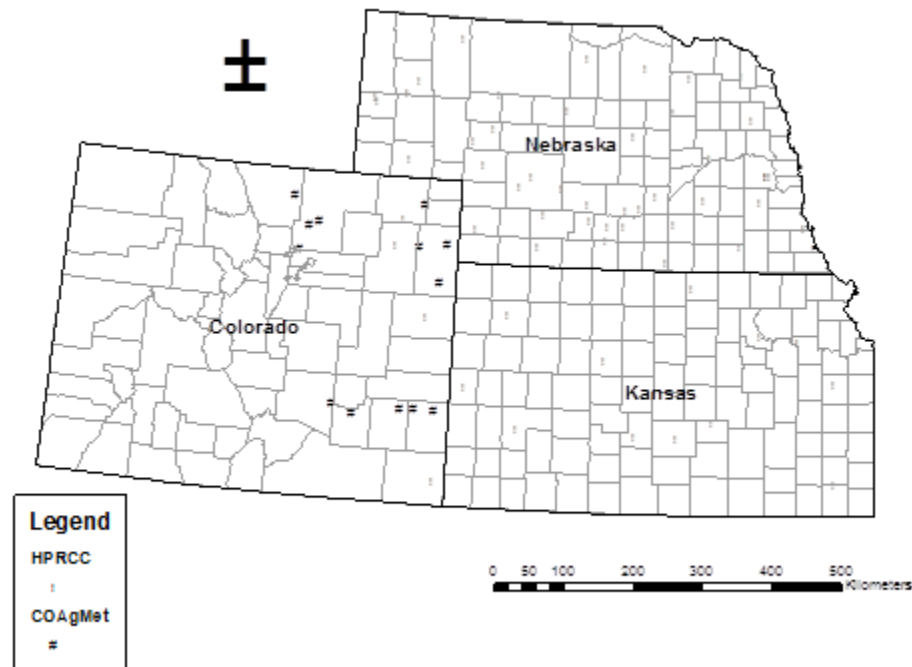


Figure 2.1. Location of automated weather stations used in analysis.

file: *AWDNStationFormat.csv*. Additionally the latitude, longitude, and elevation of each site were included in the file. The height of the temperature sensor, the height of the anemometer, and the estimated height of the vegetation surrounding the weather station were also incorporated into the *AWDNStationFormat.csv* file. These characteristics are necessary for computing reference crop evapotranspiration ET using the ASCE Standardized Penman-Monteith method as described by Allen et al. (2005). The standardized reference crop ET is given by:

$$ET_{sz} = \frac{0.408 \Delta (R_n - G) + \gamma \frac{C_n}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \quad (2.1)$$

where:

- ET_{sz} standardized reference crop evapotranspiration for short (ET_{os}) or tall (ET_{rs}) surfaces (mm d^{-1} for daily time steps or mm h^{-1} for hourly time steps),
- R_n calculated net radiation at the crop surface ($\text{MJ m}^{-2} \text{d}^{-1}$ for daily time steps or $\text{MJ m}^{-2} \text{h}^{-1}$ for hourly time steps),
- G soil heat flux density at the soil surface ($\text{MJ m}^{-2} \text{d}^{-1}$ for daily time steps or $\text{MJ m}^{-2} \text{h}^{-1}$ for hourly time steps),
- T mean daily or hourly air temperature at 1.5 to 2.5-m height ($^{\circ}\text{C}$),
- u_2 mean daily or hourly wind speed at 2-m height (m s^{-1}),
- e_s saturation vapor pressure at 1.5 to 2.5-m height (kPa), calculated for daily time steps as the average of saturation vapor pressure at maximum and minimum air temperature,
- e_a mean actual vapor pressure at 1.5 to 2.5-m height (kPa),
- Δ slope of the saturation vapor pressure-temperature curve ($\text{kPa } ^{\circ}\text{C}^{-1}$),
- γ psychometric constant ($\text{kPa } ^{\circ}\text{C}^{-1}$),
- C_n numerator constant that changes with reference type and calculation time step, and
- C_d denominator constant that changes with reference type and calculation time step.

Values for the numerator and denominator constants depend on the calculation time step and the type of reference crop as listed in Table 2.1.

The hourly and daily data and the *AWDNStationFormat.csv* file were used in a Visual Basic program (PMETSz) to calculate the Penman-Monteith reference ET for both

Table 2.1. Parameters for the Standardized ASCE Penman-Monteith equation.

Calculation Time Step	Short Reference, ET _{os}		Tall Reference, ET _{rs}		Units for ET _{os} , ET _{rs}	Units for R _n , G
	C _n	C _d	C _n	C _d		
Daily	900	0.34	1600	0.38	mm d ⁻¹	MJ m ⁻² d ⁻¹
Hourly during day	37	0.24	66	0.25	mm h ⁻¹	MJ m ⁻² d ⁻¹
Hourly during night	37	0.96	66	1.7	mm h ⁻¹	MJ m ⁻² d ⁻¹

short and tall reference crops and the Hargreaves reference ET (Hargreaves and Samani, 1985). PMETSz uses the standardized methods as described in *The ASCE Standardized Reference Evapotranspiration Equation* by Walters et al. (2005). The procedure is detailed in the program listed in Appendix 1.

Some weather stations measure wind speed at 3 m above the soil surface, while other stations measure the wind at a height of 2 m. The Penman-Monteith method requires wind data measured at a height of 2 m above the soil surface. Furthermore, the vegetation surrounding many automated weather stations is seldom as short as required for a “reference surface” (*i.e.*, frequently clipped to a height of 0.12 m). The measured wind speed was adjusted to represent conditions for a “reference surface” measured at 2 m above the soil and to account for the approximate vegetation height. The adjustment is given by:

$$u_2 = u_z U_{r1} U_{r2}$$

$$\text{where } U_{r1} = \frac{\text{Ln}\left(\frac{2 - d_{zr}}{z_{omr}}\right)}{\text{Ln}\left(\frac{z_w - d_{za}}{z_{oma}}\right)} \quad \text{and} \quad U_{r2} = \frac{\text{Ln}\left(\frac{z_e - d_{za}}{z_{oma}}\right)}{\text{Ln}\left(\frac{z_e - d_{zr}}{z_{omr}}\right)} \quad (2.2)$$

where:

u_2	wind speed at 2 m above the ground surface (m s^{-1})
u_z	measured wind speed at z_w m above the ground surface (m s^{-1})
U_{r1}	adjustment for anemometer height at the weather station
U_{r2}	adjustment for vegetative conditions at the weather station
z_w	height of wind speed measurement above ground surface (m)
d_{zr}	zero plane displacement for reference weather station vegetation (m) ($d = 0.67 h_r$)
z_{omr}	aerodynamic roughness for reference weather station vegetation (m) ($z_{omr} = .123 h_r$)
d_{za}	zero plane displacement for actual weather station vegetation (m) ($d = 0.67 h_v$)
z_{oma}	aerodynamic roughness for actual weather station vegetation (m) ($z_{oma} = .123 h_v$)
Z_e	height of internal boundary layer (m)

PMETsz outputs three files: a count file (.cnt), an hourly file (.hrl), and a daily file (.day). The hourly files and the daily files contained the new standard format for the weather data as well as the various computed reference ETs, and several intermediate values. The AWDN weather data network contains flags in the weather data to indicate weather data corrections, missing data replacement, or other data errors that occurred. The count file contains the number and type of data flags for each weather station.

Quality Check of Data

The availability of the weather data from the HPRCC or CoAgMet does not ensure the quality of the data or the weather station. Very few weather stations are situated in a standard position¹ to take weather measurements. Investigations of the weather stations show that the surroundings for some weather stations are obstructed by trees and buildings. Other weather stations are situated on bare ground or grass that was not maintained at a height at 0.12 m. Figures 2.2-2.5 show pictures of weather stations

¹ A Location centered on a large nearly level expanse of a fully-watered grass maintained at a height of 0.12m.

from the HPRCC and CoAgMet networks where the conditions around the station are substandard.



Figure 2.2. Weather station at St. John, KS. The immediate surrounding area includes a windbreak. The weather station is situated above bare ground. (<http://wdl.agron.ksu.edu/metadata.php>)



Figure 2.3. Weather station located at Scandia, KS. The weather station is located in direct proximity to a building. (<http://wdl.agron.ksu.edu/metadata.php>)



Figure 2.4. Weather station located at Peckham, CO. The surrounding area is bare ground. (<http://coagmet.com/>)



Figure 2.5. Weather station located at Gothenburg, NE. The surround grass cover is not kept at 0.12-m height. (www.hprcc.unl.edu)

The automated weather data were used to calibrate the Hargreaves method. In some cases the automated station data networks include flags in the data to indicate errors or adjustments to the data. Adjustments were made when the measured data fell outside of quality control criteria or when data were missing. The networks often estimate values for days with poor data quality or where the measurements are missing. While the estimated data may be appropriate for many uses, estimates were not used in the calibration of the Hargreaves method. The PMETsz program counts the number of flags that are associated with the raw data and records the number of flags in the daily and hourly files.

After computing the reference ET, PMETsz examines the measured temperature, relative humidity and radiation. The ratio of the measured radiation to the clear sky radiation is computed and categorized into specific ranges. A comparison is also made between the daily minimum air temperature and the dew point temperature. The number of days each year that fell into specified categories was reported in the count file.

The relationship between the measured solar radiation and the clear sky solar radiation was the first criterion used to determine the quality of the weather data and station. The measured radiation should approach the theoretical clear sky value for periods of during the day and year. The ratio of measured radiation to clear sky radiation was plotted for each hour of the middle third of the day (8 AM to 5 PM). This was done for every day of the year, for each complete year that the weather station was operational. Each year was examined to determine if the sensor accurately measured the incoming radiation. If the ratio fell below 0.9 for an extended period of time, the entire year was discarded from future calculations. This process was based on manual examination of the

plots. Examples of a good year (Figure 2.6) and years that were discarded (Figures 2.7 and 2.8) are shown below. The average radiation for the day was calculated and compared to the clear sky radiation. The number of days that the ratio of the average measured radiation to clear sky was above 0.9 or between 0.75-0.90 was also used as a check on data quality of the years that were discarded.

The second quality criterion was the difference between the minimum air temperature and dew point temperature. The dew point temperature should not drop much below the minimum air temperature for weather stations that represent reference sites. When the minimum temperature is much higher than the dew point temperature the ambient conditions around the weather station are usually drier than would be expected for an irrigated agricultural region. The High Plains often experiences frontal storms or climatic changes during the day. Occasionally the rapid change of conditions during the day affects the minimum air temperature more than the average daily dew point. This can cause positive or negative differences between the minimum air temperature and the dew point temperature. If the daily difference exceeded thresholds the day was omitted from further consideration. Three temperature differences were analyzed (2, 4, and 6°C). If the daily difference exceeded the threshold then the day was not included in further calculations.

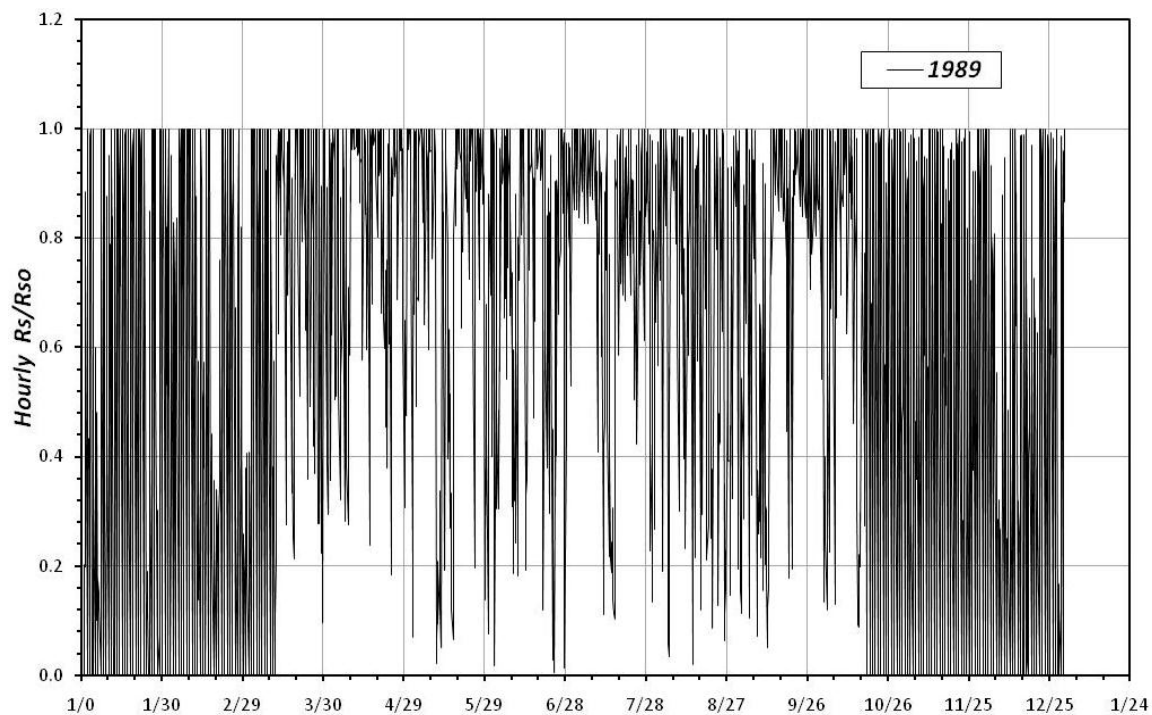


Figure 2.6. Example of a good year of data from Curtis, Nebraska based on the hourly ratio of measured radiation to clear sky radiation in 1989.

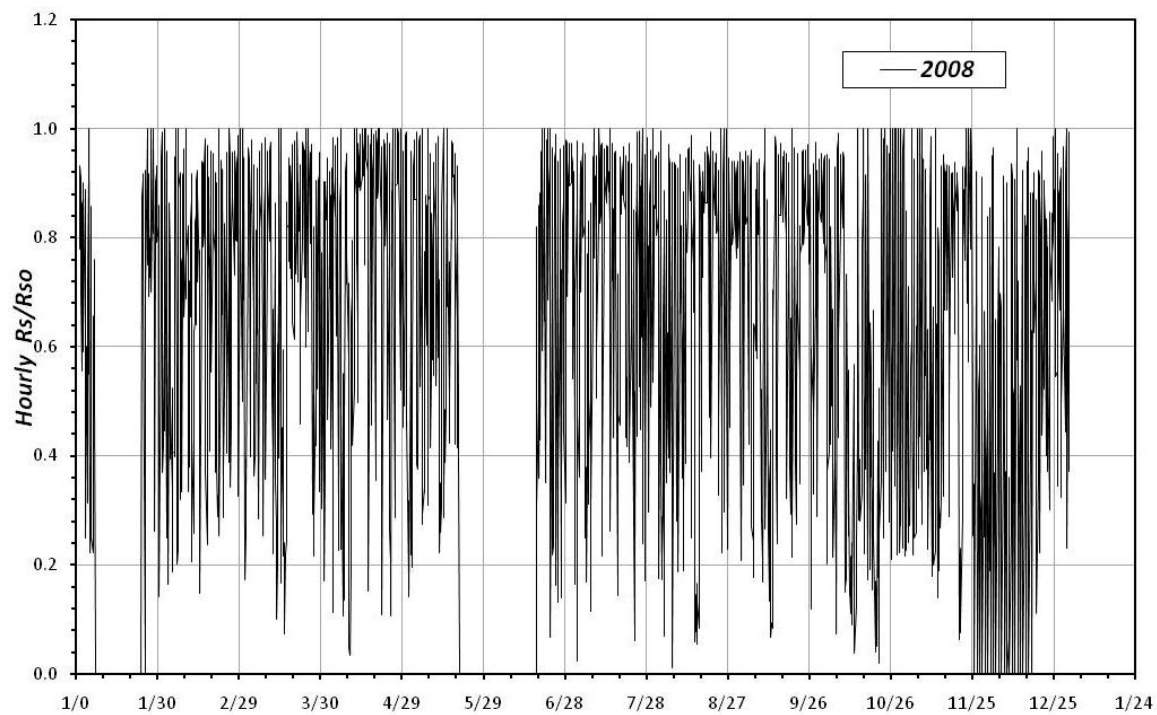


Figure 2.7. Example of a year of data from Fort Collins, Colorado that was discarded due to missing radiation data for extended periods in 2008.

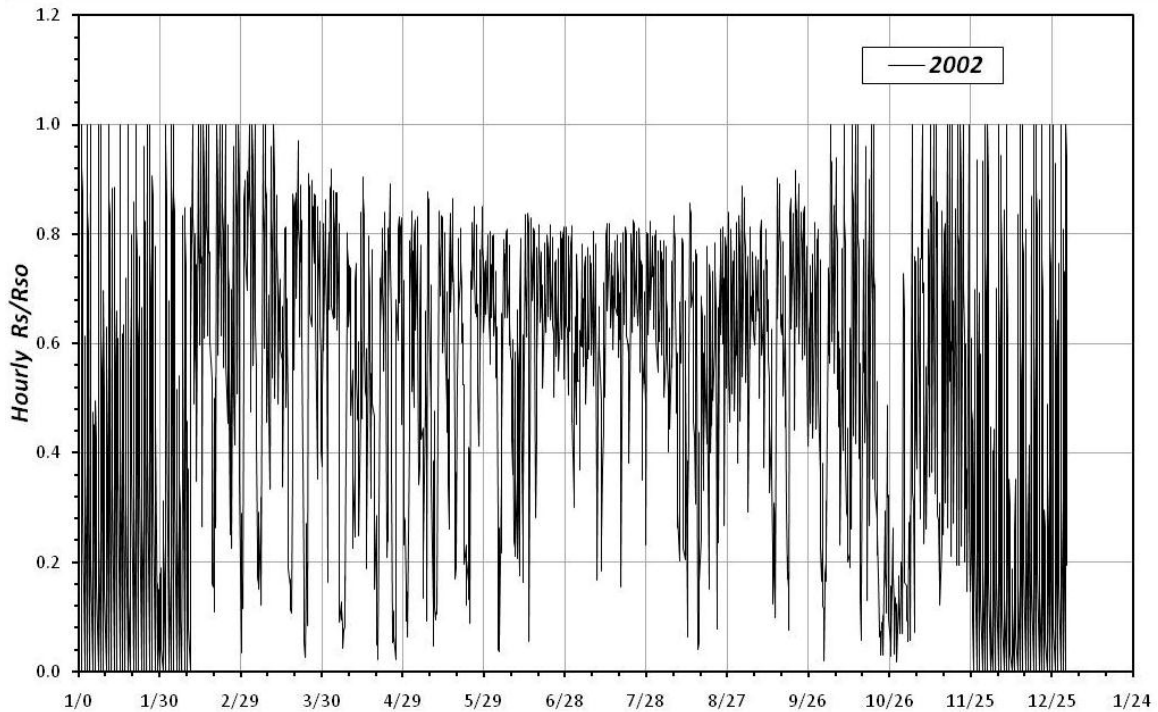


Figure 2.8. Example of a year of data from Manhattan, Kansas that was discarded because the maximum ratio of measured hourly solar radiation to hourly clear sky solar radiation is consistently less than 0.9 for long periods.

The final quality criterion was the total number of data flags for a given day. If the number of flags exceeded a threshold, set at 3, then the day was excluded from future calculations. The data that met these quality criteria were separated according to month. This process was conducted for 73 weather stations across Kansas, Nebraska, and the front range of Colorado. The monthly data for each station were combined into one file that contained every data point from each weather station that met the quality criteria. The entire process is shown in Figure 2.9.

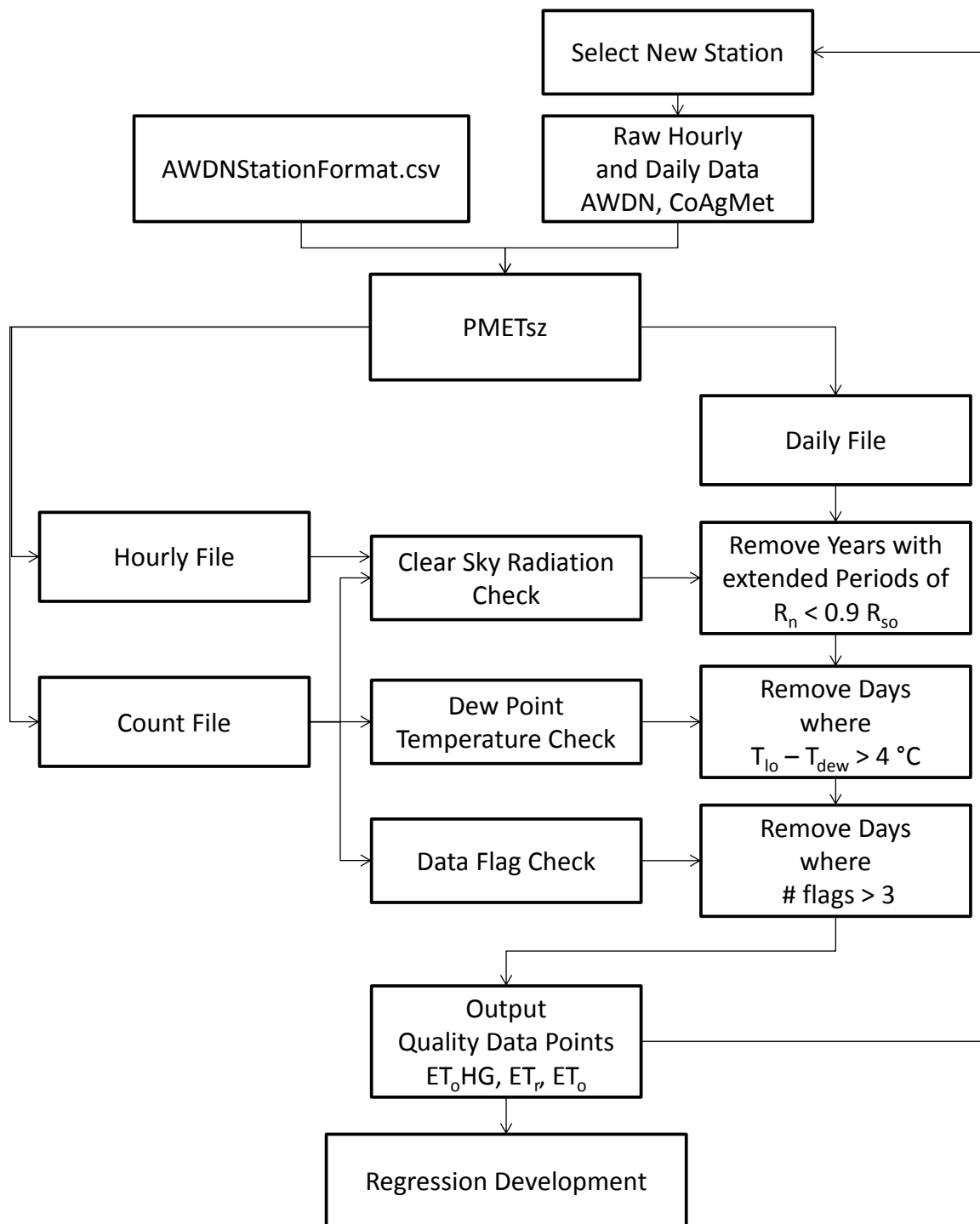


Figure 2.9. Weather data quality check flow chart for determining the quality data points used to develop the region wide relationship between Hargreaves ET, Penman-Monteith ET_r and the geographical location of the weather station.

Developing Regression Function

Research has shown that the Penman-Monteith technique is the most reliable method for estimating reference crop ET; however, the NWS stations do not provide enough data for the Penman-Monteith method, but are compatible with the Hargreaves method for computing reference crop ET.

To improve the reliability of the Hargreaves method it was calibrated against data for the Penman-Monteith method for the AWDN stations. AWDN stations are distributed across the region and their siting may introduce variability. Therefore, the calibration was based on the geographical distribution of AWDN stations. This smoothed the data for the stations and provided a means to apply the calibration to the NWS stations.

Two regression equations were evaluated to form the region-wide model for the Hargreaves method. The Hargreaves function predicts the reference crop ET for a short reference crop based on the maximum and minimum daily air temperature and the extraterrestrial radiation and is given by:

$$ET_oHG = 0.0023 \sqrt{T_{\max} - T_{\min}} (T_{\text{mean}} + 17.8) R_a \quad (2.3)$$

where:

ET_oHG	short crop reference ET from the Hargreaves method, (mm d ⁻¹)
T_{\max}	maximum daily air temperature, (°C)
T_{\min}	minimum daily air temperature, (°C)
T_{mean}	mean daily air temperature, $T_{\text{mean}} = (T_{\max} + T_{\min}) / 2$
R_a	extraterrestrial radiation, (mm d ⁻¹).

A second degree polynomial based on latitude and longitude was used to adjust the Hargreaves ET equation coefficients across the region for a tall reference crop:

$$ET_r = a + (b + c \text{ Long} + d \text{ Long}^2 + e \text{ Lat} + f \text{ Lat}^2) ET_oHG^s \quad (2.4)$$

where:

ET_r reference evapotranspiration for a tall crop, mm d^{-1}

Lat latitude, decimal degrees

Long longitude, decimal degrees.

The second regression relationship used a power function based on longitude:

$$ET_r = a + (b + c \text{ Long}^d) ET_o HG^e \quad (2.5)$$

Regression coefficients were obtained for each expression by minimizing the sum of squares with a nonlinear optimization procedure. This was done for each month and each dew point-minimum temperature difference (*i.e.*, 2, 4, 6°C). The spread in results between the three thresholds was minimal, as shown in Figure 2.10; thus, the 4°C threshold was chosen. The regression coefficients are listed in Table 2.2.

Table 2.2. Regression coefficients for each month.

	Jan	Feb	Mar	Apr	May	Jun
a	0.29	0.33	0.00	-0.44	-2.25	-2.88
b	-1.24	-0.48	-0.16	0.32	0.66	.97
c	7.80 E-4	5.05 E-4	3.83 E-4	2.38 E-4	9.96 E-5	8.91 E-5
d	1.77	1.75	1.77	1.74	1.99	1.94
e	1.32	1.34	1.21	1.26	1.03	1.03

	Jul	Aug	Sep	Oct	Nov	Dec
a	-1.15	-0.91	-1.80	-1.16	-0.17	0.22
b	0.79	0.47	0.77	1.44	0.13	-1.85
c	3.72 E-5	1.30 E-4	1.28 E-4	2.32E-4	3.96 E-4	1.02 E-3
d	1.77	1.79	2.01	1.78	1.81	1.76
e	1.22	1.21	0.89	0.84	1.00	1.24

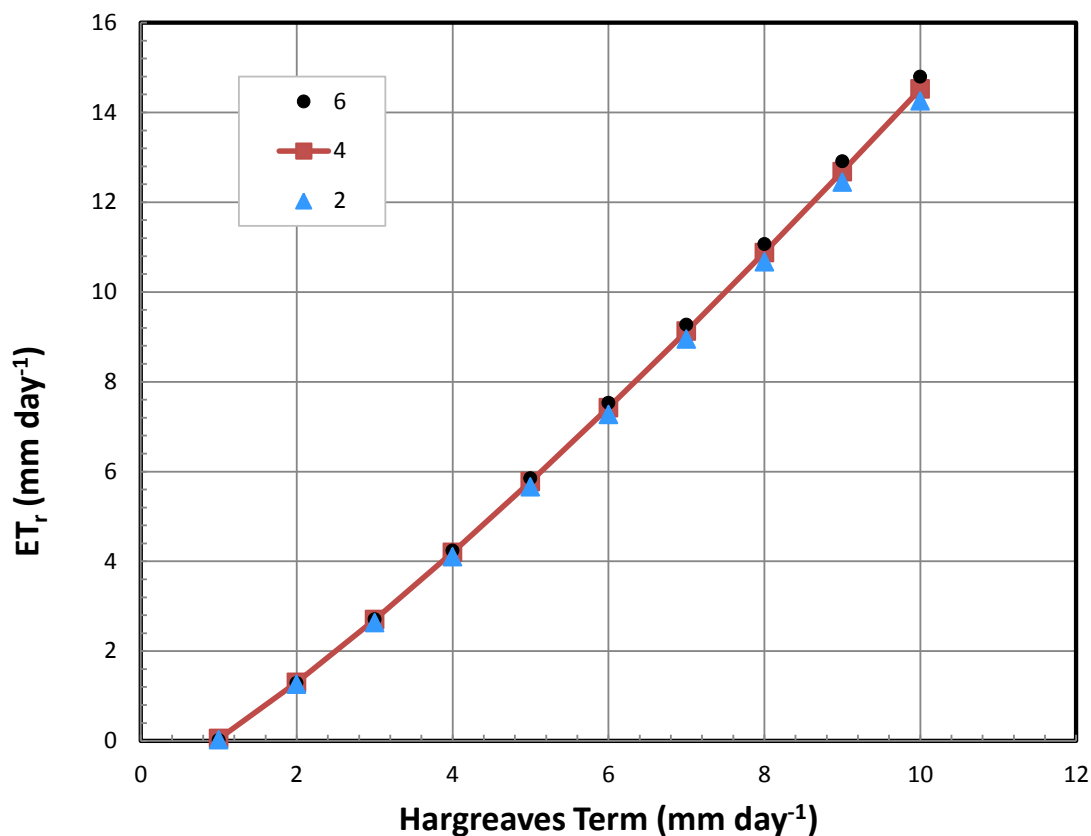


Figure 2.10. Comparison of the regression results for 2, 4, and 6°C differences between the low temperature and the dew point temperature for the month of August evaluated at 100 degrees west longitude.

A comparison between the Equations 2.4 and 2.5 was made for 39 and 41 degrees north latitude (Figure 2.11). The difference between the models is minimal. Furthermore, little difference occurred between 39 and 41 degrees north latitude. The regression model using Equation 2.5 is simpler model, requires less information and yields similar results compared to the more complex model using Equation 2.4.

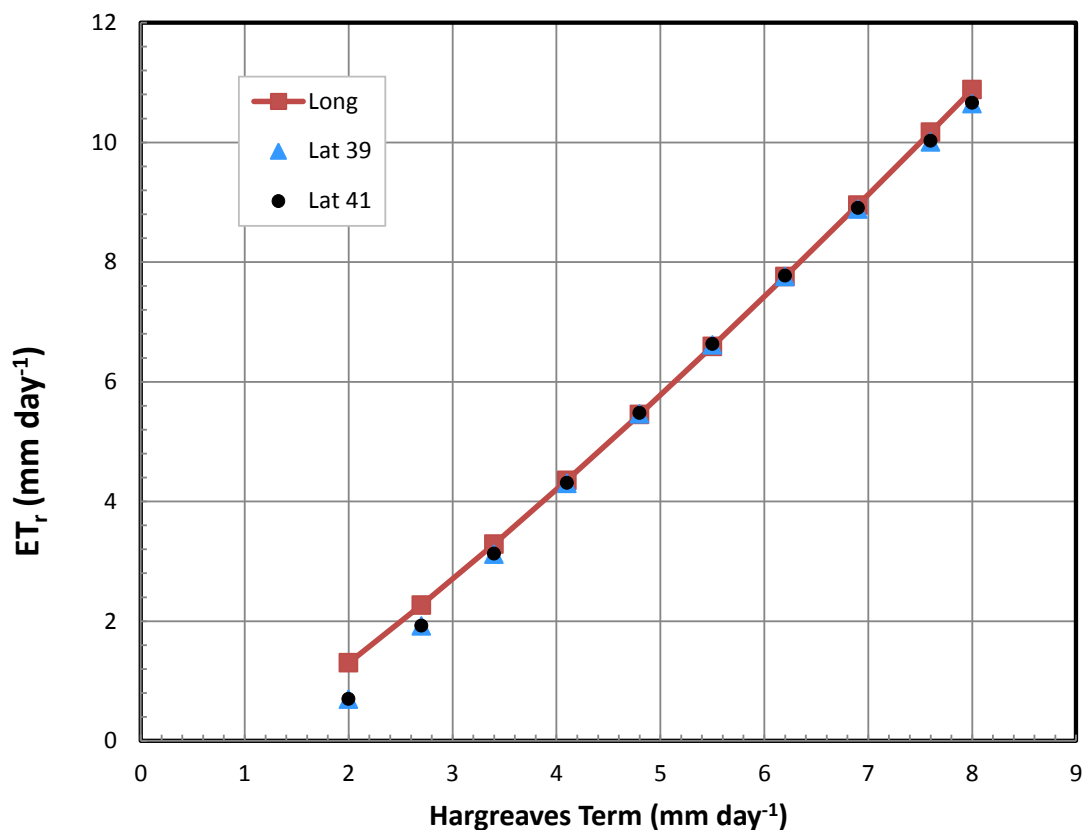


Figure 2.11. Comparison of regression results for equation 2.4 and 2.5 for the month of August. Both equations are evaluated at 100 degrees west longitude. Equation 2.4 is evaluated at latitudes of 39 and 41 degrees north.

The regression coefficients were compared to regression coefficients obtained from an earlier project encompassing only the Republican River Basin, which is smaller than the region considered here. The results in Figure 2.12 show that both models predict approximately the same ET_r for the selected AWDN and CoAgMET stations.

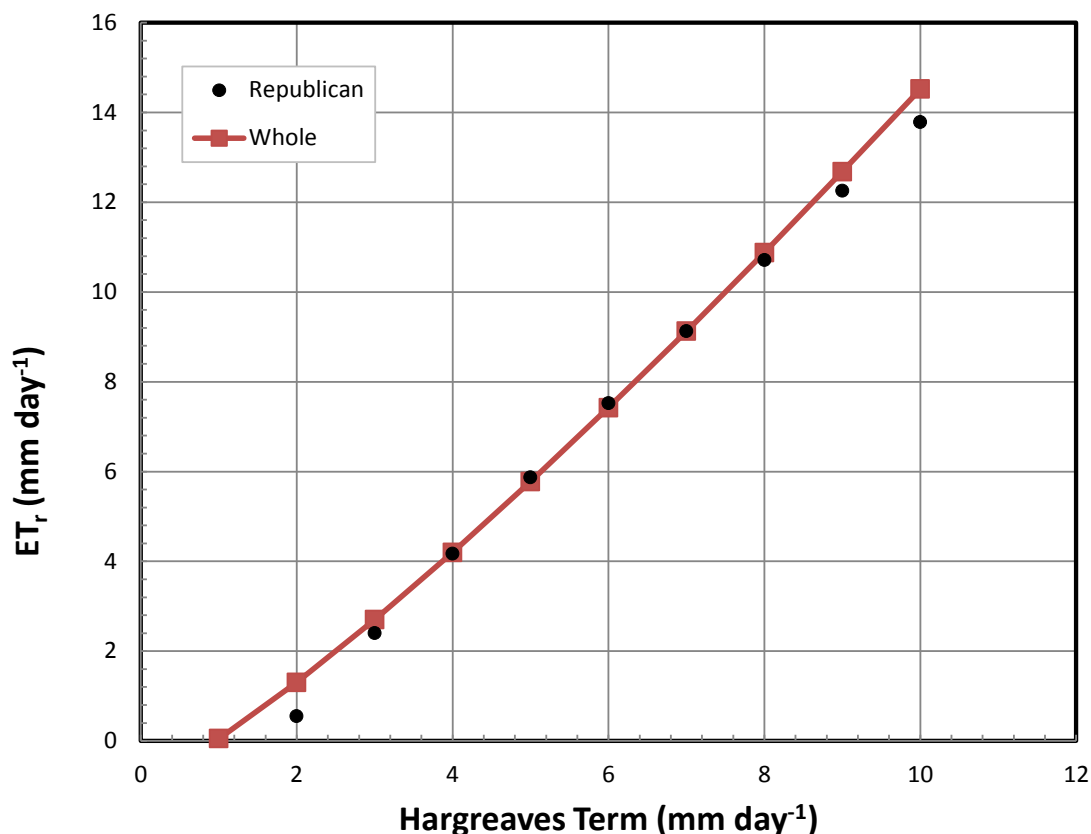


Figure 2.12. Comparison of regression results from the Republican River Basin project to the regression coefficient obtained from the larger region for the month of August evaluated at 100 degrees west longitude.

Validation of the Regression Model

Results from the regression model were compared to the original calculated Penman-Monteith ET for several weather stations across the region. The tall-crop reference ET was computed using the Hargreaves ET calculated in $PMET_{sz}$ and the regression coefficients. The comparisons of the average weekly ET for each method are presented in Figures 2.13-2.20.

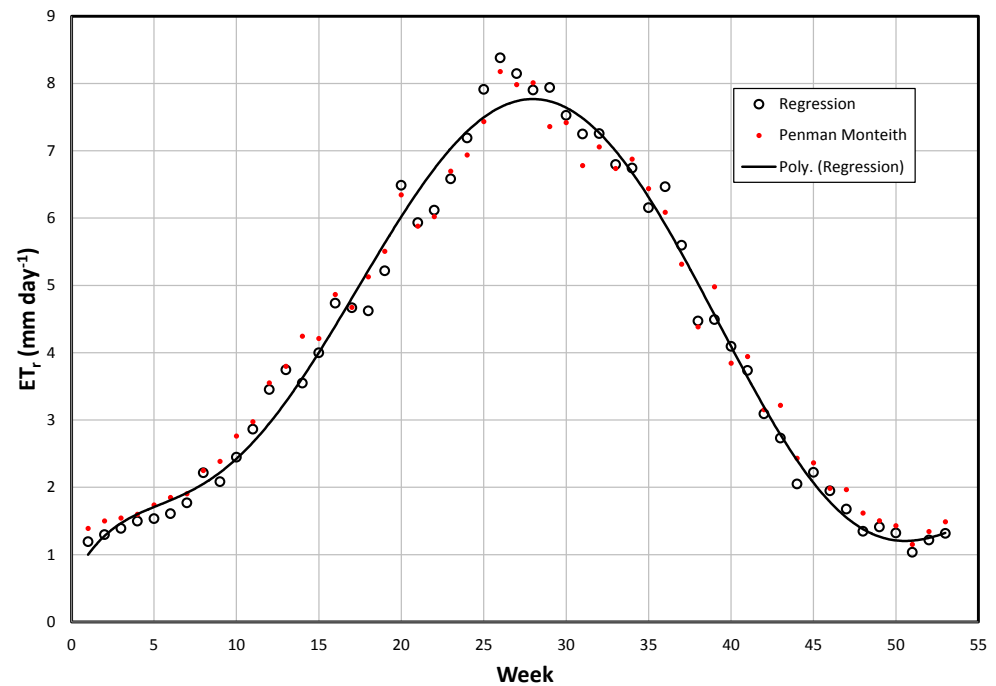


Figure 2.13 Average weekly ET_r comparison between Penman-Monteith and the regression model for Alliance, NE.

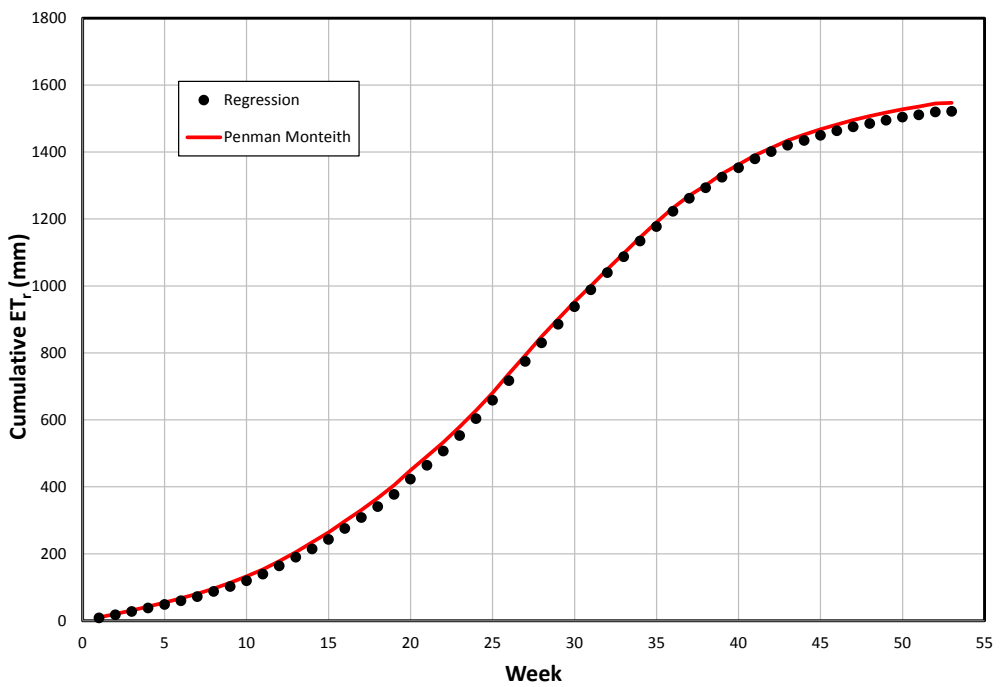


Figure 2.14. Cumulative ET_r comparison between Penman-Monteith and the regression models using average weekly ET_r at Alliance, NE.

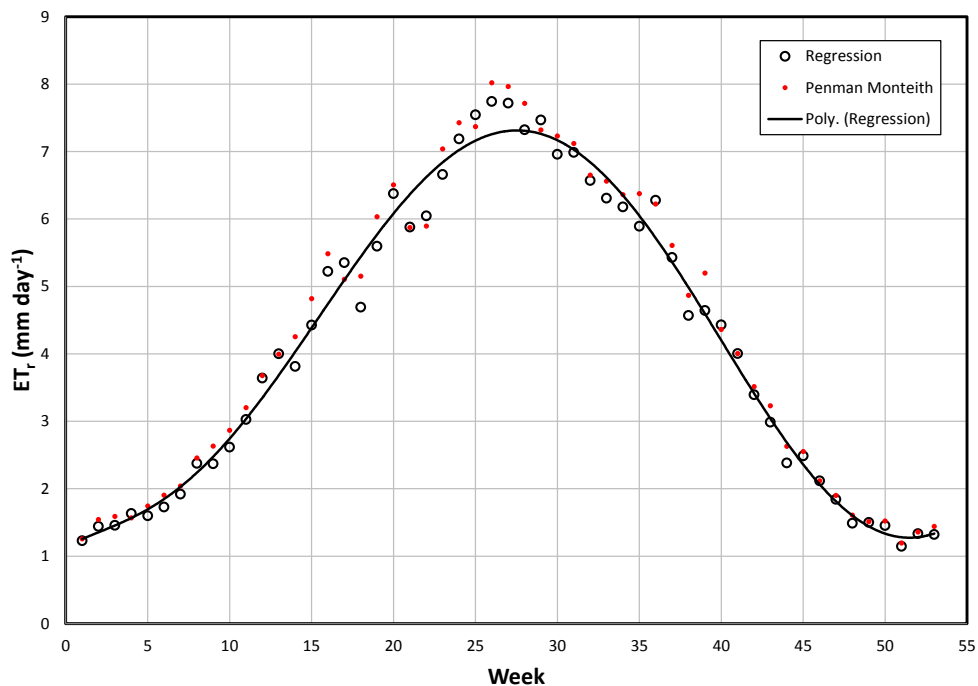


Figure 2.15. Average weekly ET_r comparison between Penman-Monteith and the regression model for Curtis, NE.

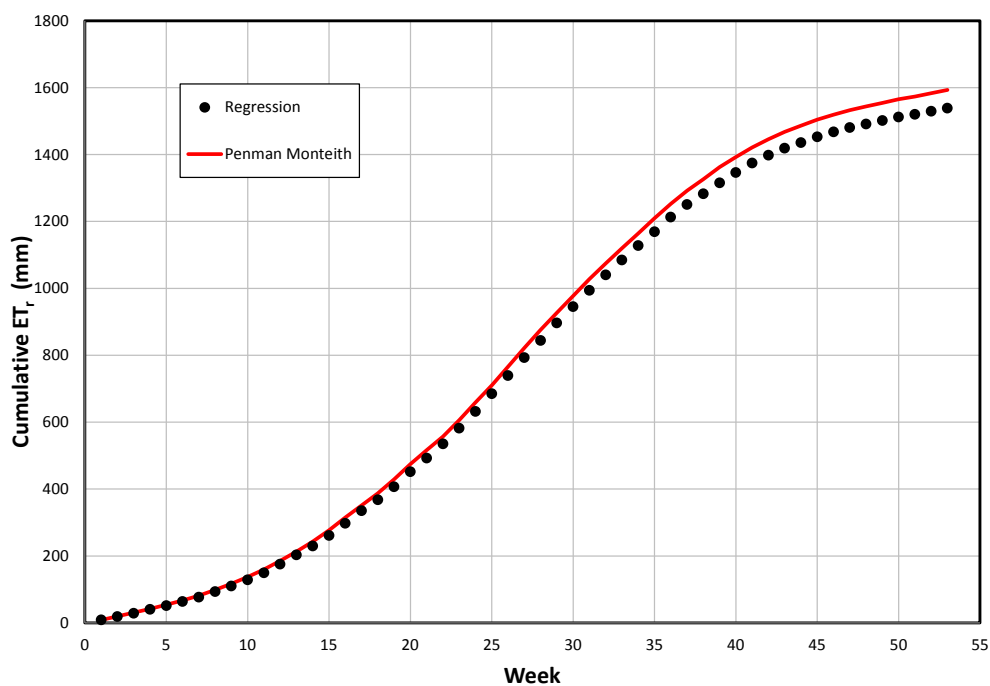


Figure 2.16. Cumulative ET_r comparison between Penman-Monteith and the regression model using average weekly ET_r at Curtis, NE.

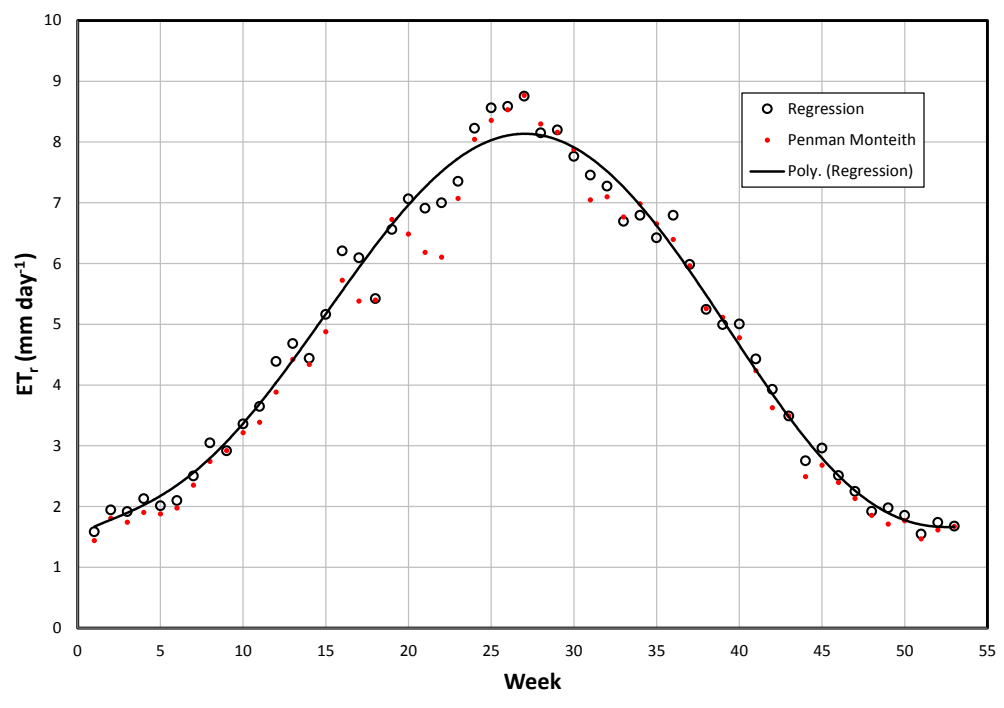


Figure 2.17. Average weekly ET_r comparison between Penman-Monteith and the regression model for Tribune, KS.

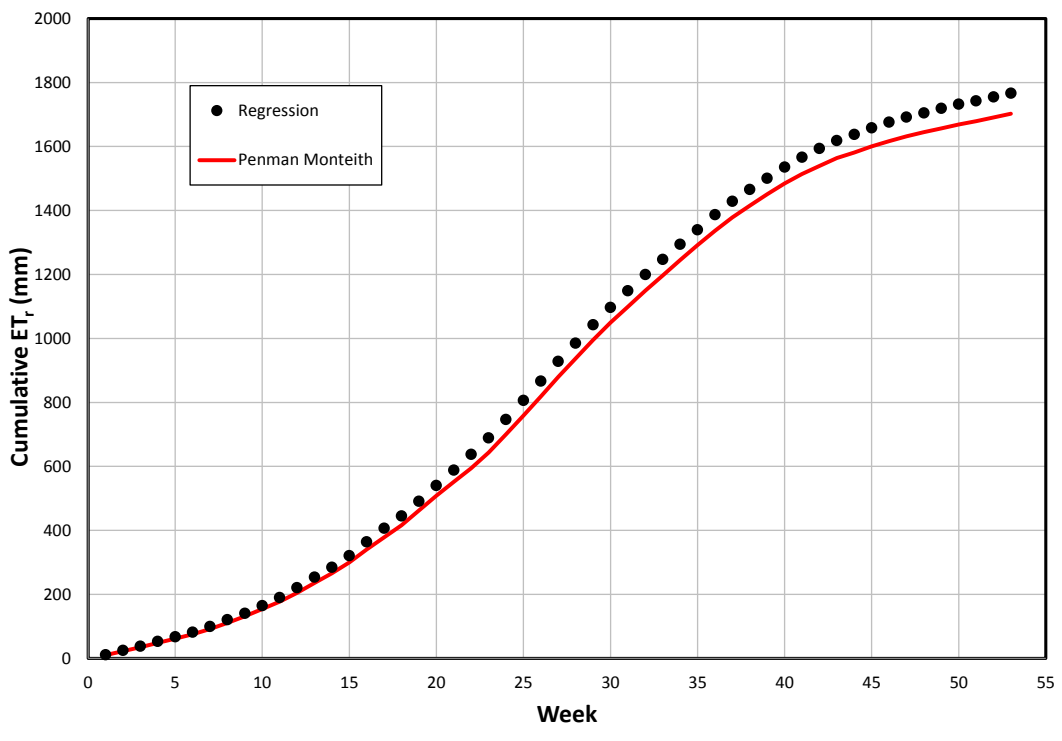


Figure 2.18. Cumulative ET_r comparison between Penman-Monteith and the regression model using average weekly ET_r at Tribune, KS.

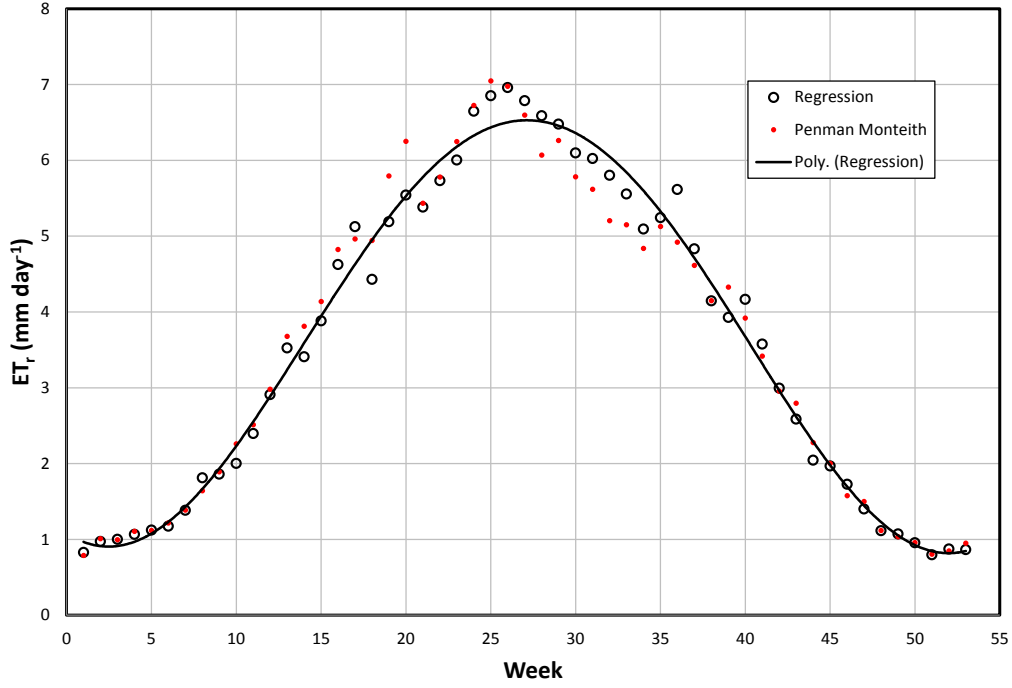


Figure 2.19. Average weekly ET_r comparison between Penman-Monteith and the regression model for Mead, NE.

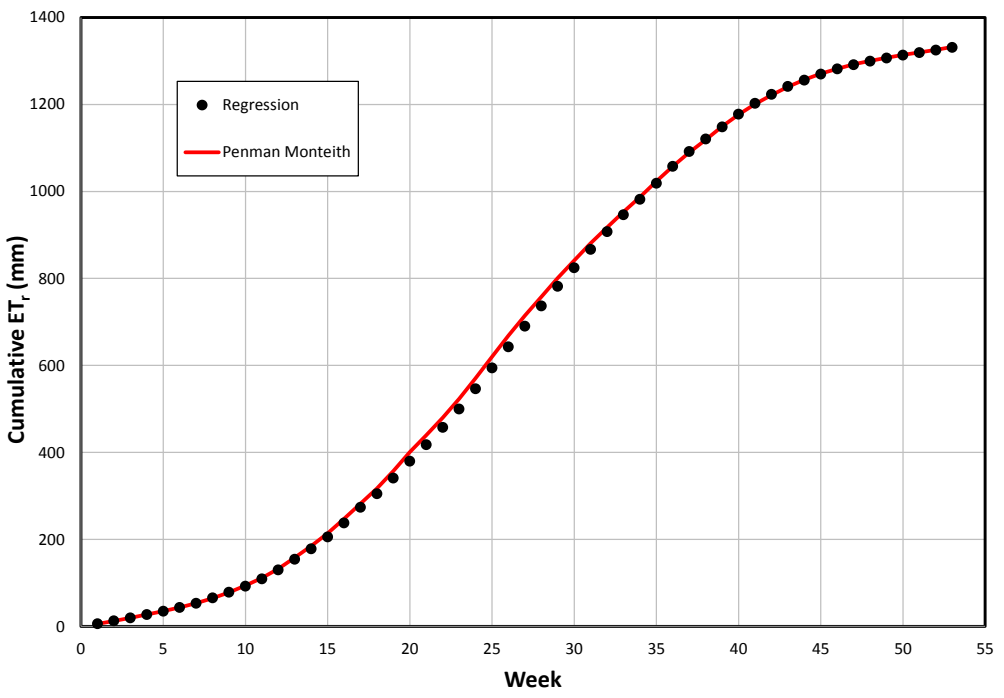


Figure 2.20. Cumulative ET_r comparison between Penman-Monteith and the regression model using average weekly ET_r at Mead, NE.

While there was variation for the stations shown in Figures 2.13-2.20, the regression model generally predicted ET_r with reasonable accuracy. The average predicted cumulative seasonal ET_r was always within ± 75 mm of the cumulative seasonal ET_r as computed using the Penman-Monteith method with the data measured at the weather stations. The difference between the methods was always less than 5% of the annual ET_r and was often much closer. The weekly average ET_r predicted by the regression model tracked throughout the year for each of these stations with the difference consistently less than 10% of the average weekly ET_r value.

Summary

Accurate weather data are important in modeling crop production. Weather stations are located throughout Nebraska, Kansas, and eastern Colorado; however, few stations collect data required to calculate reference crop ET using the Penman-Monteith method. None of those stations have operated long enough to facilitate analysis of regional water use trends over a prolonged period. Data available from weather stations that measured air temperature and precipitation covers a very long period but are not adequate for the Penman-Monteith method. The Hargreaves method can compute reference crop ET based on air temperature but research has shown that the Hargreaves method is not as accurate as the Penman-Monteith method. A methodology was developed to calibrate the Hargreaves method to the Penman-Monteith method.

A longitude dependent regression model was created for each month to convert Hargreaves reference ET for a short reference crop to ET_r for the Penman-Monteith method. The regression model accurately predicted the Penman-Monteith reference ET

throughout Nebraska, Kansas, and eastern Colorado; and allowed for the application of the regression model to the location of the NWS stations.

3. Calibration of the AquaCrop Simulation Model

Background

The relationship between water stress timing throughout the growing season and harvestable yield needs to be considered to develop an intraseasonal strategy for deficit irrigation. The number of combinations of water stress and timing, added to the unpredictability of local weather conditions, necessitate the use of crop growth modeling to simulate stressed conditions at different times throughout the growing season.

Numerous crop models are available to simulate intraseasonal conditions. Several considerations were involved in choosing the model to use. First and foremost, the model must be able to accurately replicate conditions that are experienced in the field. The next consideration was the types of crops that the model was able to simulate. Some models were developed for a single crop, while others are designed to apply to a wide variety of crops. In spite of confining the scope of this research to corn, a model that is capable of simulating multiple crops is desired. The protocol developed for intraseasonal irrigation management for corn can be used to develop similar strategies for other irrigated crops. This makes the ability of the model to simulate multiple types of crops highly desirable.

The model should be water and/or ET based. The basis of this research is concerned with the reaction of crops to varying levels of water stress at different times throughout the growing season. This leads to the desire for the model to incorporate reactions of the crop to water stress at different times throughout the growing season. It is important for the model to exhibit these characteristics, while at the same time reducing the number of crop specific parameters and thereby the overall complexity and uncertainty of the model.

AquaCrop Model

The Food and Agriculture Organization (FAO) developed the AquaCrop model (<http://www.fao.org/nr/water/aquacrop.html>). AquaCrop is a water-based model that simulates plant processes at the canopy level for a point in the field. It uses climatic, crop, field, and management inputs to simulate crop growth and hydrological processes shown in the water balance:

$$\Delta SW = P - RO - DP + I_{net} - ET \quad (3.1)$$

where:

P	precipitation (mm)
RO	runoff (mm)
DP	deep percolation (mm)
I_{net}	net irrigation (mm)
ET	evapotranspiration (mm)

AquaCrop has been successfully used to simulate crop growth in several parts of the world (Heng et al., 2009). Furthermore, AquaCrop can readily be adjusted for a wide variety of crop types including grains, tubers, and forage crops. It can also accommodate a wide variety of soils, field management conditions, irrigation techniques and strategies, and initial conditions.

Canopy cover plays an important role in simulating the ET consumption of water in the AquaCrop model. The development of the canopy cover is time based, but can be impeded and eventually reduced by water stress. The AquaCrop model splits ET into evaporation and transpiration. A crop coefficient method is used to relate ET_0 to crop transpiration. Unlike FAO-56 which uses fixed values (or values changing at a constant rate) for the crop coefficient, the crop coefficient used the AquaCrop model is related

directly to canopy cover which is adjusted for micro-advective effects (Reas et al., 2009) as shown in Equation 3.2.

$$Tr = K_{s_{sto}} Tr_x \quad \text{and} \quad Tr_x = (CC^* Kcb) ET_o \quad (3.2)$$

where:

Tr	Actual transpiration rate (mm day ⁻¹)
K _{s_{sto}}	Stomata closure stress coefficient
Tr _x	Maximum rate of transpiration (mm day ⁻¹)
CC*	Canopy cover adjusted for micro-advective effects
Kcb _x	Maximum crop transpiration coefficient
ET _o	Short crop reference ET (mm day ⁻¹)

Evaporation is simulated using the two stage process described by Ritchie (1972). Evaporation experiences a reduction proportional to crop canopy cover.

Evaporation can be further mitigated using mulches.

The simulation of stress by the AquaCrop model was a major selling point in choosing the model. AquaCrop simulated three different reactions by the crop to reduced levels of water in the root zone. Limited water during canopy expansion reduces the rate of expansion and potentially the total amount of leaf area developed. As the crop experiences lower levels of water in the root zone, the stomata in the leaf close reducing the rate of transpiration. The consequence of water stress is the early senescence of the crop. Early senescence stress and expansion stress reduce transpiration by reducing the canopy cover.

AquaCrop only considers net irrigation, so any application efficiency must be taken into account outside of the model. Precipitation comes directly from the weather data file. AquaCrop uses a modified curve number approach to estimate runoff. A curve number is a model input parameter antecedent moisture content II (AMC II). AquaCrop

then adjusts the curve number based upon soil moisture content from AMC I at permanent wilting point to AMC III at field capacity. The infiltrated water then fills the soil profile from the top layer down. A layer is filled to saturation before the next layer receives water from the event. Then, over the course of a few days the water between field capacity and saturation drains to the layer below it. Any water that drains out of the soil profile becomes deep percolation.

AquaCrop employs a convex stress coefficient to adjust water use rates to the amount of soil water stress. As the soil moisture content in the root zone moves from the upper threshold to the lower threshold for the stress coefficient, the effect of the stress is increased. The stress coefficients are calculated using equation 3.3.

$$0 \leq K_s = 1 - \frac{e^{D_{rel} * f_{shape}} - 1}{e^{f_{shape}} - 1} \leq 1 \quad (3.3)$$

where:

K_s	Stress Coefficient
D_{rel}	Relative depletion of the soil between the stress coefficient thresholds
f_{shape}	Shape factor of the stress function

Aboveground biomass production is dependent upon transpiration. They are related using the water productivity normalized for ET_0 and CO_2 (Steduto et al., 2009). The harvestable yield is computed by partitioning biomass into grain for corn using the harvest index.

Field Data

Data was acquired from the Carbon Sequestration Program conducted at the University of Nebraska Agricultural Research and Development Center near Mead, NE

over the period from 2002-2005. Three field sites were included in the field research. Continuous irrigated corn was grown on site 1. An irrigated soybean-corn rotation was grown on site 2. A rainfed soybean-corn rotation was grown on site 3. Aboveground biomass and leaf area index were measured throughout the growing-season using destructive sampling. Eight to nine samples were taken each year at each location.

Energy fluxes were measured every hour with an eddy covariance flux tower system at each site. Evapotranspiration was estimated using the latent energy (LE) measurement and from energy balance closure (EB). The energy balance uses conservation of energy to predict latent energy by measuring the difference between sources and other consumptions of the radiant energy. The energy balance was found by Suzyer and Verma (2009) using equation 3.4:

$$EB = R_n - S_H - S_S - S_m - S_c - S_p \approx LE \quad (3.4)$$

where;

R_n	net solar radiation (mm day ⁻¹)
S_H	Sensible Heat (mm day ⁻¹)
S_S	Storage in the soil (mm day ⁻¹)
S_m	Storage in mulch/crop residue (mm day ⁻¹)
S_c	Storage in the crop canopy (mm day ⁻¹)
S_p	Photosynthetic Storage (mm day ⁻¹)

Calibration

Output from the AquaCrop model was compared to the measured biomass, canopy cover, evapotranspiration, and yields. Many of the parameters used in AquaCrop are not measureable properties and need to be determined iteratively through calibration. The fitting process began with the fully irrigated sites. First the simulated canopy cover was fit to the measured LAI using the canopy development parameters in the model. Next the biomass was fit to the measured data using the water productivity and the

transpiration crop coefficient. At the same time the simulated evapotranspiration was compared to the latent energy and energy balance from the eddy covariance measurements. Finally, the harvest index was adjusted to match measured yields. This process was repeated frequently to tease out a set of parameters that produced results consistent with the measured data.

The rainfed sites were simulated after the model was parameterized to adequately simulate irrigated conditions. Stress coefficients were adjusted to fit simulations to the rainfed sites data. The simulation results were compared to measured data. Selected model parameters were adjusted until the model also simulated the rainfed conditions.

Environment: Weather Data

The climatic inputs used by AquaCrop are precipitation, short-crop reference evapotranspiration (ET_o), minimum and maximum daily air temperatures, and atmospheric carbon dioxide concentration as measured at Mauna Loa, Hawaii. The minimum and maximum temperatures and reference ET_o were taken from local weather stations. There are three AWDN weather stations located in close proximity to the research fields: Mead, Mead Turffarm, and Mead Agronomy Farm. The Mead Turffarm weather station was chosen due to the quality of the weather data, the distance from the field sites, and because the conditions surrounding the weather station are similar to those required for computing reference crop ET. The weather station data were processed using the PMETsz program described in Chapter 2.

The precipitation file was taken directly from measurements at the Carbon Sequestration Plots. The precipitation files from the fields include the irrigation water applied to sites one and two. The reported amounts of applied irrigation differed from the

amount measured in the field. The measured precipitation was cross referenced with the local weather stations and no precipitation was reported at nearby weather stations or at the rainfed site on the days of the irrigations. The measured amounts of irrigation were used as part of the precipitation file; thus, no irrigation file was needed for calibration.

Environment: Crop Parameters

The crop file contains crop-specific parameters pertaining to phenological stages, canopy and root development, evapotranspiration, water, fertility, and temperature stress (Steduto et al., 2009). In AquaCrop, canopy cover (CC) is an important component in calculating transpiration. It is a measure of what portion of the ground is covered by leaf area, and is directly related to leaf area index (LAI) by Equation 3.5:

$$CC = 1.005[1 - e^{-0.6 LAI}]^{1.2} \quad (3.5)$$

There are six parameters that determine the development of canopy cover: canopy growth coefficient (CGC), canopy decline coefficient (CDC), maximum canopy cover, days to emergence, days to senescence, and days to full maturity. The parameter values were iteratively determined by fitting the canopy cover to measured LAI from the Carbon Sequestration field sites. The CGC parameter controls the rate at which the canopy expands. It was determined to be 16.3% day⁻¹. The CDC controls how fast the canopy dies off at the end of the growing season and was determined to be 11.7% day⁻¹. By converting the maximum measured LAI to CC, the maximum canopy cover was found to be 96%. The days to emergence², max canopy, and senescence were determined to be 18, 118, and 144 days respectively. In 2005, these values were adjusted by +4 days

² The time required from sowing to reach 90% emergence.

for site 2 and +6 days to for site 3 to more accurately fit the measured CC values for the respective years.

The reproductive portion of the growth cycle consists of flowering, yield formation, and harvest index (HI) development. These are controlled by days to flowering (78), days in the flowering stage (13), and days to build up the HI (61). The flowering stage was triggered to start as the crop hit full canopy cover. Determinacy is linked to flowering. The maximum CC is reached by the middle of the flowering stage after which canopy expansion stops. The effective rooting depth was iteratively set at 1.8 m with maximum root depth achieved by the beginning of the flowering stage.

The maximum transpiration crop coefficient (K_{cb_x}) was calculated by comparing the measured energy balance from sites 1 & 2 to the standardized ET_o from the Mead Turffarm. The K_{cb_x} value was calculated separately for each year over the portion of the growing-season where the CC was equal to the maximum canopy cover (CC_x). Linear regression was used to determine the relationship. The K_{cb_x} values for each year were combined using a simple arithmetic mean, yielding a value of 1.16. A linear regression was applied to the same data points simultaneously with a resulting value of 1.15 (Figure 3.1). The small coefficient of determination illustrates that there is considerable variation on a daily basis and that the variation is not correlated to the daily reference crop ET. This value was used in further calibrating the model. These values compare favorably with the crop coefficients for the midseason as determined with the FAO-56 procedure for corn (Allen et al., 1998).

Evapotranspiration for the rainfed crops was too high when values from the irrigated calibration were used. A combination of parameters was selected for adjustment

that would lower ET in the rainfed sites without affecting the ET, yields, biomass, or canopy cover of the irrigated sites. A model similar to that for the irrigated sites was proposed; however, Kcb_x is for well-watered conditions while stress would be expected for the rainfed fields. Using the rationale that a lower plant population would have a lower maximum transpiration rate, the maximum transpiration coefficient (Kcb_x) was reduced for the rainfed condition to 1.05.

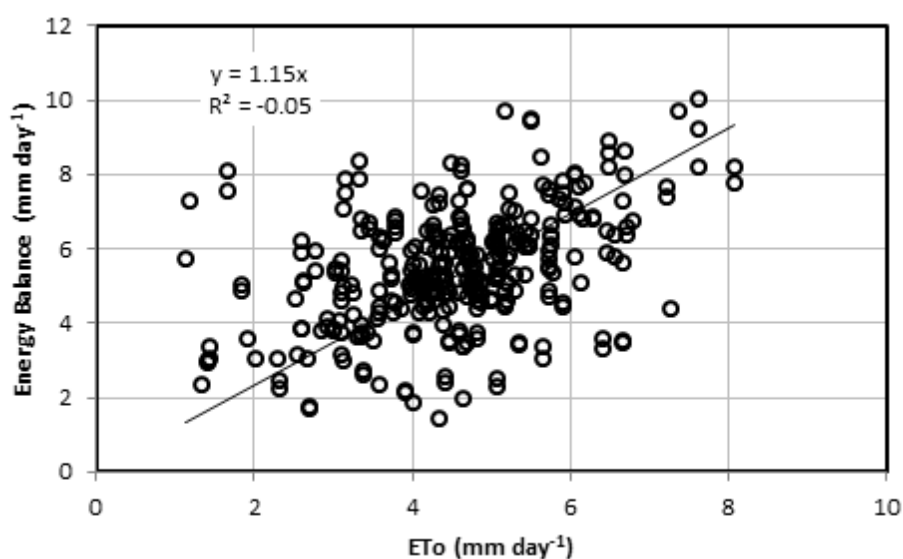


Figure 3.1. Comparison of energy balance measurements to short crop reference evapotranspiration derived from the Mead Turffarm weather station data. The examined period is over the time when $CC = CC_x$ for site 1 2002-2005 and site 2 2003, 2005.

Water productivity relates the daily transpiration divided by the daily short crop reference evapotranspiration (ET_0) to the amount of biomass that is produced each day. This value was found iteratively to be 26.0 g m^{-2} , slightly lower than the range suggested for the AquaCrop for a C4 crop. The harvestable yield produced by the crop is the product of the biomass times the harvest index (HI). The harvest index was found

iteratively to be 44% on a dry biomass basis for the grain. The HI becomes 51% when adjusted to a standard wet weight moisture content (MC) of 15.5%.

Water stress functions relate the relative soil water depletion to physiological processes. The upper and lower thresholds and the shape of the response curve are the parameters for each type of stress that define the sensitivity and severity of a depleted soil profile. The upper threshold determines when the stress begins to be experienced, while the lower threshold is the point at which the physiological process completely ceases to occur. The shape factor describes how the amplitude of the stress changes as the relative depletion moves from the upper threshold to the lower threshold. A more positive shape factor diminishes the effect of the stress for smaller relative depletions, but the effect of the stress increases more rapidly as the relative depletion approaches the lower threshold. A shape factor of 0 is linear, greater than 0 is convex, and less than 0 concave.

Each of the parameters was determined iteratively. For the expansion stress the upper threshold, lower threshold, and shape factor were 0.14, 0.72, and 2.9 respectively. For the stomata closure stress the upper threshold and shape factor were 0.59 and 6.0 respectively, while the lower threshold is set at the permanent wilting point (PWP). For the early senescence stress the upper threshold and shape factor were 0.69 and 2.7 respectively, while the lower threshold is set at the permanent wilting point (PWP). Expansion stress is relevant for a determinant crop only between emergence and the middle of the flowering stage.

Irrigation Management

AquaCrop provides several options for simulating irrigation. Standard options include determining net irrigation requirement, generation of an irrigation schedule based

upon management strategies, input an irrigation schedule, and rainfed scenarios. The irrigation scheduling option also provides alternatives for the application method: sprinkler irrigation, surface irrigation (basin, furrow, and border), and drip irrigation. The major difference between the application methods is the portion of the surface that is wetted during irrigation.

However, AquaCrop fails to incorporate application efficiency or uniformity. Net irrigation is applied directly to soil; any efficiency losses are already extracted. Application efficiency can be applied outside the model to determine gross irrigation application. Since AquaCrop is a single point model, uniformity is not considered.

The net irrigation requirement determines the amount of irrigation needed to keep the soil moisture content of the profile above a desired allowable depletion. Irrigation in the amount the relative depletion threshold is exceeded is applied every day.

AquaCrop can be used to develop an irrigation schedule based upon either management allowed depletion or a fixed time interval. The depletion level and depth of irrigation can be designated at different times throughout the simulated period to achieve management goals. An irrigation schedule can be directly inputted into the program by specifying the date and depth of the irrigation. The rainfed option was used to fit the AquaCrop model to the data from the Carbon Sequestration project. The measured precipitation files included the applied irrigation.

Field Management

The field management file allows for consideration of soil fertility, crop residue, and surface practices. It is assumed that the soil fertility is a non-limiting factor, and thus

was not considered. Runoff from the surface of the field was allowed, while no storage of water on top of the field was considered.

The non-growing season evaporation can be controlled using mulches or crop residue. Two properties of the mulch are needed: the amount of the soil surface that is covered, and the percentage reduction of soil evaporation. The crop rotation means that there was both soybean and corn residue on the ground at different times throughout the experiment. The assumption was made that the residue uniformly covered the soil surface and that the reduction of soil evaporation differed with residue type. The percent reduction in soil evaporation iteratively determined with AquaCrop was 18% and 50% for soybean and corn residue respectively.

Soil Properties

A single soil class was used to represent all the fields. The Natural Resource Conservation Service's Web Soil Survey was used to determine the soil types present in the fields. The fields consisted primarily of a Yutan silty clay loam, Tomek silt loam, and a Filbert silt loam. The method by Saxton (2005) was used to determine soil properties. Average values of 14%, 35%, 1.5%, and $1.8 \mu\text{m s}^{-1}$ were used for sand content, clay content, organic material content, and saturated hydraulic conductivity respectively. This yields a field capacity of 0.38, a permanent wilting point of 0.22, a saturated volumetric water content of 0.48, and a saturated hydraulic conductivity of 6.25 mm hr^{-1} . A NRCS curve number of 80 was used for the corn crop.

Simulation Initial Conditions

The initial soil water content can be inserted either as layers with constant volumetric water contents (VCW) or volumetric water contents at specific depths with

linear interpolation between the defined depths. At the Carbon Sequestration Program research plots the soil moisture content was measured every day at depths 0.10, 0.25, 0.50, and 1.00 m. The soil moisture content measured on the planting date for each individual year and site. The soil profile beneath 1.00 m was assumed to be constant at the water measured at 1.0 m.

Simulation Period

The simulation period was linked to the growing cycle; beginning on the planting date and ending on the day that the fully irrigated crop's green canopy cover was 0%.

Results

The AquaCrop model was able to accurately recreate field scenarios for 2002-2005. Biomass predictions had a linear regression slope of 1.00 and $R^2 = 0.98$. The canopy cover predictions had a linear regression slope of 1.00 and $R^2 = 0.94$. Yields had a linear regression slope of 1.00 and $R^2 = 0.84$ with a standard error of 0.72 Mg ha^{-1} . These results can be seen in Figures 3.2-3.4.

The comparison of simulated to measured biomass on the yearly basis resulted in regression slopes with a range from 0.88 to 1.15 with R^2 values greater than 0.99. The yearly canopy cover regression slopes ranged from 0.94 to 1.05 with R^2 values greater than 0.85.

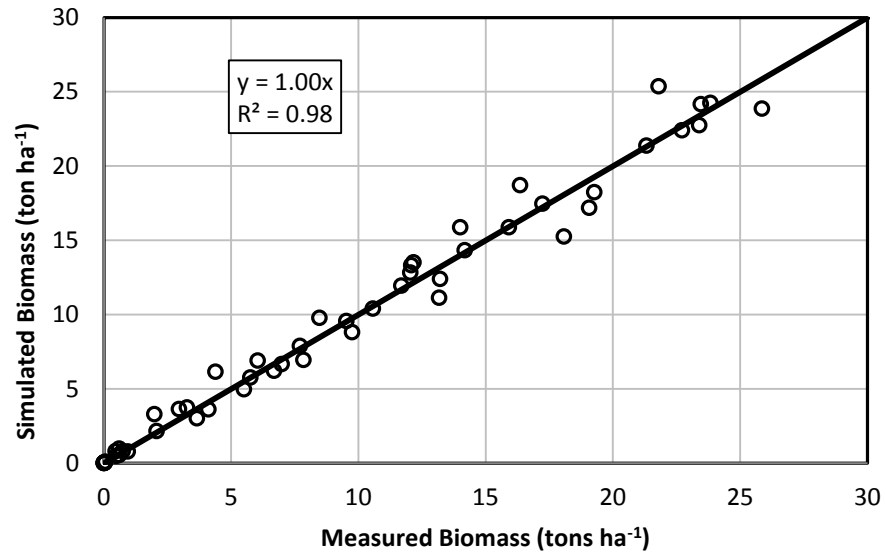


Figure 3.2. Measured vs. simulated aboveground biomass for years 2002-2005.

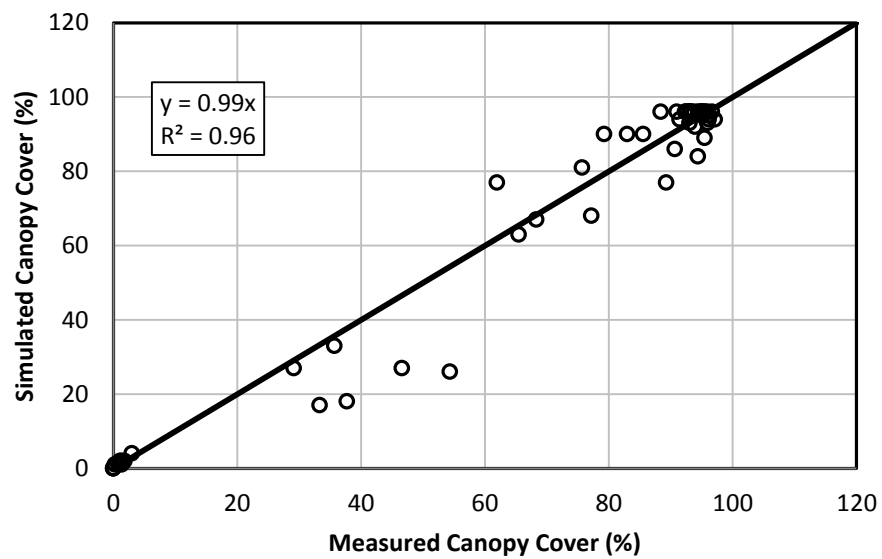


Figure 3.3. Measured vs. simulated canopy cover for years 2002-2005.

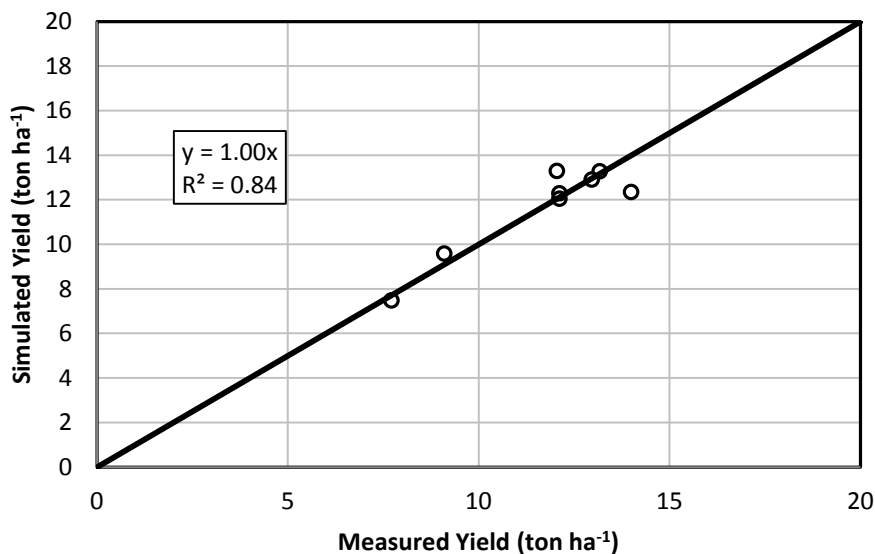


Figure 3.4. Measured vs. simulated yields for years 2002-2005.

In comparing the predicted evapotranspiration to the measured energy balance and latent energy AquaCrop was able to predict growth stage ET rates between the measured values in 60% of the simulated growth stages. Of the growth stages where the predictions were not within the measured ranges 65% were over predicted and 35% under predicted. About 20% of the error occurred in the pre-emergence stage and 30% occurred during senescence while simulation results for the majority of the growing season were very reasonable. Furthermore, the error was less than 0.2 mm day⁻¹ half of the time (Table 3.1), while the error was greater than 0.5 mm day⁻¹ 20% of the time.

Table 3.1. Comparison of predicted evapotranspiration (P ET) to energy closure (EC) and Latent Energy (LE) for growth stages for corn. All units are in mm day^{-1} .

Year	ET Measurement	Growth Stage					
		Pre-Emergence (mm day^{-1})	Vegetative 1 (mm day^{-1})	Vegetative 2 (mm day^{-1})	Flowering (mm day^{-1})	Grain Fill (mm day^{-1})	Senescence (mm day^{-1})
2002 Site 1	EC	2.9	3.6	6.9	6.6	4.8	2.1
	LE	1.8	2.6	5.5	5.5	4.6	2.1
	P ET	2.0	3.3	6.5	6.1	4.8	2.0
2003 Site 1	EC	1.9	3.1	6.0	5.3	5.0	2.1
	LE	1.6	2.7	5.2	4.9	4.8	2.1
	P ET	2.0	2.8	5.8	4.9	4.8	2.4
2004 Site 1	EC	2.2	2.9	4.6	4.7	4.6	3.7
	LE	1.5	2.3	4.0	4.4	4.3	3.5
	P ET	2.0	2.4	4.4	4.5	4.5	3.0
2005 Site 1	EC	2.3	2.8	6.3	6.5	4.5	2.6
	LE	1.6	2.2	5.7	5.6	4.0	2.2
	P ET	1.8	2.5	6.8	6.2	4.8	2.6
2003 Site 2	EC	2.6	3.9	6.6	5.6	5.1	2.6
	LE	1.9	3.3	5.7	5.0	4.7	2.3
	P ET	2.4	3.4	5.9	4.8	4.8	2.6
2005 Site 2	EC	2.2	3.2	6.7	5.9	4.6	3.1
	LE	1.6	2.9	5.9	5.2	3.9	2.6
	P ET	2.3	3.3	6.9	5.7	4.7	3.3
2003 Site 3	EC	2.0	3.2	5.4	4.5	3.3	1.4
	LE	1.9	3.0	5.0	4.1	2.9	1.2
	P ET	2.4	3.1	5.2	3.4	1.9	1.5
2005 Site 3	EC	1.7	2.8	5.1	5.4	4.0	2.9
	LE	1.3	2.5	4.8	5.1	3.6	2.5
	P ET	2.0	2.6	6.2	5.1	3.2	1.5



Under
Predict



Over
Predict

Seasonal cumulative evapotranspiration shows a consistent trend. The predicted evapotranspiration lies between the measured latent energy and energy balance closure curves most of the time. The slopes of the three ET curves appear to be relatively parallel during the growing season. Exceptions occur in the middle of June for all three sites in 2005 when the predicted ET rate increases at a faster rate than either of the two measured values. The ET for the rainfed crops differs towards the end of the growing season when the model predicts that the profile runs out of readily available water. The seasonal cumulative evapotranspiration curves can be seen in Figures 3.5-3.12.

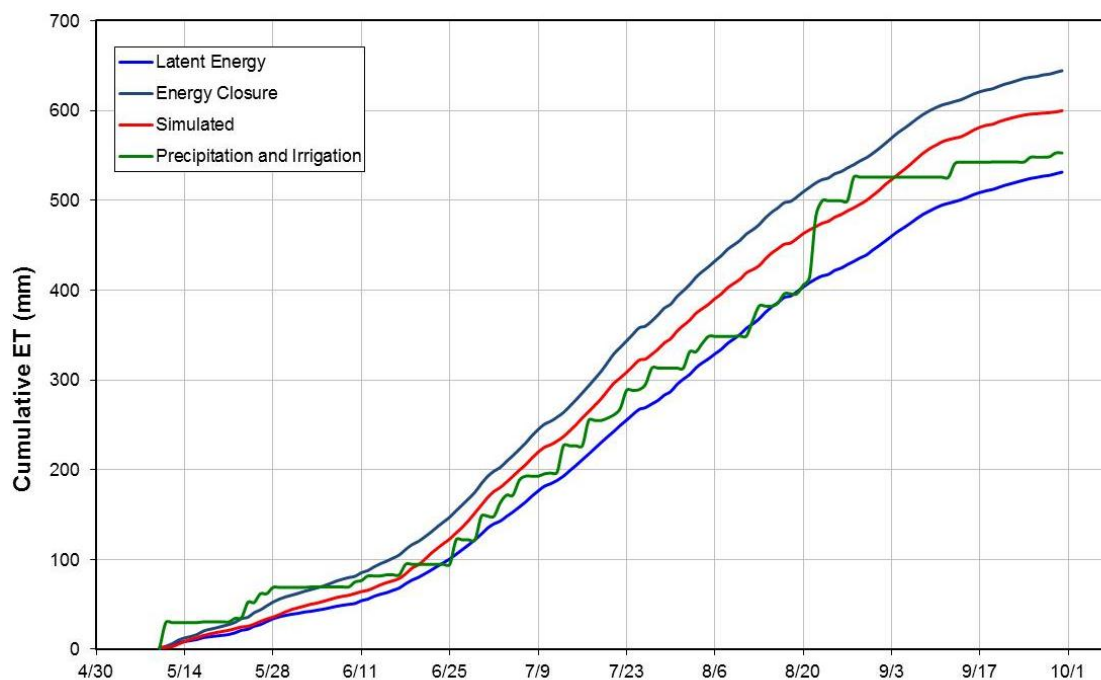


Figure 3.5. Cumulative predicted and measured evapotranspiration for continuous irrigated corn at Site 1 near Mead, NE in 2002.

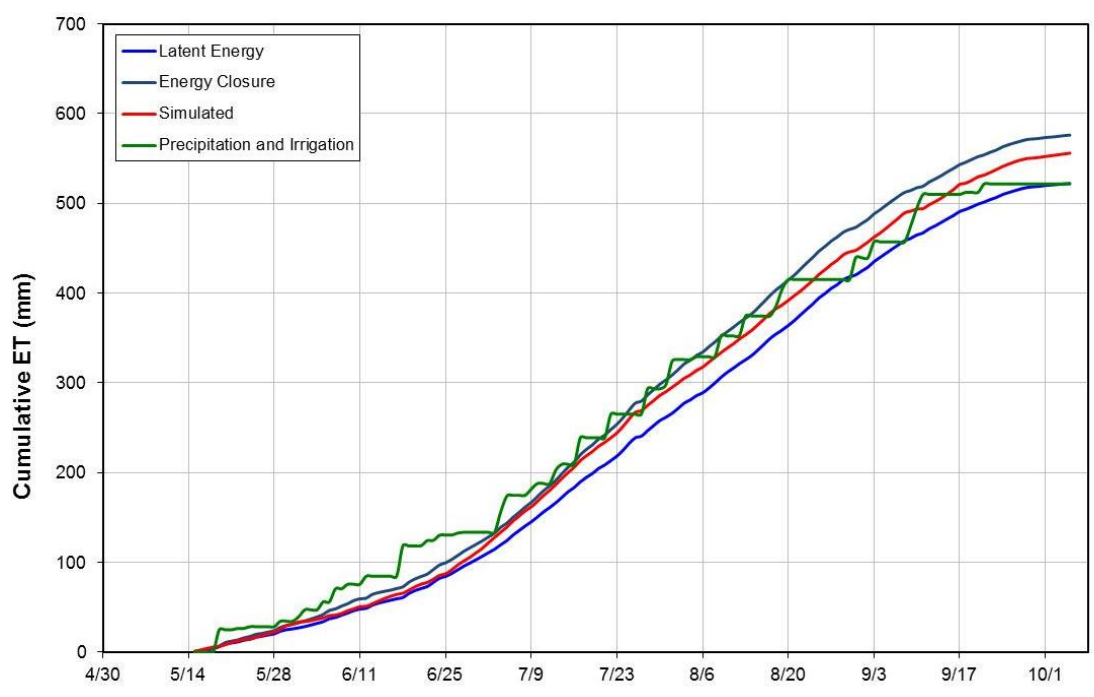


Figure 3.6. Cumulative predicted and measured evapotranspiration for continuous irrigated corn grown at Site 1 near Mead, NE in 2003

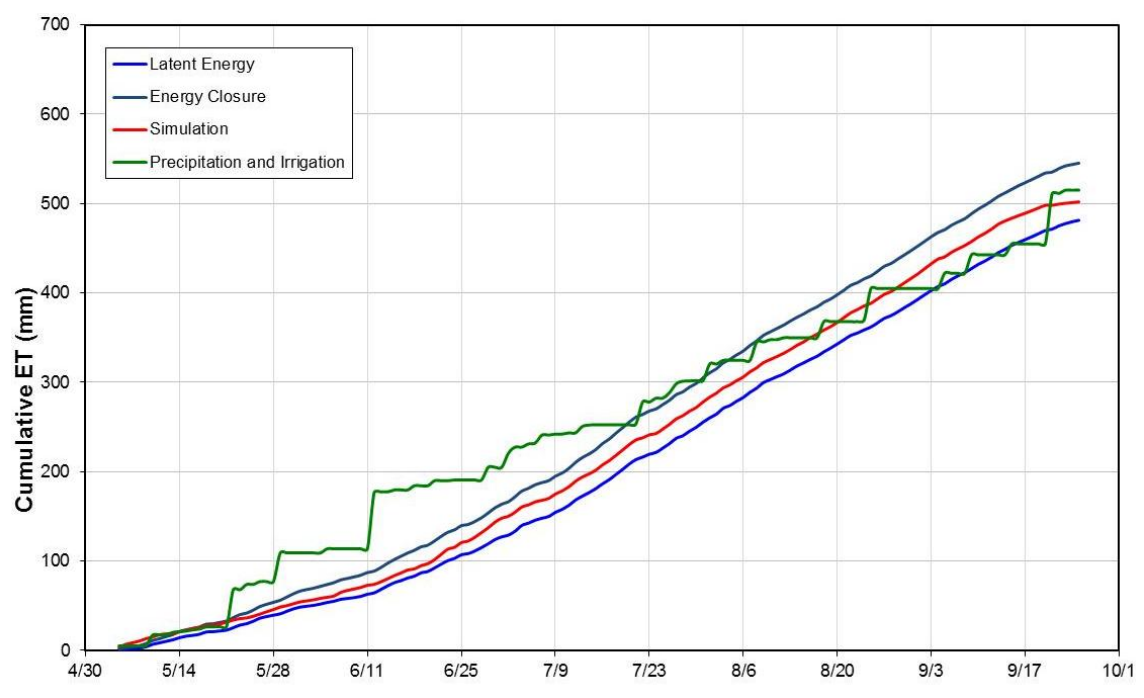


Figure 3.7. Cumulative predicted and measured evapotranspiration for continuous irrigated corn grown at Site 1 near Mead, NE in 2004.

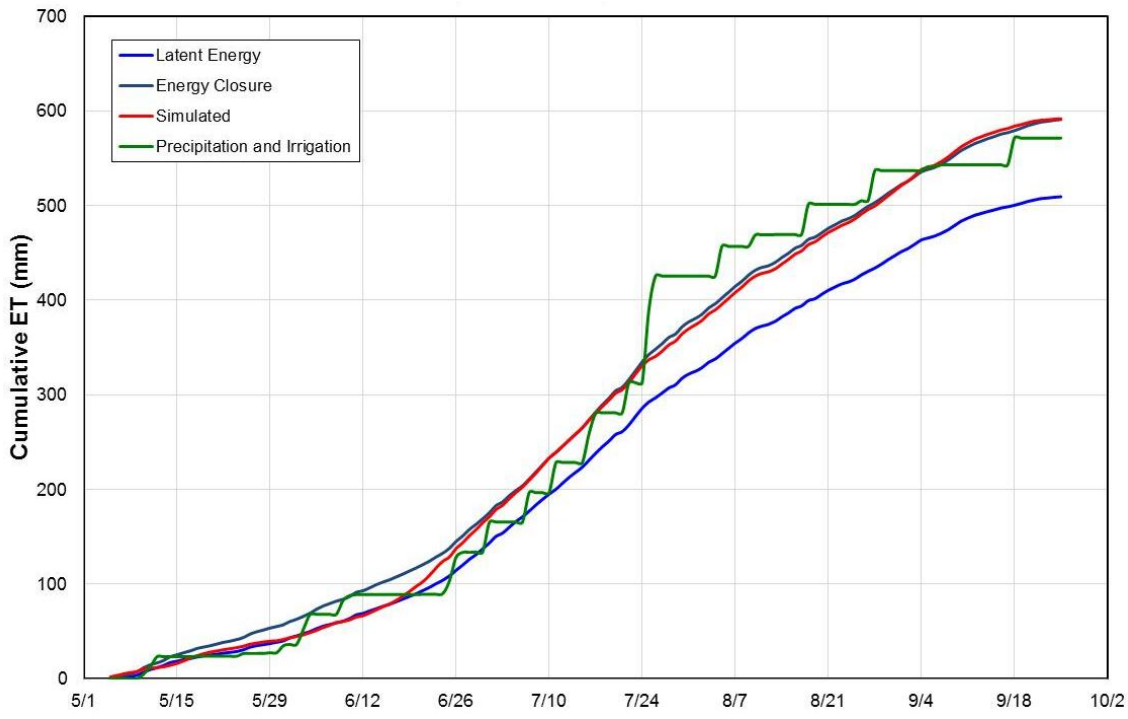


Figure 3.8 Cumulative predicted and measured evapotranspiration for continuous irrigated corn grown at Site 1 near Mead, NE in 2005.

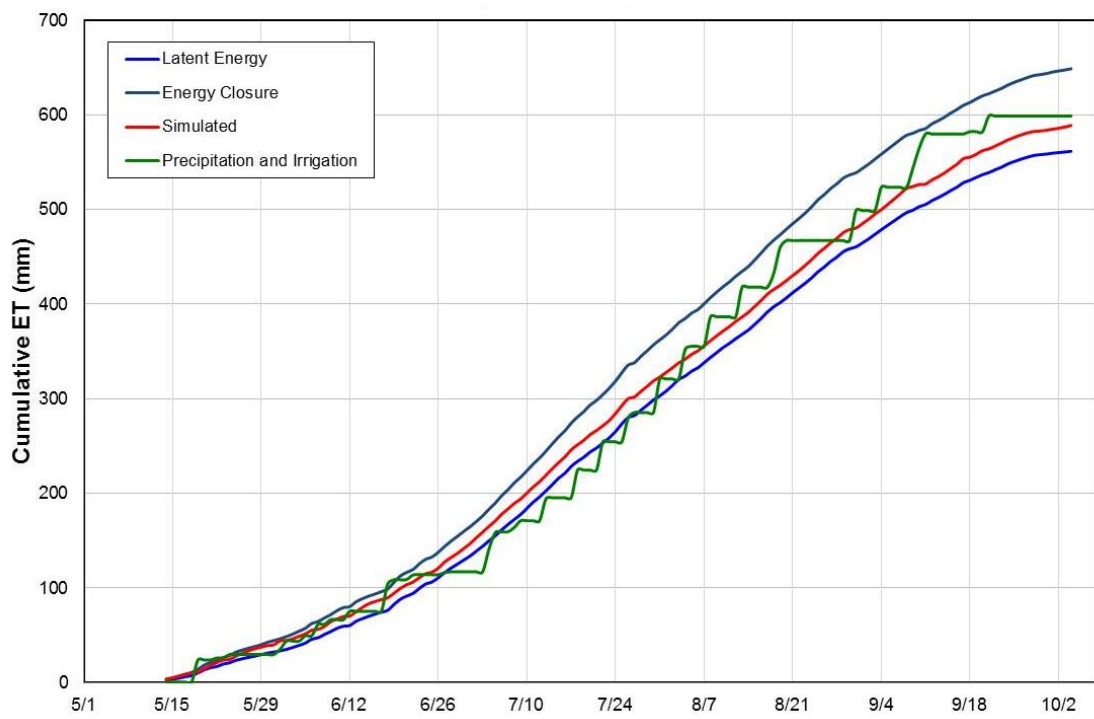


Figure 3.9. Cumulative predicted and measured evapotranspiration for irrigated corn in a corn-soybean rotation grown at Site 2 near Mead, NE in 2003.

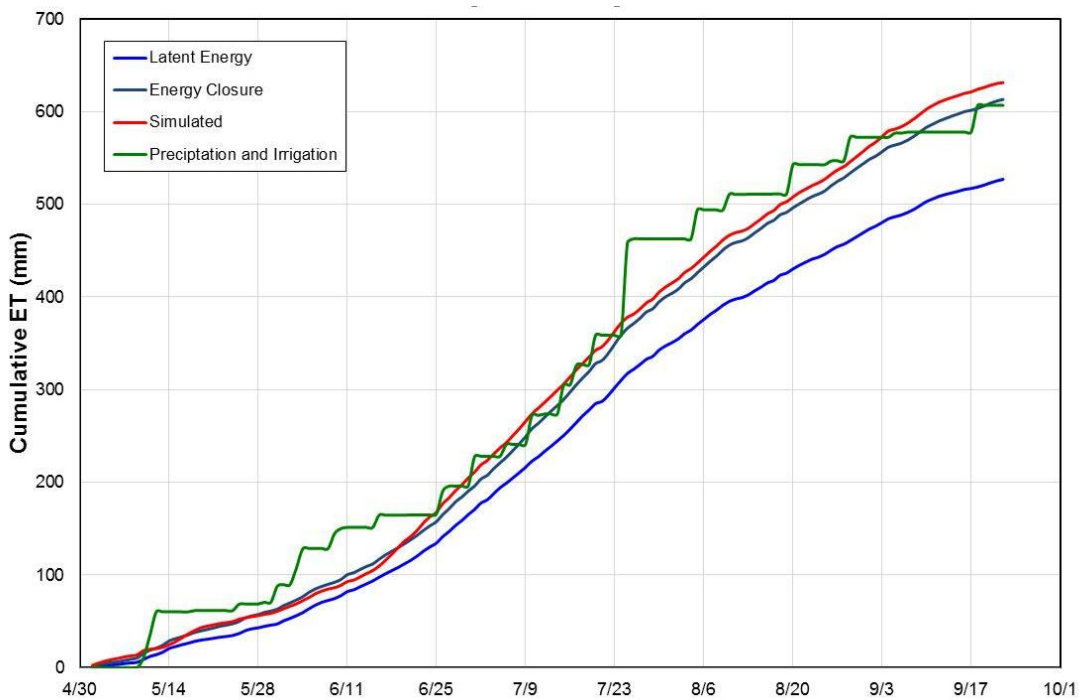


Figure 3.10. Cumulative predicted and measured evapotranspiration for irrigated corn in a corn-soybean rotation grown at Site 2 near Mead, NE in 2005.

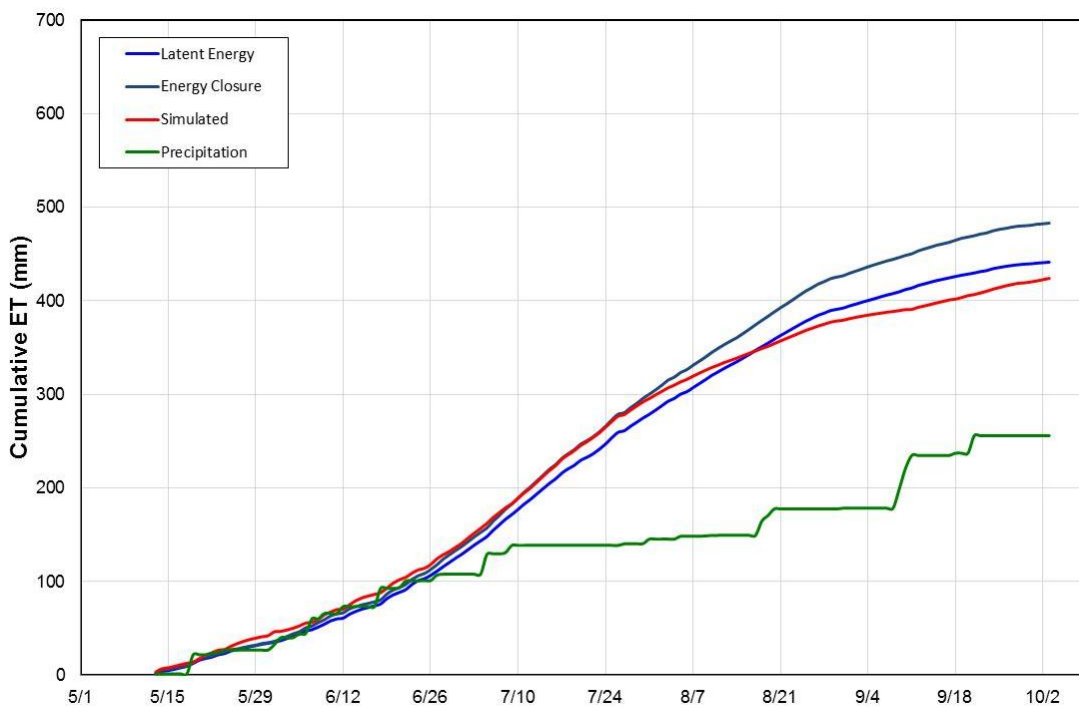


Figure 3.11. Cumulative predicted and measured evapotranspiration for rainfed corn in a corn-soybean rotation grown at Site 3 near Mead, NE in 2003.

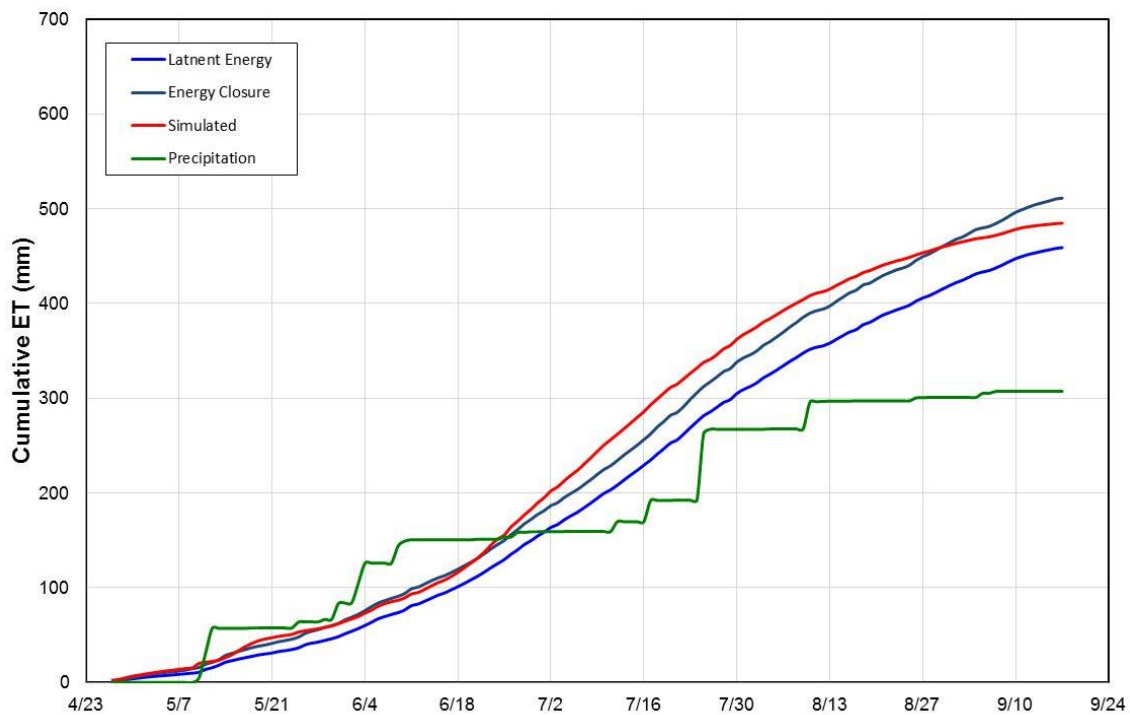


Figure 3.12. Cumulative predicted and measured evapotranspiration for corn in rainfed corn-soybean rotation grown at Site 3 near Mead, NE in 2005.

Conclusions and Discussion

AquaCrop was able to accurately simulate the field experiments. Predictions of biomass, canopy cover, and yields were for the most part within 10% of the measured value. Predicted evapotranspiration tracks between the measured latent energy and energy closure patterns. The relative slopes of the cumulative curves appear to be parallel for a majority of the time for each site and year.

Further consideration should be made to improve the accuracy of the model under stressed conditions. Only two years of rainfed cropping during the experiment experienced stressed conditions. Additional data points would help ensure the model's robustness. Furthermore, experiments should be conducted to look at rainfed irrigated crops at the same population, as opposed to rainfed cropping with a reduced population which was the case at site 3.

Further investigation of the root depth and initial soil moisture content has the potential to improve the quality of the model's output. Measurements of soil water content stopped at 1.00 m, yet the root depth exceeded this amount. Linking the simulations to the growing season fails to take into account the effects of potential mining of the soil profile the previous year and the effects of the non-growing-season on water content in the soil profile. Because the measurements are limited to depths above one meter, these simulations may have provided more water higher in the profile than was actually there. This could lead to using a deeper root zone. By using a deeper root zone and different distribution of water the crop would not have access to the water deeper in the profile until a later point in time; potentially moving transpiration from earlier to later in a given growing season.

Error can be due to the difference between the scopes of measurements compared to the scope of the model. AquaCrop essentially models what is occurring at a single point in the field. Meanwhile the Eddy-Covariance towers are measuring fluxes which require large flat areas with uniform vegetation (Rana and Katerji, 2000). Hydrologic process such as water moving into or within the field can be captured by field instrumentation, but were not considered in the modeling process.

As with any model, there is going to be some degree of error. Continued manipulation of the model and parameter adjustment could potentially improve the quality of the output. This model is highly non-linear which means that a multitude of combinations of parameters that yield suitable results, suggesting a need for caution when this model is applied to different situations. The robustness of this model was explored using a sensitivity analysis. However, once the model is calibrated to field conditions it can provide reliable estimates of ET during the season and during the dormant season to a lesser extent.

Acknowledgements

I would like to thank Dr. Shashi Verma, Dr. Andrew Suyker, and other members of the Carbon Sequestration Program for providing climatic and crop data for use in this project.

4. Sensitivity Analysis

A sensitivity analysis was performed to determine how the simulated results from AquaCrop were influenced by several parameters that were used to fit the model to the field data from the Carbon Sequestration project near Mead, Nebraska. The parameter values found during the model fitting and reported in the previous chapter were used as the base run to investigate the effect that changing the parameters has on the AquaCrop model output.

The sensitivity analysis was conducted for two scenarios; fully irrigated corn and rainfed corn. Both scenarios used climatic data from 2003 and a silty clay loam soil. The year 2003 was chosen because the rainfed crop experienced expansion, stomata closure, and early senescence water stress while the fully irrigated crop did not experience any stress. The fully irrigated scenario included the irrigation amounts that were measured at Site 1 and used the initial soil water content measured at Site 1. The rainfed scenario used the precipitation file and initial soil water content from Site 3. A constant population of 84,000 plants ha⁻¹ was used in both simulated scenarios as opposed to a reduced population for a rainfed crop.

The following parameters were altered during the analysis: canopy ageing, canopy growth coefficient (CGC), canopy decline coefficient (CDC), stress thresholds and shape factors for expansion, senescence, and stomata closure, harvest index, maximum crop coefficient (K_{cb_x}), root depth and shape factor, and water productivity. Different initial soil water contents, populations, and mulch effects were also examined. The impacts of changing a parameter were explored for the following AquaCrop outputs: yield, aboveground biomass, canopy cover, ET at different growth stages and for the

entire season. All comparisons are made to the base simulation. Tables 4.1-4.2 give an overview of the reaction of the model to changes in model parameters, showing the percent change in the desired output from changing an input parameter.

Table 4.1. Sensitivity of evapotranspiration to selected model parameters. Units are percent change in ET due to varying a parameter over the specified range.


	Parameter Range			Irrigation	Evapotranspiration												
	Base	Low	High		Pre-emergence	Vegetative		Flowering		Grain Fill		Senescence		Seasonal			
Canopy Ageing	0	0.05	0.3	Full	0.0	0.0	0.0	-0.2	-0.5	-3.6	-1.5	-8.6	-1.7	-13.0	-0.6	-4.1	
				None	0.0	0.0	0.0	0.0	-0.3	-1.8	-0.4	-1.1	1.0	6.3	0.0	0.1	
CGC	16.3	15.3 (-6.1%)	17.3 (+6.1%)	Full	0.0	0.0	-2.6	2.3	0.0	0.0	0.0	0.0	0.0	0.0	-1.2	1.1	
				None	0.0	0.0	-1.5	1.2	4.3	-3.3	4.9	-4.6	6.7	-4.0	0.5	-0.4	
CDC	11.7	10.7 (-8.5%)	12.7 (+8.5%)	Full	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.3	-4.6	0.6	-0.5
				None	0.0	0.0	0.0	0.0	0.0	-0.3	3.4	-3.0	15.0	-3.7	1.5	-0.6	
Expansion Stress Lower Threshold	0.72	0.67 (-6.9%)	0.77 (+6.9%)	Full	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				None	0.0	0.0	-0.1	0.0	0.8	0.0	0.4	-0.2	0.3	-0.7	0.1	0.0	
Expansion Stress Shape Factor	2.9	2.0 (-31%)	4.0 (+38%)	Full	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				None	0.0	0.0	-0.3	0.3	1.5	-0.3	0.8	-0.6	1.7	-2.0	0.2	-0.1	
Expansion Stress Upper Threshold	0.14	0.1 (-29%)	0.2 (+43%)	Full	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				None	0.0	0.0	-0.4	0.3	1.0	-0.8	0.6	-0.6	1.3	-2.3	0.0	-0.1	
Harvest Index	44	42 (-4.5%)	46 (+4.5%)	Full	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				None	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.3	-0.3	0.0	0.0	
Kcb _x	1.15	1.05 (-8.7%)	1.25 (+8.7%)	Full	0.0	0.0	-7.1	7.2	-8.5	9.2	-8.8	8.6	-7.4	8.0	-7.3	7.4	
				None	0.0	0.0	-4.2	3.6	6.1	-5.8	15.0	-16.0	26.3	-2.7	1.5	-0.3	
Root Depth	1.8	1.6 (-11%)	2.0 (+11%)	Full	0.3	0.3	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
				None	0.0	0.0	-3.3	2.4	-18.0	17.5	-25.1	24.1	-1.0	26.3	-6.7	7.7	
Root Shape	1.3	1.0 (-23%)	1.5 (+15%)	Full	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				None	0.0	0.0	-0.5	0.2	2.3	-0.3	1.9	-0.4	2.7	-1.3	0.3	0.0	
Early Senescence Shape Factor	2.7	2.0 (-26%)	3.5 (+30%)	Full	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				None	0.0	0.0	0.0	0.0	-0.3	0.5	-6.8	7.0	-3.7	23.3	-1.0	2.5	
Early Senescence Upper Threshold	0.69	0.6 (-13%)	0.8 (+16%)	Full	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				None	0.0	0.0	-0.1	0.0	-4.1	1.0	-22.8	17.3	-3.3	45.0	-3.3	5.3	
Stomata Closure Shape Factor	6.0	5.0 (-33%)	4.0 (-17%)	Full	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				None	0.0	0.0	-0.1	-0.1	0.3	0.3	0.2	0.0	0.3	0.0	0.0	0.0	
Stomata Closure Upper Threshold	0.59	0.55 (-6.8%)	0.65 (+10%)	Full	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				None	0.0	0.0	-1.2	1.0	-3.8	9.9	4.9	-4.2	19.7	-3.7	0.9	0.8	
Water Productivity	26	24 (-7.7%)	28 (+7.7%)	Full	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				None	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.3	-0.3	0.0	0.0	
Effect of Mulch	50%	40%	60%	Full	15.1	-16.0	3.2	-3.4	0.0	0.0	0.0	-0.1	1.7	-1.5	2.6	-2.8	
	18%	0%	40%	None	12.3	-17.3	-0.3	-2.2	-4.6	14.9	-5.3	15.2	11.0	7.0	0.8	0.5	
Initial Soil Water Content	86	60 (-30%)	100 (+16%)	Full	-0.6	0.6	-0.7	0.0	0.0	0.0	-3.6	0.0	-4.2	0.0	-1.7	0.0	
				None	-2.8	1.2	-18.0	4.3	-38.2	25.6	-39.7	26.8	6.7	31.0	-19.0	10.4	
Population	84000	75000 (-10%)	90000 (+7.1%)	Full	0.0	0.0	-1.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	-0.4	0.3	
				None	0.0	0.0	-0.5	0.3	2.3	-0.5	1.5	-0.8	2.7	-2.0	0.3	-0.1	


Parameters that exhibit the largest negative changes.

Parameters that exhibit the largest positive changes.

Table 4.2. Sensitivity of crop responses to select model parameters. Units are percent change in output parameter due to varying an input parameter over the specified range.

	Parameter Range			Irrigation	Harvestable		Seasonal		Max Canopy	
	Base	Low	High		Yield		Biomass		Cover Reached	
Canopy Ageing	0	0.05	0.3	Full	-0.8	-4.6	-0.8	-4.6	0.0	0.0
				None	9.4	37.7	0.0	0.0	0.0	0.0
CGC	16.3	15.3 (-6.1%)	17.3 (+6.1%)	Full	-2.0	1.7	-2.0	1.7	0.0	0.0
				None	36.6	-22.2	-0.7	0.3	-1.0	1.0
CDC	11.7	10.7 (-8.5%)	12.7 (+8.5%)	Full	0.4	-0.3	0.4	-0.3	0.0	0.0
				None	40.7	-26.7	2.4	-1.4	0.0	0.0
Expansion Stress Lower Threshold	0.72	0.67 (-6.9%)	0.77 (+6.9%)	Full	0.0	0.0	0.0	0.0	0.0	0.0
				None	-0.5	0.0	-0.6	0.2	-1.0	1.0
Expansion Stress Shape Factor	2.9	2.0 (-31%)	4.0 (+38%)	Full	0.0	0.0	0.0	0.0	0.0	0.0
				None	-0.9	0.4	-0.9	0.4	-1.0	1.0
Expansion Stress Upper Threshold	0.14	0.1 (-29%)	0.2 (+43%)	Full	0.0	0.0	0.0	0.0	0.0	0.0
				None	9.1	-3.0	-0.2	0.2	0.0	1.0
Harvest Index	44	42 (-4.5%)	46 (+4.5%)	Full	-4.6	4.5	0.0	0.0	0.0	0.0
				None	-3.1	6.2	0.0	0.0	0.0	0.0
Kcb _x	1.15	1.05 (-8.7%)	1.25 (+8.7%)	Full	-8.7	8.7	-8.7	8.7	0.0	0.0
				None	46.5	-37.1	6.2	-2.9	3.0	-1.0
Root Depth	1.8	1.6 (-11%)	2.0 (+11%)	Full	0.0	0.0	0.0	0.0	0.0	0.0
				None	-47.2	60.0	-14.3	16.0	-2.0	3.0
Root Shape	1.3	1.0 (-23%)	1.5 (+15%)	Full	0.0	0.0	0.0	0.0	0.0	0.0
				None	31.5	-0.1	0.1	-0.1	-2.0	0.0
Early Senescence Shape Factor	2.7	2.0 (-26%)	3.5 (+30%)	Full	0.0	0.0	0.0	0.0	0.0	0.0
				None	-30.6	45.2	-2.7	5.8	0.0	0.0
Early Senescence Upper Threshold	0.69	0.6 (-13%)	0.8 (+16%)	Full	0.0	0.0	0.0	0.0	0.0	0.0
				None	-54.8	56.6	-9.9	14.6	0.0	0.0
Stomata Closure Shape Factor	6.0	5.0 (-33%)	4.0 (-17%)	Full	0.0	0.0	0.0	0.0	0.0	0.0
				None	-2.6	-1.1	0.0	0.0	0.0	0.0
Stomata Closure Upper Threshold	0.59	0.55 (-6.8%)	0.65 (+10%)	Full	0.0	0.0	0.0	0.0	0.0	0.0
				None	39.8	-28.2	1.9	0.4	0.0	0.0
Water Productivity	26	24 (-7.7%)	28 (+7.7%)	Full	-7.7	7.7	-7.7	7.7	0.0	0.0
				None	-7.7	7.7	-7.7	7.7	0.0	0.0
Effect of Mulch	50%	40%	60%	Full	0.0	0.0	0.0	0.0	0.0	0.0
	18%	0%	40%	None	-30.2	57.6	-5.8	14.4	-1.0	3.0
Initial Soil Water Content	86	60 (-30%)	100 (+16%)	Full	-1.7	0.0	-2.0	0.0	0.0	0.0
				None	-86.5	67.2	-45.1	21.4	-18.0	3.0
Population	84000	75000 (-10%)	90000 (+7.1%)	Full	-0.8	0.5	-0.8	0.5	0.0	0.0
				None	30.9	-3.1	-0.3	0.0	0.0	0.0

 Parameters that exhibit the largest negative changes.

 Parameters that exhibit the largest positive changes.

Major Influences on Model Output

Impacts on Evapotranspiration

Mulch and the initial soil water content had the largest effect on ET prior to emergence. Increased levels of mulch and drier initial soil conditions reduced ET prior to emergence. The largest influence on pre-emergence ET was due to the effect of mulch which exhibited an inverse relationship. For irrigated crops, a $\pm 10\%$ change in the effect of mulch (base 50%) changed ET by 15% to -16% prior to emergence. For rainfed conditions changing the mulch effect by +18 to -22% (base 18%) caused a change of pre-season ET by 12% to -17% respectively. Varying the fractional available soil water from 0.86 to 1.00 or 0.60 caused ET prior to emergence to vary by about $\pm 3\%$.

Vegetative ET was sensitive to several parameters. The parameters can be divided into those that affect both irrigated and rainfed scenarios, and those that only have an effect on the rainfed scenario. The parameters that had the largest influence on vegetative ET for both situations are CGC (a parameter change of $\pm 6.1\%$ resulted in ET variation of -2.6% to 2.3%) and K_{cb_x} (a parameter change of $\pm 8.7\%$ resulted in ET variation of -7.1% to 7.2%). Evapotranspiration in a rainfed system was strongly affected by the rooting depth where changing of the maximum depth by $\pm 11\%$ resulted in an ET variation of -3.3% to 2.4%. Changing root depth did not affect ET predictions for irrigated crops. A change in the initial soil water content (SWC_i) exhibited a large influence over vegetative ET for the rainfed scenario (30% reduction of SWC_i resulted in an 18% reduction in vegetative ET). Larger reductions in SWC_i exacerbated the reduction in vegetative ET for the irrigated and rainfed scenarios.

Several parameters influence ET during the flowering and grain fill stages. To affect both fully irrigated and rainfed scenarios the parameters that have the largest influence are K_{cb_x} and canopy ageing. In the irrigated scenario a change of $\pm 8.7\%$ for K_{cb_x} resulted in ET changes of -8.5% to 9.2% for the flowering stage and -8.8% to 8.6% for the grain fill stage. For the rainfed scenario the relationship inverted with changes of 6.1% to -5.8% for the flowering stage and 15% to -16% grain fill stage. Any increase to the canopy ageing coefficient reduces ET. The later in the growing season the greater the influence of the canopy ageing coefficient. Numerous parameters can have an influence over ET during these stages for the fully irrigated crop; however, the changes were experience during the more extreme changes in those parameters.

Parameters that displayed a greater level of influence over the rainfed crop included CGC, stress coefficient parameters, root depth and shape, the effect of mulch, initial soil water content and the plant population. The influence of the CDC is dependent upon whether early senescence has occurred. The parameters that had the largest influence on rainfed crop are SWCi (-40% TO 27%), root depth (a change of $\pm 11\%$ resulted in a change of -25% to 24%), the stomata closure upper threshold during the flowering stage (a change of -7% to 10% resulted in changes of -4% to 10%), and the early senesce upper threshold during grain fill (a change of -13% and 16% resulted in changes of -22% to 17% respectively). The parameters changed the accessibility of the water during the early growing season which changes the amount of water available later in the growing season as can be seen in Figure 4.1.

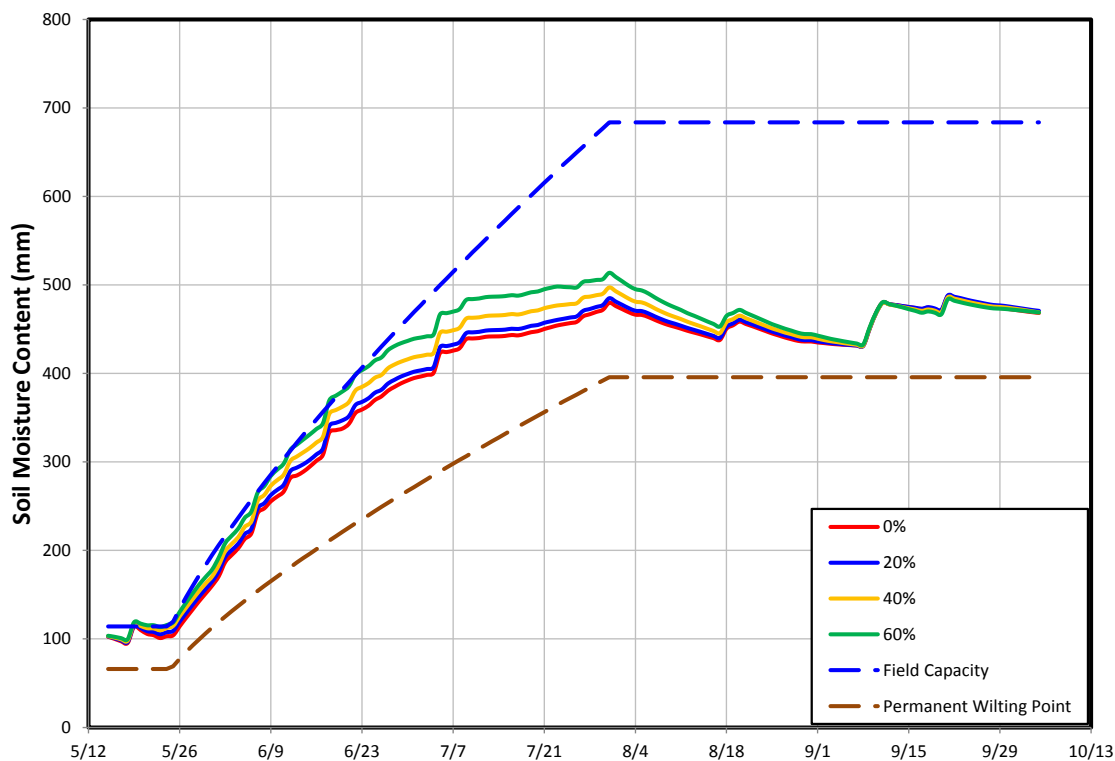


Figure 4.1. Change in soil moisture content from a change in the reduction of soil evaporation due to mulch.

Several parameters impacted ET during senescence. The K_{cb_x} parameter and canopy ageing continued to have a large influence over both the fully irrigated crop and the rainfed crop. The CDC became relevant for non-stressed crops during this period of the growing season. When the CDC is decreased by 8.5%, ET during senescence increased by 5.3% and 15% for the irrigated and rainfed crops respectively as the time period over which the green canopy senesced increased. Parameters that have an influence over the rainfed crops that do not affect the fully irrigated crop include the stress coefficient parameters, root depth and shape, initial soil water content, effect of mulch, and those parameters which sway the accessibility of water at different times during the growing season.

Crop Responses

Parameters that impacted canopy cover for the fully irrigated scenario are the CGC and CDC. Parameters that influence the amount of water used or the accessibility of water during the growing season can have an indirect effect on the canopy cover during rainfed scenarios. Early senescence stress coefficient parameters directly affect canopy cover.

Biomass production was influenced by parameters that affected the productive consumption portion of the ET, i.e. transpiration. When a parameter did not change the total seasonal ET, but just shifted the consumption of water within the season there were still changes in timing and rate at which biomass was produced. Water productivity was the only parameter that has a direct (linear) effect on biomass production without providing an effect on ET or canopy development.

Harvestable yields are also affected by parameters that influenced biomass production. Parameters that decreased the number of days before full maturity when the crop completely senesced (due to early senescence stress), expressed a larger influence on harvestable yields than other parameters. Parameters such as CDC and the early senescence stress coefficient can reduce the effect of stress and allow the harvest index to reach its maximum level. Other parameters such as K_{cb_x} and root depth change when water in the soil profile is accessible to the plant. The maximum harvest index was the only parameter that can affect harvestable yields without changing other model outputs.

The sensitivity analysis shows the interrelated dependency of the different parameters. Changing a parameter had several effects on the model output. Changing

another parameter can counteract the magnitude of the effect of the original parameter. For example, decreasing the upper threshold of stomata closure can shift the accessibility of water from earlier to later in the growing season increasing the harvestable yield. However, the increase in yields can be mitigated by decreasing the upper threshold for early senescence. Evapotranspiration consumption was transferred from earlier to later in the growing season. This interrelated dependency of parameters leads to non-unique solutions with the possibility of several combinations that result in an accurate depiction of field data.

Conclusions

Several parameters are utilized in AquaCrop that define the growth of a plant. Many of these parameters do not have a physical means that can be readily measurable in the field. From this arises a concern about the accuracy of the parameter values. The sensitivity analysis investigated how much the model results would change from a change in a parameter or how much the parameter could change without having an effect on model output.

The maximum crop coefficient exhibited the largest impact on yields, ET, and plant growth for both the irrigated and rainfed scenarios. Numerous parameters influenced the rainfed crop while having a minimal effect on the irrigated crop. The parameters that ET and crop production were most sensitive to were root depth throughout the growing season, the early senescence parameter after the grain fill stage began, and the stomata closure threshold during the flowering and senescence. But, the initial soil water content bore the greatest influence over both ET and crop production for the rainfed crop.

The sensitivity analysis can be used to develop conclusions about further calibration of the AquaCrop model for corn or for calibrating the model for another crop.

Suggestions for calibrating the model include:

1. Canopy cover for non-stressed conditions should be the starting point for the calibration. The canopy cover is an integral part of ET consumption in the AquaCrop model. Accurately modeling the canopy cover will reduce the number of iterations need to calibrate the model. Trying to calibrate ET first often results in a change in canopy cover which in turn changes ET.
2. Calibrate the non-stressed ET throughout the growing season. There are only a few parameters that affect non-stressed ET during the growing season. Several of which are either measurable such as Initial soil water content or are easy to back calculate from measured data such as Kcb_x .
3. Calibrate the canopy cover and ET consumption throughout the year for stressed conditions using those parameters that do not affect non-stressed conditions.
4. Calibrate biomass for non-stressed conditions using water productivity.
5. Calibrate yields for non-stressed conditions using the harvest index.

Several iterations may be necessary for steps 3-5 to reach the desired level of accuracy. ET and canopy cover are influenced simultaneously by several parameters.

The parameters also affect biomass and yields.

5. Intraseasonal Irrigation Management Strategy

In-Season Irrigation Management Strategies

There have been several proposals about how to allocate irrigation water throughout the growing season. A management allowed depletion (MAD) irrigation strategy stipulates depletion thresholds throughout the growing season. If the soil water content in the root zone falls below a threshold an irrigation event is triggered.

Numerous combinations of MAD strategies are possible. Klocke et al. (2004) used two MAD methods. The first allowed 50% depletion during the vegetative and reproductive stages and 60% depletion at maturity. The second was the water miser strategy. The Water Miser strategy, also called delayed irrigation, instructs producers to delay irrigation until two week before tasseling unless the soil water depletion exceeds 70%. During the reproductive stages a threshold depletion of 50% was used with the Water Miser strategy while 60% depletion was targeted at maturity.

ET replacement has been used as an irrigation management strategy to determine the effect of stress on corn (Tolk et al., 1998, and Lamm and Troojen 2003). The ET replacement strategy applies irrigation based upon ET consumption. Depending upon system characteristics, the rate at which ET is replenished is variable. The subsurface drip irrigation system in Colby, Kansas had the capability to deliver water daily. Meanwhile, at Bushland, Texas the ET consumption was allowed to accumulate to some threshold and then replenished all at once. Both studies also used partial ET replacement in which only a percentage of the ET consumption was replenished as a form of deficit irrigation.

Ultimately, the goal with deficit irrigation is to maximize the average value of the limited water resources. Strategically this is equivalent to applying water during the growing season until the marginal value of an additional unit of water returns less than the long-term average value of the water. The difficulty in determining the marginal value during the season is that the entire season must be analyzed to compute crop yield. This essentially requires two simulations with only a unit change in annual water application to evaluate the marginal change in crop yield. For a specific irrigation season this requires knowledge about the future climatic conditions which is not possible. Two alternatives for the lack of knowledge about future conditions are to either develop strategies for average future conditions, or to simulate optimal strategies for specific years to develop general guidelines.

The long-term average net return from deficit irrigation is also needed. The Water Optimizer program was developed to maximize the net return when the annual or multi-year supply of irrigation water is less than required for full yields. The results from the program provide an annual target for crop yields and the average annual net return. The target yield can serve as a surrogate to the average net return goal in determining the optimal intraseasonal irrigation schedule.

Objectives

1. Determine when during the growing season an additional unit of water is the most valuable.
2. Determine how much water is necessary to reach selected yield goals.
3. Develop a simple irrigation strategy to efficiently apply water to meet a yield goal.

Methodology

AquaCrop Model Setup

Curtis, Nebraska was chosen as the site to investigate different within season irrigation strategies. Curtis is located in the Republican River valley in southwest Nebraska. It is also located in the Middle Republican Natural Resource District. This is significant due to limits on the depth of water that can be applied as irrigation. Secondly, as opposed to Mead, Nebraska, Curtis tends to have higher seasonal ET values and lower amounts of precipitation. These aspects are important as we investigate irrigation and the relationship between irrigation, water stress, and yields.

Climatic data for Curtis was acquired for the AWDN weather station at Curtis from the High Plains Regional Climate Center. The data was conditioned and the short crop reference ET_o was calculated using the PMETSz program described in chapter 2. This data was used to create the precipitation, temperature, and reference ET files for the AquaCrop Model. The atmospheric carbon dioxide concentration measurements at Mauna Loa, Hawaii were once again used.

The growing season (May-August) precipitation was examined to determine the sample of years to use during this investigation. A stratified sampling technique was employed by dividing the years 1988-2008 into quarters based upon intraseasonal precipitation. One year was randomly chosen out of each stratum to ensure representation over the range of climatic conditions that exist in the region. Coincidentally, the years chosen for this investigation all occurred during the final 10 years of the investigation: 2002, 2003, 2005, and 2007. The intraseasonal precipitation amounts were 6.57 inches in 2002, 8.63 inches in 2003, 12.32 inches in 2005, and 16.39

inches in 2007. The NWS weather data was used to determine frequency that the amount of seasonal precipitation will be exceeded. The 16.39 inches in 2007 will be exceeded 17% of the time. Conversely, the 6.57 inches experienced in 2002 will be exceeded 99+% of the time. In the 60 years of available data at Curtis, 2002 was the driest during the growing season. The within season precipitation amounts for 2003 and 2005 will be exceeded 86% and 47% of the time respectively. The distribution of within season precipitation can be seen in Figure 5.1.

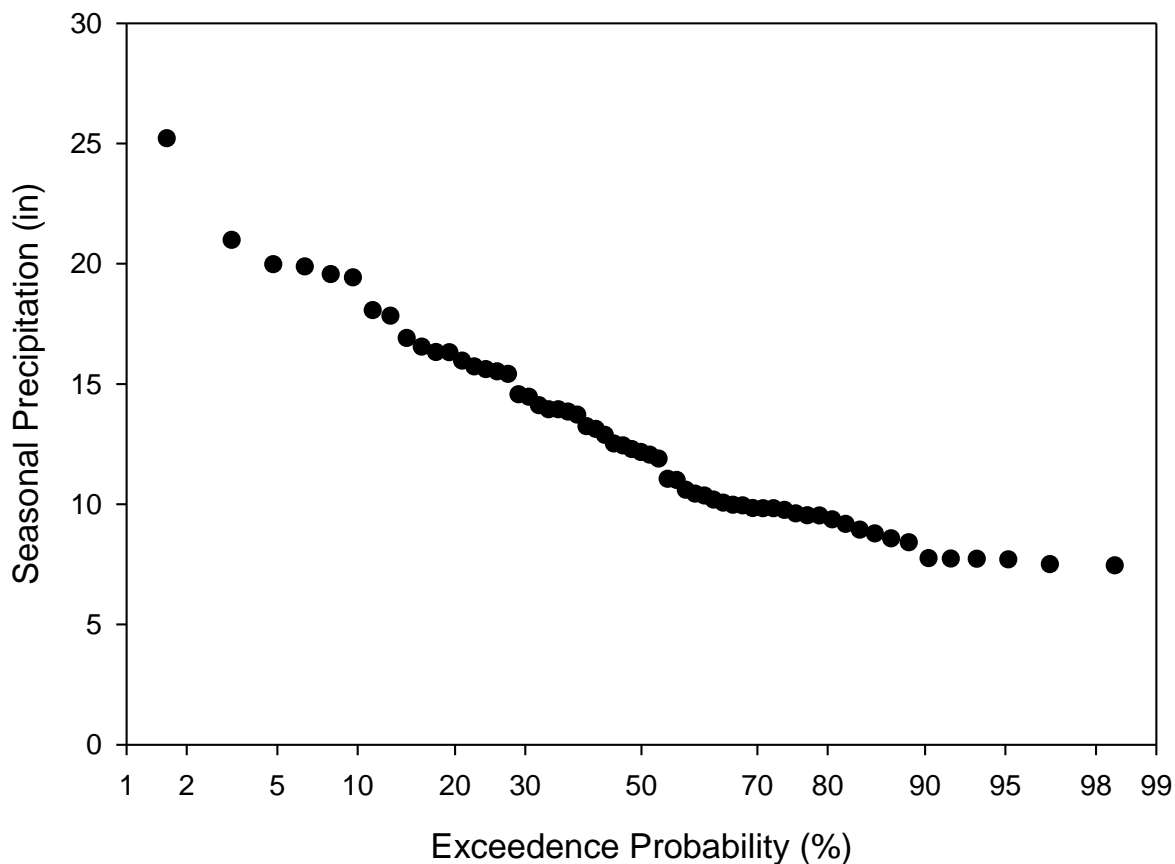


Figure 5.1. Seasonal rainfall exceedence probability curve for Curtis, NE 1948-2008.

A Holdrege Silt Loam soil, a soil that is prevalent in the area, was used for this investigation. Using the Natural Resource and Conservation Service's web soil survey, the physical properties of the soil were acquired. For a Holdrege Silt Loam soil, the clay

content is 22.8%, the sand content is 10.3%, the organic material is 0.84% and the bulk density is 1.48 g cm^{-3} . The Saxton equation (Saxton 2005) was used to determine the volumetric water content of the soil at saturation, field capacity, permanent wilting point to be 0.442 mm mm^{-1} , 0.334 mm mm^{-1} , and 0.144 mm mm^{-1} respectively. The saturated hydraulic conductivity was found to be 6.25 mm hr^{-1} .

The crop and field management files developed in Chapter 3 were used for all simulations.

Optimized Irrigation Schedule

The AquaCrop model was used to run a series of simulations varying the timing of irrigation, initial water content of the soil profile, and a nominal irrigation system capacity. Three system capacities were simulated by manually requiring a certain number of days between irrigation events. The system capacities that were investigated were 1 inch every 3, 4, or 5 days. These values correspond to capacities of $6.98 \text{ gal min}^{-1} \text{ acre}^{-1}$, $5.24 \text{ gal min}^{-1} \text{ acre}^{-1}$, and $4.19 \text{ gal min}^{-1} \text{ acre}^{-1}$ using an application efficiency of 90%. All three capacities were investigated for each of the four years using an initial soil water content of 75% of total available water. However, three initial water contents were investigated: 50%, 75%, and 90% of total available water. All three initial soil water contents were investigated using a system capacity of 1 inch of net irrigation applied every 3 days. These initial soil water contents correspond to 6.75 inches, 10 inches, and 12 inches of available water in the maximum root zone (5.9 ft) respectively. The initial water in the soil profile was distributed uniformly at all depths.

Initially the rainfed crop was simulated. The model output was recorded. Beginning 21 days after planting, one inch of net irrigation was applied at 10-day

intervals until the crop no longer displayed green canopy cover. The marginal yield resulting for each 10-day interval was examined and the maximum marginal yield was identified. Additional simulations were conducted to identify the specific day within the 10-day interval that generated the greatest marginal yield. The model output was recorded. This irrigation event was used as the base run for determining the optimal second irrigation.

The soil water depletion has a strong impact on yield; thus, the application of 1 inch of water that generated the highest marginal yield gravitated towards days where a precipitation event occurred, as long as there was sufficient storage available in the root zone. When the soil can store the water from both the precipitation and irrigation events; the soil water depletion is relatively smaller than if the irrigation event occurred on a subsequent or preceding day. The smaller soil water depletion results in a diminished reduction of yield. Occasionally a marginal yield spike occurred early in the growing season that was not representative of irrigation events for other days surrounding the precipitation event. Irrigating on days when there was a small rain also minimizes the amount of evaporation that occurs from wet soil. This could also affect the marginal yield spike.

A couple of rules were developed to determine the quantity of net irrigation that could be applied on a given day. If less than 11 mm of precipitation occurred on a given day, 25 mm of net irrigation was applied. If the precipitation event is greater than 11 mm and less than 36 mm the difference between 36 mm and the precipitation amount was applied as net irrigation. The top layer of soil holds 11 mm of readily evaporable water. By wetting the soil a portion of the water is lost to non-productive evaporative

consumption. Applying water on a day with a small precipitation event reduces the number of times that the soil surface is wetted, thereby reducing the non-productive consumption. Reducing the amount of net irrigation in response to precipitation was done to be consistent in the analysis designed to evaluate the impact of adding an additional unit of water to the soil profile. If the precipitation event was greater than 36 mm, no irrigation was allowed on that day.

To find the second irrigation event, a series of simulations were conducted applying a unit of irrigation during a 10-day interval; the marginal yields were examined and additional simulations were applied to find the optimal day for the irrigation. This continued as long as the crop had not senesced to the point that there was no green canopy cover. Furthermore, the irrigation was not allowed to encroach upon capacity limits for days between the first and second irrigations. The closest days prior to and after previously determined irrigations, as limited by the nominal capacity, were also simulated with an additional unit of net irrigation. The marginal yield was examined for the irrigations throughout the growing season. Additional simulations were conducted to determine the day when an irrigation event produced the greatest marginal yield. The date with the greatest marginal yields was chosen as the next irrigation event, and used as the base for the next set of simulations. Figures 5.2-5.3 show the marginal yield for a unit of irrigation applied at several times throughout the growing season along with the green canopy cover and soil water depletion from the previously determined irrigation events.

If the next irrigation event occurred chronologically prior to the previous irrigation events by more than the capacity limitation, the next irrigation event was used

as part of a base run to double check that prior determined irrigation events are part of the yield maximizing irrigation strategy. If the next irrigation event occurred after or within the time period limited by systems capacity for prior irrigation events, then the next irrigation became part of the optimal irrigation strategy.

This process was repeated to find ensuing irrigation events. Determining the timing of additional units of irrigation continued until the seasonal yields reached the yield goal of 190 bushels per acre at 15.5% moisture content. As the seasonal yields approach 190 bushels per acre the marginal yields declined and became more consistent across the portion of the growing season that was still available for applying irrigation.

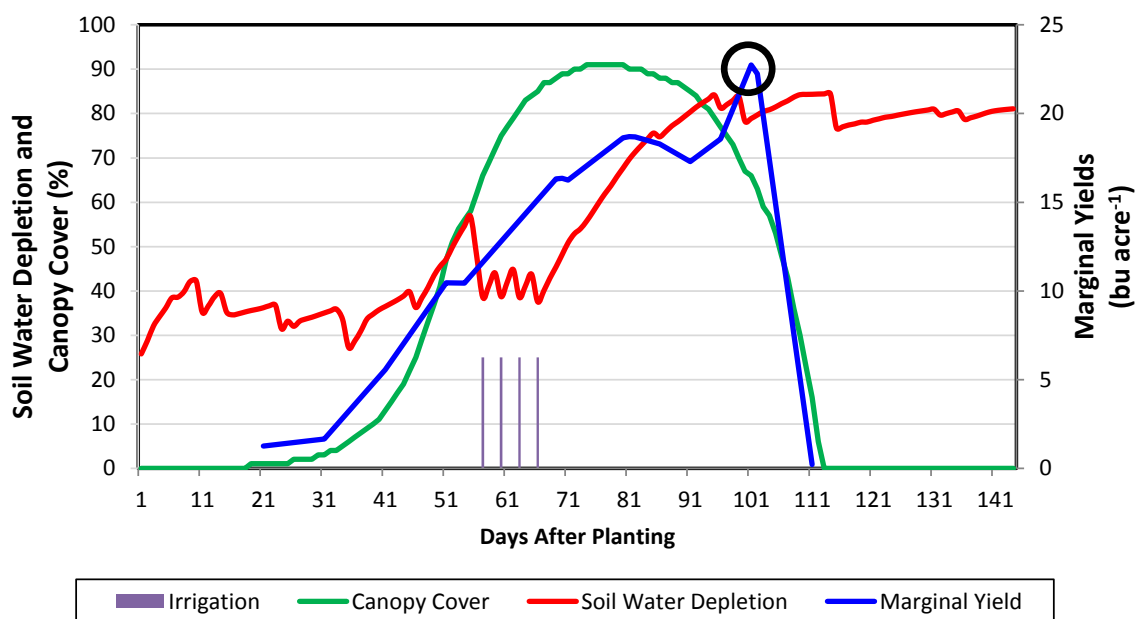


Figure 5.2. Choosing the 5th optimal inch of net irrigation in 2002 for a capacity of 1 inch net irrigation every three days and an initial soil water availability of 0.75.

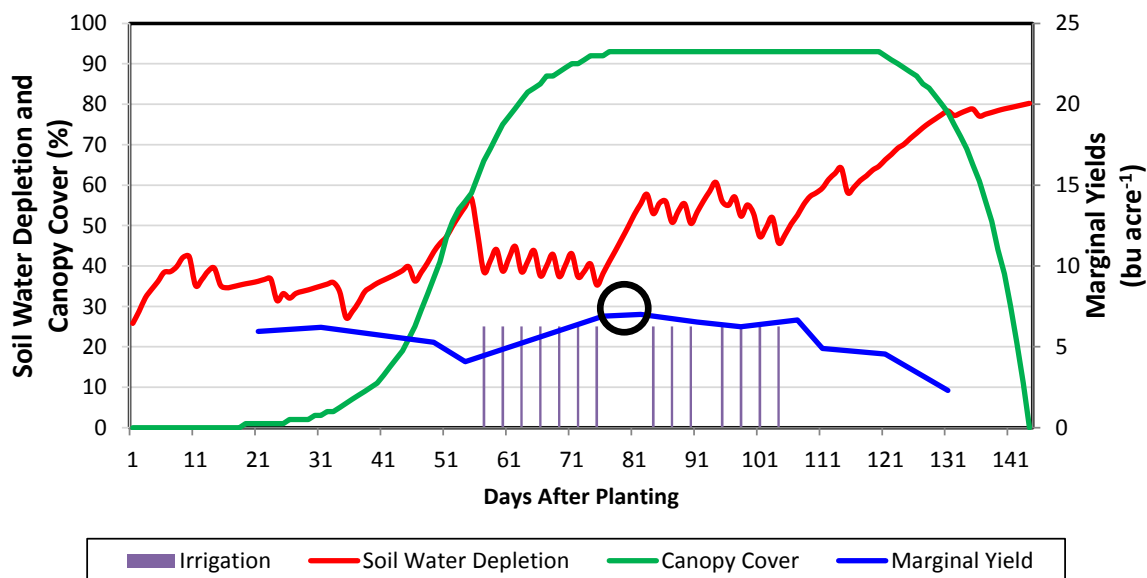


Figure 5.3. Choosing the 15th optimal inch of net irrigation in 2002 for a capacity of 1 inch net irrigation every three days and an initial soil water availability of 0.75.

Water Miser Strategy

The Water Miser strategy is defined as a management allowed depletion of 70% from planting to 68 days after planting (DAP) and then 50% depletion till the end of the growing season with an ending depletion goal of 60%. The Water Miser strategy was applied to each scenario that was simulated.

Results

The optimized and Water Miser strategies displayed many similarities especially for larger quantities of irrigation. Convergence of model output goes to the claim that as the volume of effective water applied increases, the importance of the timing of the irrigation decreases. Differences can be noted, if the year was dry during the early portion of the growing season, there was a tendency for the yields to diverge at the very end.

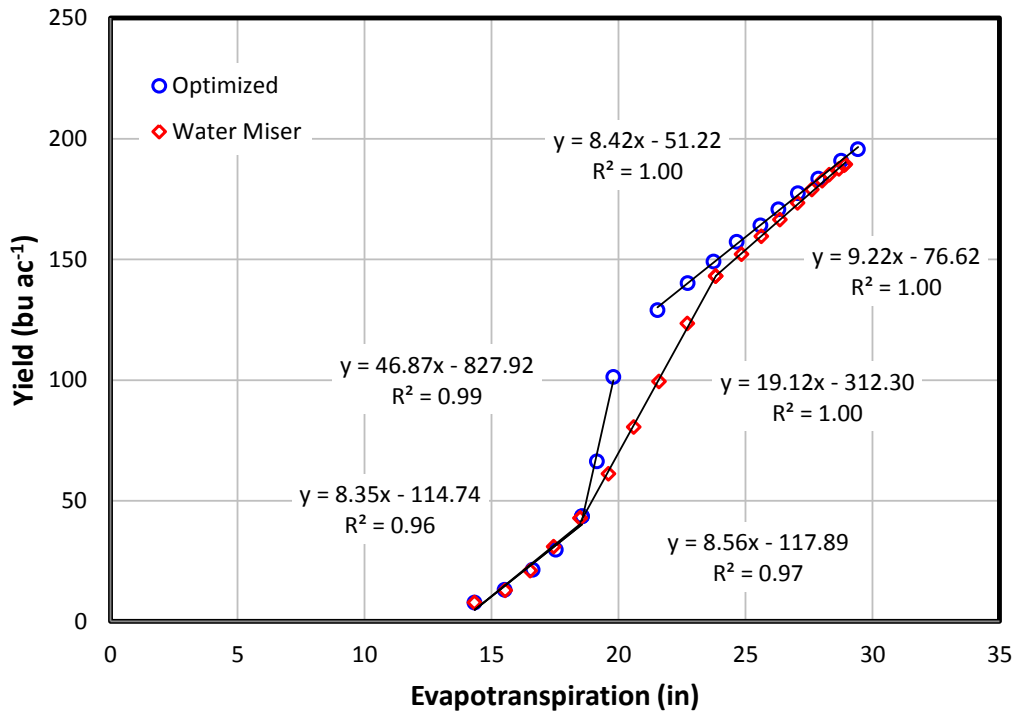


Figure 5.4. Comparison of yield and ET for 2002 with an initial water availability of 0.75 and a capacity of 1 inch of net irrigation applied in 3 days.

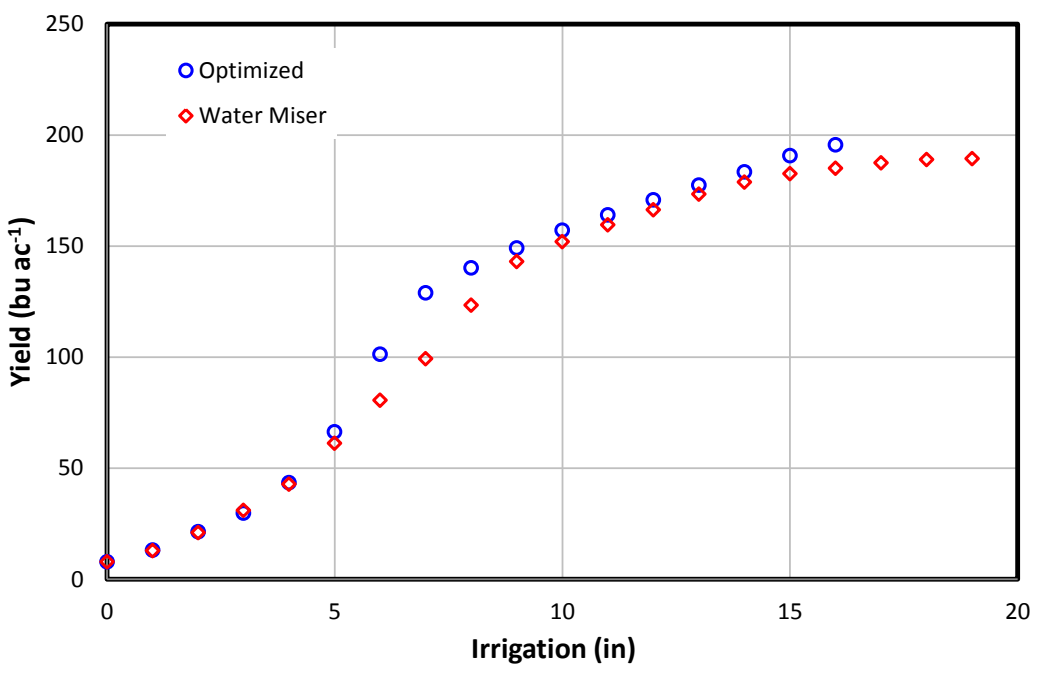


Figure 5.5. The comparison of yield and irrigation for 2002 with an initial soil water availability of 0.75 and a capacity of 1 inch of net irrigation applied in 3 days.

This can be attributed to an excessive amount of stress early in the growing season, reducing the maximum potential yield that the crop can obtain.

At lower levels of irrigation the ET lines and the irrigation production functions diverged for differing strategies illustrating the importance of irrigation timing for a limited supply of water. Several optimized and Water Miser irrigation and ET production function are illustrated in Figures 5.3-5.10, while Tables 5.1-5.4 show the timing of irrigations.

Table 5.1. Distribution of irrigation applications during 2002 growing season for the optimized distribution and Water Miser strategy: initial soil water availability of 75%, capacity 1 inch applied every three days, and simulated planting date of May 1.

Irrigation Number	Optimized		Water Miser	
	Days After Planting	Yield (bu ac ⁻¹)	Days After Planting	Yield (bu ac ⁻¹)
1	57	13	64	13
2	60	21	67	21
3	63	30	70	31
4	66	43	73	43
5	101	66	76	61
6	104	101	79	81
7	87	129	82	99
8	84	140	85	123
9	69	149	88	143
10	90	157	91	152
11	72	164	94	160
12	98	171	97	166
13	95	177	100	173
14	75	183	104	179
15	46	191	108	183
16	81	196	112	185
17	-	-	120	187
18	-	-	125	189
19	-	-	128	189

In 2002 the optimized process prescribed the application of 16 inches of net irrigation from 46-104 DAP with the final inch of water adding an additional 5 bu ac⁻¹. Meanwhile, the Water Miser strategy applied 19 inches of water and extend the irrigation season to 128 DAP. It should also be noted that for the final inch of net irrigation applied using the Water Miser strategy had a marginal product of 0 bu ac⁻¹. This was the product of allowing excessive stress during the early portion of the growing season combined with inadequate rules to end the irrigation season.

The production function shown in Figure 5.4.-5.5. displays some unique characteristics. Examining the ET production function, 3 distinct discernable regions were identified. The first and third regions exhibited yield increases from an increase in ET with approximately the same slope (~8.4); however this slope is probably too flat. The second region revealed a significant increase in the yield returns for an additional unit of ET (~46.9). The slope greatly exceeds what is expected at Curtis, NE (12-14).

For the optimized distribution, the first four irrigations were concentrated before the flowering stage. This minimized the stress the crop was subjected to during pollination and maximized the potential Harvest Index the crop could achieve. Furthermore, irrigations during vegetative stage increased the level of canopy cover. The next four irrigations occurred during the grain fill and exhibited the largest marginal yields. These irrigations extended the life of the crop to maturity, thereby allowing full harvest index development. Subsequent irrigations were used to diminish reductions in transpiration and increase canopy cover.

Similar inferences can be drawn from the sigmoidal shape of the irrigation production function. These characteristics were experienced for both the Water Miser

and optimized distribution methods and occurred during years when total seasonal precipitation was relatively small and the amount of soil water at the beginning of the growing season was depleted. A similar yield response was not found in a review of literature and may be unique to the AquaCrop model.

Table 5.2 Distribution of irrigation applications during the 2003 growing season for the optimized distribution and Water Miser strategy: initial soil water availability of 75%, capacity 1 inch applied every three days, and simulated planting date of May 1.

Irrigation Number	Optimized		Water Miser	
	Days After Planting	Yield (bu ac ⁻¹)	Days After Planting	Yield (bu ac ⁻¹)
1	80	63	66	59
2	83	82	69	72
3	86	104	72	87
4	102	118	76	105
5	105	147	81	126
6	89	156	85	142
7	56	164	88	161
8	62	172	93	169
9	108	179	96	176
10	65	186	99	183
11	111	192	106	189
12	-	-	109	195
13	-	-	113	200
14	-	-	116	202
15	-	-	121	204
16	-	-	126	204

In 2003 the optimized process prescribed applying 11 inches of net irrigation from 56-111 DAP, while the Water Miser strategy applied 16 inches of net irrigation over an irrigation season extended to 126 DAP. Once again the Water Miser strategy continued to apply irrigation water at the end of the growing season with a relatively low marginal yield, but the strategy produced an additional 12 bushels per acre. The temporal distribution of irrigations is shown in Table 5.6.

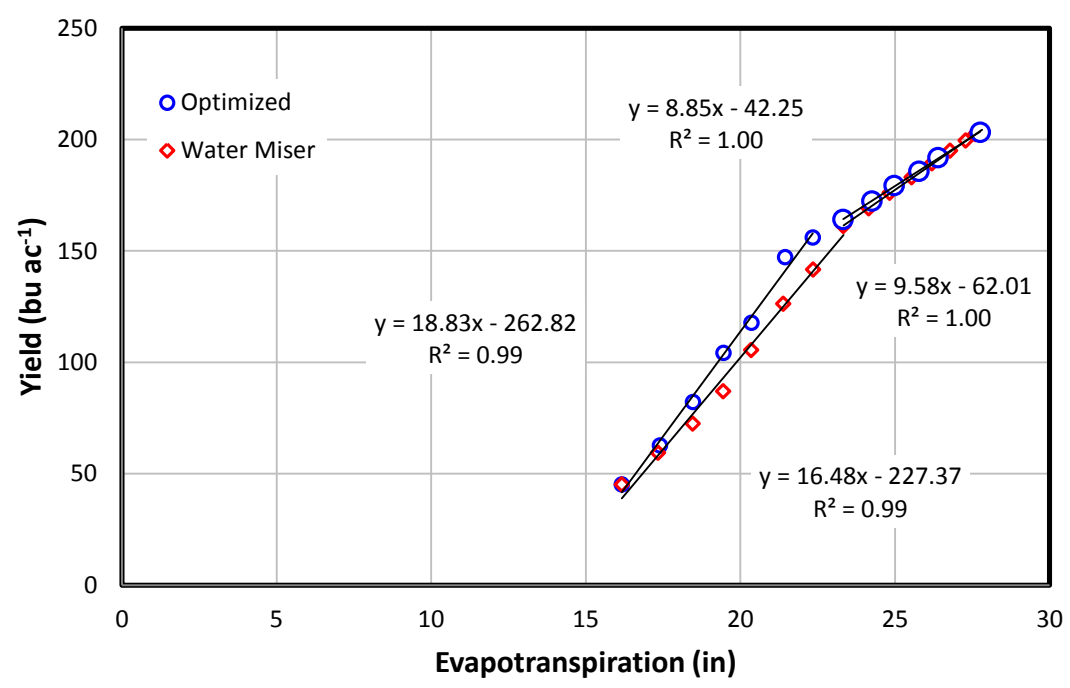


Figure 5.6. Comparison of yield and ET for 2003 with an initial water availability of 0.75 and a capacity of 1 inch of net irrigation applied in 3 days.

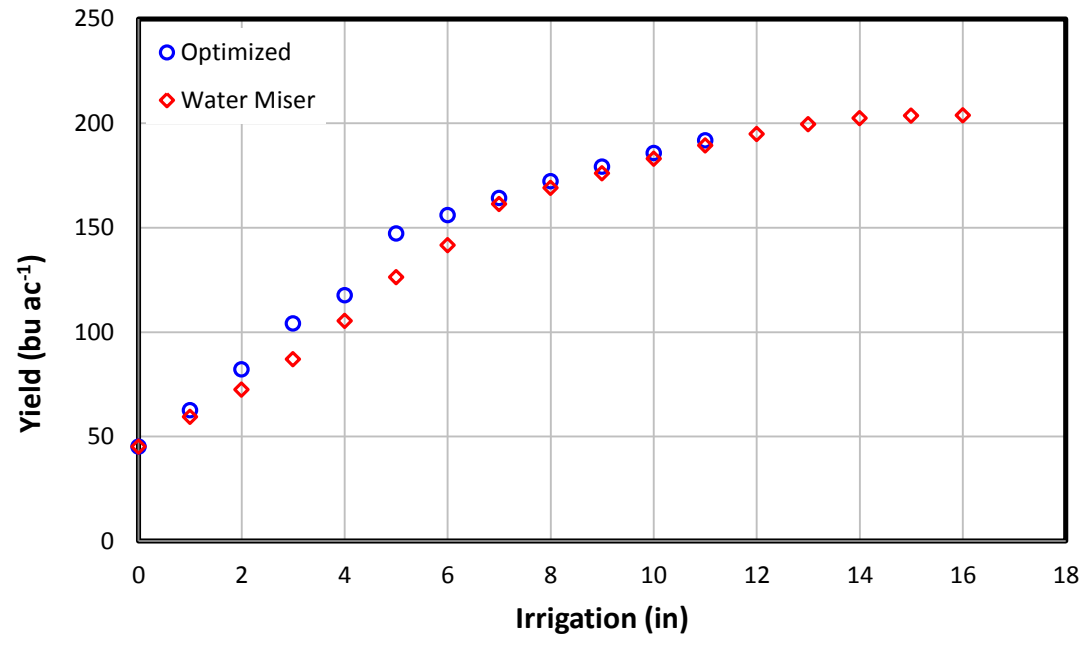


Figure 5.7. The comparison of Yield and Irrigation for the year 2003 with an initial soil water availability of 0.75 and a capacity of 1 inch of net irrigation applied in 3 days.

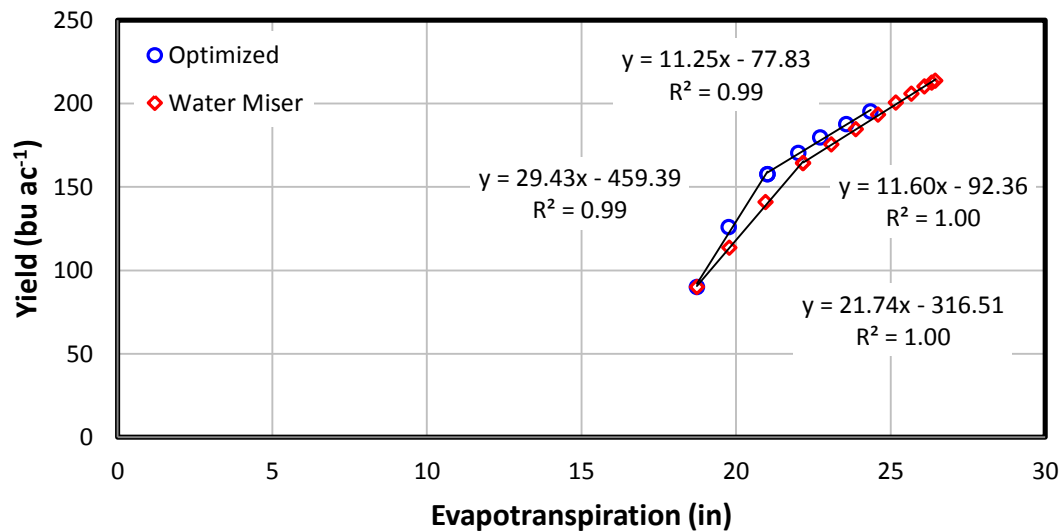


Figure 5.8. Comparison of yield and ET for 2005 with an initial water availability of 0.75 and a capacity of 1 inch of net irrigation applied in 3 days.

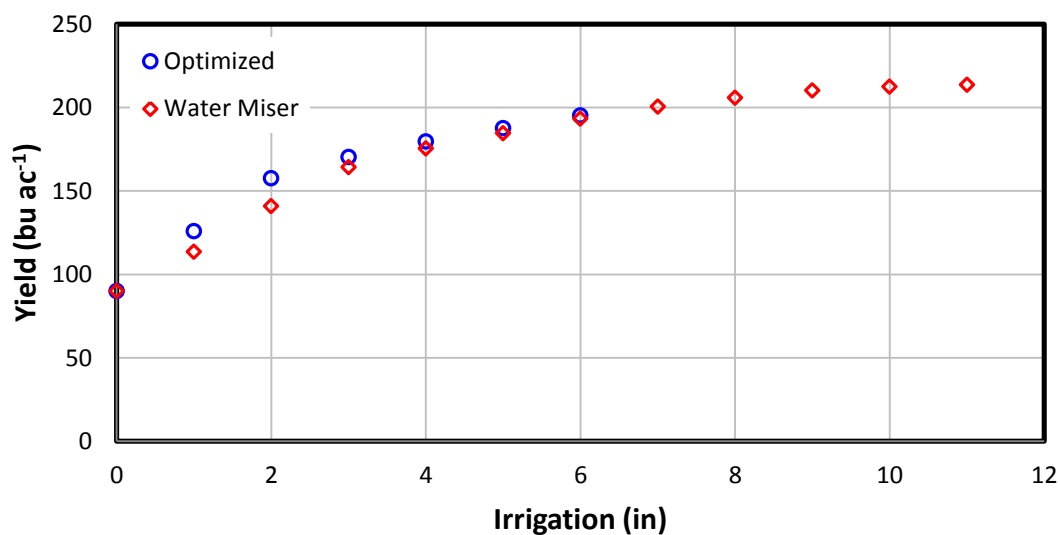


Figure 5.9. The comparison of Yield and Irrigation for the year 2005 with an initial soil water availability of 0.75 and a capacity of 1 inch of net irrigation applied in 3 days.

Table 5.3. Distribution of irrigation applications during the 2005 growing season for the optimized distribution and Water Miser strategy: initial soil water content 75%, capacity 1 inch applied every three days.

Irrigation Number	Optimized		Water Miser	
	Days After Planting	Yield (bu ac ⁻¹)	Days After Planting	Yield (bu ac ⁻¹)
1	95	126	78	114
2	98	157	81	141
3	92	170	84	164
4	101	180	89	175
5	89	188	92	185
6	86	195	95	193
7	-	-	98	200
8	-	-	101	206
9	-	-	110	210
10	-	-	118	212
11	-	-	122	214

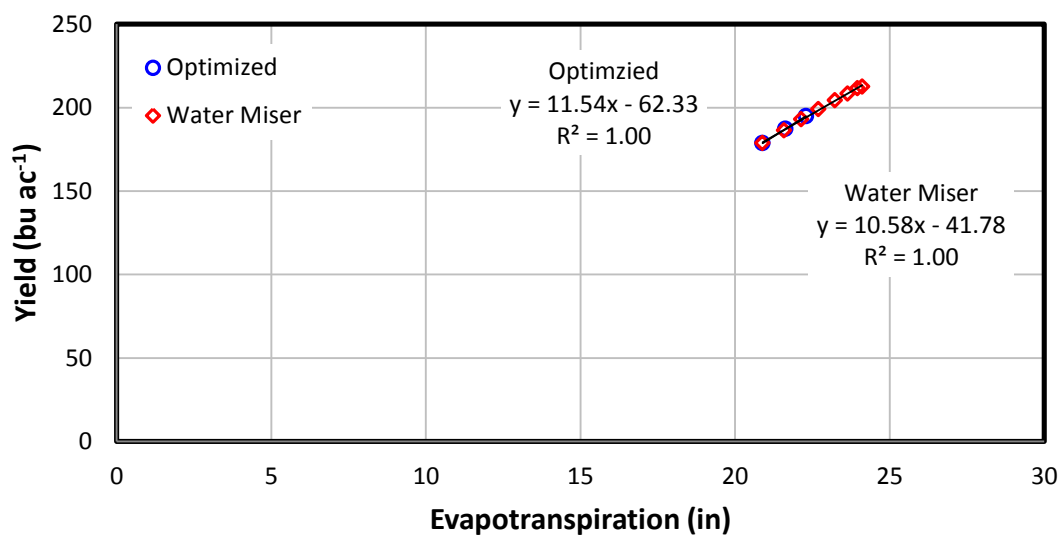


Figure 5.10. Comparison of yield and ET for 2007 with an initial water availability of 0.75 and a capacity of 1 inch of net irrigation applied in 3 days.

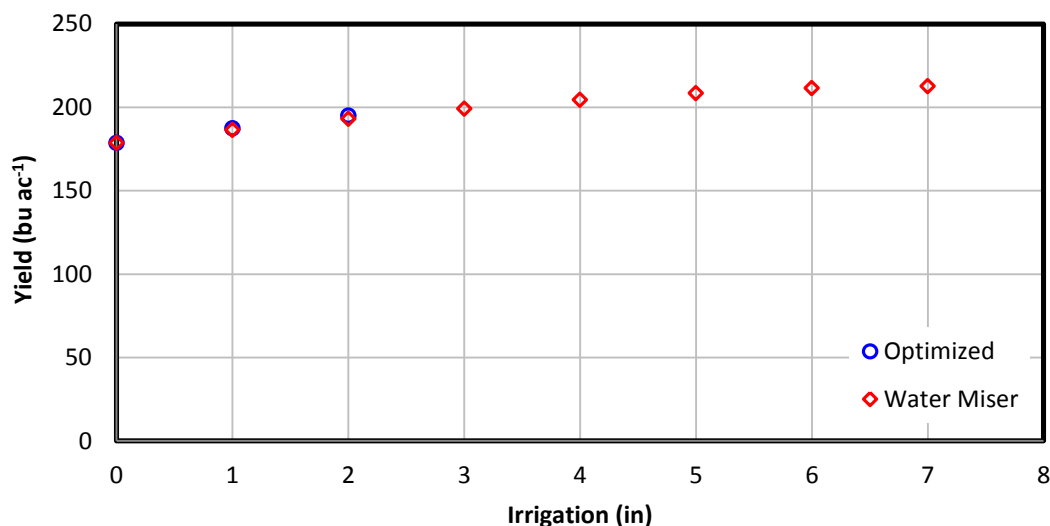


Figure 5.11. The comparison of Yield and Irrigation for the year 2007 with an initial soil water availability of 0.75 and a capacity of 1 inch of net irrigation applied in 3 days.

Table 5.4. Distribution of irrigation applications during the 2007 growing season for the optimized distribution and Water Miser strategy: initial soil water availability of 75%, capacity 1 inch applied every three days, and simulated planting date of May 1.

Irrigation Number	Optimized		Water Miser	
	Days After Planting	Yield (bu ac ⁻¹)	Days After Planting	Yield (bu ac ⁻¹)
1	101	187	82	186
2	90	195	86	193
3	-	-	95	199
4	-	-	106	204
5	-	-	110	208
6	-	-	114	212
7	-	-	121	213

In 2005 and 2007, the Water Miser strategy prescribed putting on five more inches of net irrigation in comparison to the optimized distribution. These extra five inches produced an additional 18-19 bushels per acre.

Regression Model Development

The optimized distribution used complete and perfect knowledge to determine when an inch of net irrigation would provide the greatest marginal returns. However, uncertainty about the future exists during the growing season. A producer is limited to applying irrigations in chronological order.

Using the data developed during the creation of the optimized distribution, a regression model was employed to develop a decision engine about whether or not a producer should irrigate. The purpose of the regression model is to produce a desired yield level while minimizing the amount of water applied.

A yield goal is an important component of irrigation management when trying to determine the level of deficit irrigation that a producer is willing to accept. For each combination of year, initial soil water content, and nominal capacity; data from the optimized distribution for the inch of net irrigation that exceeds a yield goal of 150, 160, 170, 180, or 190 bushels per acre at 15.5% moisture content was compiled, given that the inch did not also exceed a higher yield goal.

Table 5.5. Optimized results for a capacity of 1 inch net irrigation in 3 days and a 0.75 initial available soil water for selected yield goals.

Yield Goal (bu ac ⁻¹)	2002			2003			2005			2007		
	Yield (bu ac ⁻¹)	ET (in)	Irr. (in)	Yield (bu ac ⁻¹)	ET (in)	Irr. (in)	Yield (bu ac ⁻¹)	ET (in)	Irr. (in)	Yield (bu ac ⁻¹)	ET (in)	Irr. (in)
150	149	23.7	9	156	22	6	158	21.0	2	179	20.9	0
160	164	25.6	11	164	23	7	170	22.0	3	179	20.9	0
170	171	26.3	12	172	24	8	170	22.0	3	179	20.9	0
180	183	27.9	14	179	25	9	180	22.7	4	187	21.6	1
190	191	28.8	15	192	26	11	195	24.4	6	195	22.3	2

Table 5.6. Optimized results for a capacity of 1 inch net irrigation in 3 days and a 0.50 initial available soil water for selected yield goals.

Yield Goal (bu ac ⁻¹)	2002			2003			2005			2007		
	Yield (bu ac ⁻¹)	ET (in)	Irr. (in)	Yield (bu ac ⁻¹)	ET (in)	Irr. (in)	Yield (bu ac ⁻¹)	ET (in)	Irr. (in)	Yield (bu ac ⁻¹)	ET (in)	Irr. (in)
150	157	25.2	14	154	22.7	10	159	20.7	5	156	18.7	1
160	163	26.1	15	163	23.6	11	168	21.7	6	165	19.5	2
170	170	26.9	16	170	24.5	12	178	22.4	7	175	20.3	3
180	Not achieved			183	25.8	14	186	23.2	8	183	21	4
190	Not achieved			189	26.8	15	193	24.0	9	190	21.8	5

Table 5.7. Optimized results for a capacity of 1 inch net irrigation in 3 days and a 0.90 initial available soil water for selected yield goals.

Yield Goal (bu ac ⁻¹)	2002			2003			2005			2007		
	Yield (bu ac ⁻¹)	ET (in)	Irr. (in)	Yield (bu ac ⁻¹)	ET (in)	Irr. (in)	Yield (bu ac ⁻¹)	ET (in)	Irr. (in)	Yield (bu ac ⁻¹)	ET (in)	Irr. (in)
150	149	23.7	7	157	22.4	4	163	21.4	2	191	22.0	0
160	165	25.7	9	167	23.4	5	163	21.4	2	191	22.0	0
170	173	26.8	10	174	24.2	6	173	22.3	3	191	22.0	0
180	180	27.4	11	181	25.0	7	182	23.1	4	191	22.0	0
190	192	29.0	13	194	26.5	9	190	23.9	5	191	22.0	0

The growing season was split into 10 day increments. Cumulative, incremental, and point in time values for ET, net irrigation, effective precipitation, soil water depletion, and canopy cover were extracted from the data for each yield goal, year, initial soil water content, and nominal system capacity. The combination of net irrigation, effective precipitation, and the initial soil water content (mm) was calculated to determine the field water supply (FWS), or the amount of water that has been made available to the crop at a point during the growing season. Linear regression modeling

was incorporated to develop a relationship between the number of days after planting, the yield goal and the field water supply as shown in Equation 5.1.

$$FWS = a + b * DAP + c * Yield\ Goal \quad (5.1)$$

This model predicted the FWS values in the calibration set with a high degree of accuracy $R^2 \approx 0.8$. However, implementation of this model failed to achieve yield goals during the validation of the model. Furthermore, the distribution of the irrigation events did not resemble the irrigation event distributions that were experienced in the optimized irrigation procedure.

Investigation into the data suggested that the quantity of needed FWS was dependent upon the amount of ET experienced by the crop. ET is representative of the amount of water removed from the soil. A higher level of ET experienced by the crop signifies a larger level of water being removed from the soil; thereby, the supply of water that is needed by the crop at different times during the growing season.

The average amount of cumulative ET experienced by each system combination across all four years for a given yield goal was calculated for each 10 day increment during the growing season. A third degree polynomial was fit to the data to create the continuous function $ET_{ave} = f(DAP)$. The ratio of the actual amount of cumulative ET experience by the crop over the average ET expected for a given yield goal at a point during the growing season was used to alter the FWS needed by the crop. A higher level of ET would increase the FWS that the crop would require to meet a yield goal and vice versa. This was accomplished by using Equation 5.2.

$$FWS = a + b * DAP * \frac{ET}{ET_{ave}} + c * Yield\ Goal \quad (5.2)$$

Once again the model predicted the calibration data set with a high degree of accuracy $R^2 > 0.9$, but the implementation failed to meet yield goals or mimic the distribution of the optimized irrigation events.

Furthermore, most producers do not have the means or equipment to measure the actual ET amounts experienced by their deficit irrigated crops; while the ET values for a well-watered crop (ET_{ww}) are readily available. The actual cumulative ET values were replaced with the cumulative ET_{ww} values. Eliminating the actual cumulative ET values eliminates the remaining ties to the specific system; or, for a given yield goal the required FWS would be constant for a given year. The initial soil water content (SWC_i , % of max root depth) was implemented to capture some of the lost system specific information as shown in Equation 5.3.

$$FWS = a + b * DAP * \frac{ET_{ww}}{ET_{ave}} + c * Yield\ Goal + d * SWC_i \quad (5.3)$$

The R^2 dropped to approximately 0.88. Once again, the implementation of the model failed to accurately predict yield amounts and the timing of irrigation events. A large amount of irrigation was being applied in the early portion of the growing season (DAP 30-60) and late in the growing season (DAP >120).

The data used to create the regression model included all the data points from all the years. Data points from early in the growing season may not have been representative of the minimum FWS. Precipitation patterns in the Curtis area tend to be heaviest in the early portion of the growing season. Larger amounts of early rainfall could cause these data points to skew the necessary FWS; thereby causing the regression model to predict a larger FWS early in the growing season.

Output from the regression model begins to increase after emergence, the optimized FWS slope increases at a slower rate. In the middle of the year the FWS slope increases and overtakes the predicted values, leading to the model predicting not to irrigate. At the end of the year, the FWS begins to level off while the regression continues to grow leading to model predicting more irrigations than necessary.

The problem of applying irrigation water early and late in the growing season can be that a linear regression model is fitted to a non-linear data set. A piece-wise regression model was implemented. The model was defined with the early portion being from 0 to 50 DAP, the middle portion from 50 to 120 DAP, and the late portion from 120 to 144 DAP. Equation 5.3 was still used with different coefficients for each time period. The coefficients are shown in Table 5.4. The entire model exhibited an $R^2 = 0.92 - 0.93$, however, the model did not fare as well in any of the three individual portions.

Table 5.8. Regression coefficients for piece wise model.

Timing	R ²	Coefficient		P-value
Early 30-50 DAP	0.428	a	67.61	0.235*
		b	8.729	0.092*
		c	0.555	0.201*
		d	2.145	1.1 E-18
Middle 50-120 DAP	0.882	a	-208.0	1.2 E-13
		b	38.24	8.1 E-38
		c	3.530	5.0 E-187
		d	0.350	0.002
Late 120-144 DAP	0.755	a	-468.3	1.7 E-10
		b	73.32	1.1 E-24
		c	2.895	8.5 E-28
		d	0.047	0.818*

* Not statistically significant

The piece-wise model still required excessive early irrigation. Combined with the lack of statistical significance of the three of the coefficients in the early portion of the

growing season, the piece-wise model was shortened to the middle section. Lack of any irrigation events occurring during the late portion of the growing season within the optimized irrigation distribution led to the late portion of the piece-wise curve being dropped from the model.

Regression Application

The well-watered ET was determined using the AquaCrop model. Irrigation water was applied without limitation on either precipitation or capacity. This was done to ensure that first, the canopy expanded at its maximum rate and second, the crop was able to transpire at its maximum rate throughout the growing season.

The regression model was used to simulate irrigation only during the middle section of the year, from 50 to 120 DAP. The initial soil water content at the beginning of the year needs to be measured for the maximum root zone. The volume of available water in the root zone is the base for the field water supply. Net irrigation and effective precipitation are added to the FWS as the season progresses. Beginning 50 DAP, if the predicted FWS is greater than that of the FWS an inch of irrigation was applied, with a limitation of one inch every three day due to capacity. Before applying the irrigation, the soil water holding capacity was checked to ensure that an inch of net irrigation could be applied without exceeding field capacity minus a one inch rainfall allowance.

The regression model developed above was applied to all combination of years, yield goals, and initial soil water contents in the calibration data set. The model was able to predict yield goal with a high level of accuracy. The simulated results were usually within 10% of a yield goal. The model had a tighter predicted range for the middle yield

goals of 160, 170, and 180 bu ac⁻¹. More variation occurred for yield goals of 150 and 190 bu ac⁻¹.

In addition to accurately predicting the yield goal, the regression model accurately predicts the quantity of net irrigation that is required during the growing season. The model usually predicts either the amount of irrigation that was observed in optimized distribution or one additional inch. Occasionally the model calls for irrigation late in the season and a couple of unnecessary irrigation events are applied. In a few situations the model did not prescribe applying as much irrigation water as the optimized process. This occurred for higher yield goals in drier years; even then the irrigation amount was usually within an inch of the optimized process.

Some variance between the yield goal and the simulated results is to be expected. A method of applying discrete levels of irrigation was used. Adding an additional unit of irrigation can result in a marginal yield greater than necessary to reach a yield goal.

The acceptable range over which the model should be used is loosely defined. The model was developed using data from 50-120 DAP. However, there is evidence that the range needs to be contracted on the later end for lower yield goals. The model will occasionally prescribe applying a couple of extra inches of irrigation from 110 to 120 DAP, despite the yield goal already being achieved. These extra inches are seen in the difference between the optimally distributed irrigation events and the regression model.

Conversely, the model needs to be extended earlier into the growing season to deal with dry soils at the beginning of the growing season. In high ET years with low initial soil water content, even starting 50 DAP was not soon enough to bring the crop to full canopy, thereby limiting the maximum potential yield.

Another source of variation comes from the unpredictability of weather. There is no control of precipitation. High levels of effective rainfall during the growing season can provide the crop with enough water to exceed the yield goal. Another source of variation is tied to the maximum potential yield that the crop can produce. In AquaCrop, cooler years reduced the maximum achievable yield regardless of the amount of water available to the crop. Figures 5.12-5.15 and Tables 5.5-5.8 show the predicted yield compared to the yield goal for the calibration data.

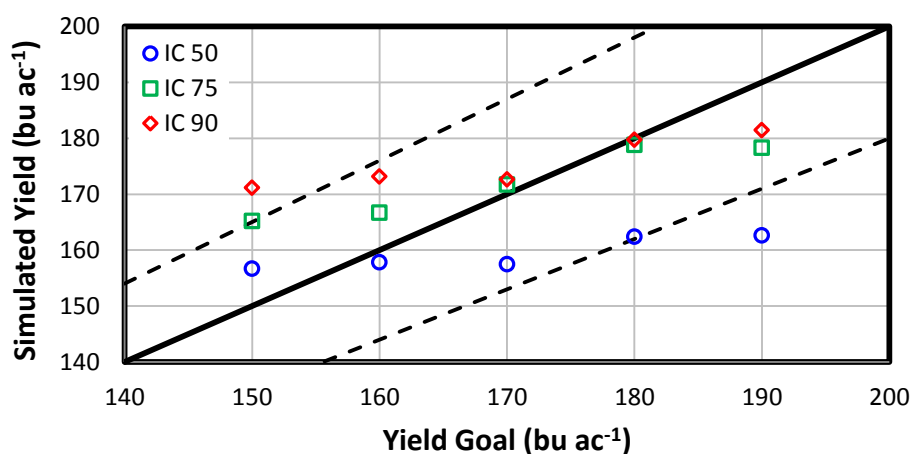


Figure 5.12. Regression results for the year 2002, showing the predicted yield vs. yield goal.

In 2002 the regression model predicted 13 of the 15 simulations within 10% of the yield goal. While simulating the low yield goal (150 bu ac⁻¹), the regression model applied irrigations during the period 110-120 DAP. The irrigation applied during this period accounted for the difference in irrigation levels between the optimized distribution and the regression model. The extra irrigations cause the yield predictions to increase for the low yield goals. For the high yield goal (190 bu ac⁻¹), by 50 DAP the crop is well behind the necessary FWS and was unable to catch up.

Table 5.9. Comparison of between regression model and optimized irrigation distribution for the year 2002.

Simulated Scenario			Regression Model			Optimized Irrigation Distribution		
Year	SWC _i (%)	Yield Goal (bu ac ⁻¹)	Yield (bu ac ⁻¹)	ET (in)	Irr (in)	Yield (bu ac ⁻¹)	ET (in)	Irrigation (in)
2002	50	150	156.7	25.6	16	156.5	25.2	14
2002	50	160	157.8	25.8	16	163.5	26.0	15
2002	50	170	157.5	25.8	16	170.2	26.9	16
2002	50	180	162.4	26.4	17	Not achieved		
2002	50	190	162.6	26.4	17	Not achieved		
2002	75	150	165.2	25.8	12	157.2	24.7	10
2002	75	160	166.7	26.0	12	164	25.6	11
2002	75	170	171.7	26.6	13	170.8	26.3	12
2002	75	180	178.8	26.5	14	183.4	27.9	14
2002	75	190	178.3	27.6	14	190.8	28.8	15
2002	90	150	171.2	26.3	11	157.9	24.8	8
2002	90	160	173.2	26.6	11	165.2	25.7	9
2002	90	170	172.7	26.8	11	173.3	26.8	10
2002	90	180	179.8	27.7	12	180.2	27.4	11
2002	90	190	181.5	27.9	12	192.3	29.1	13

 Low yield goal prediction

 High yield goal prediction

In 2003 the model was able to predict 13 of 15 simulations within 10% of the yield goal. Both errors involved applying additional late irrigations. While the model predicted the high yield goal for the low initial soil water simulation within 10%, the result indicates the need to expand the model earlier in the growing season.

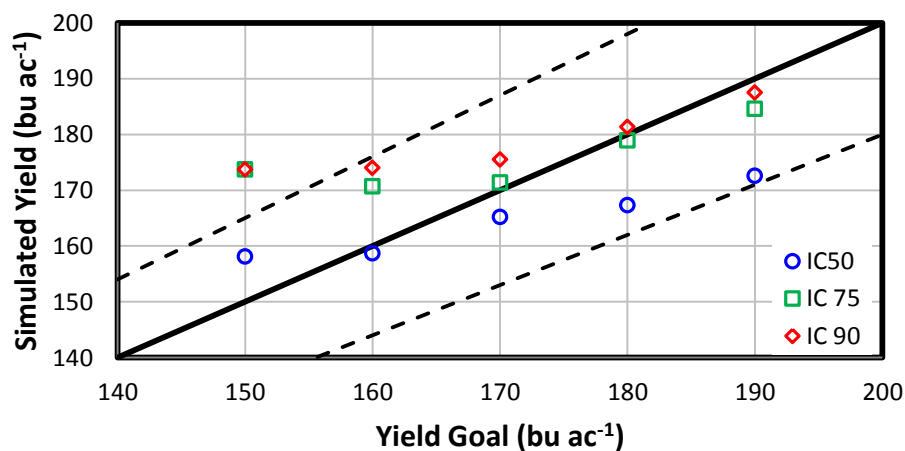


Figure 5.13. Regression results for the year 2003, showing the predicted yield vs. yield goal.

Table 5.10. Comparison of between regression model and optimized irrigation distribution for the year 2003.

Simulated Scenario			Regression Model			Optimized Irrigation Distribution		
Year	SWC _i (%)	Yield Goal (bu ac ⁻¹)	Yield (bu ac ⁻¹)	ET (in)	Irr (in)	Yield (bu ac ⁻¹)	ET (in)	Irrigation (in)
2003	50	150	158.1	23.3	12	154.5	22.7	10
2003	50	160	158.7	23.4	12	162.8	23.6	11
2003	50	170	165.2	24.1	13	170.3	24.4	12
2003	50	180	167.3	24.4	13	183.1	25.8	14
2003	50	190	172.6	24.9	14	189	26.8	15
2003	75	150	150.5	22.0	6	156	22.4	6
2003	75	160	170.7	24.0	9	164	23.3	7
2003	75	170	171.4	24.2	9	172.3	24.3	8
2003	75	180	178.9	25.0	9	179.3	25.0	9
2003	75	190	184.6	25.6	11	191.9	26.4	11
2003	90	150	173.7	24.1	7	157.4	22.4	4
2003	90	160	174.0	24.2	7	166.5	23.4	5
2003	90	170	175.5	24.4	7	174	24.3	6
2003	90	180	181.3	25.2	8	181	25.0	7
2003	90	190	187.5	25.8	9	193.8	26.5	9

Low yield goal prediction

High yield goal prediction

80% of the simulations in 2005 predicted the yield within 10% of the yield goal.

The error occurred due to extra irrigations applied late in the growing season.

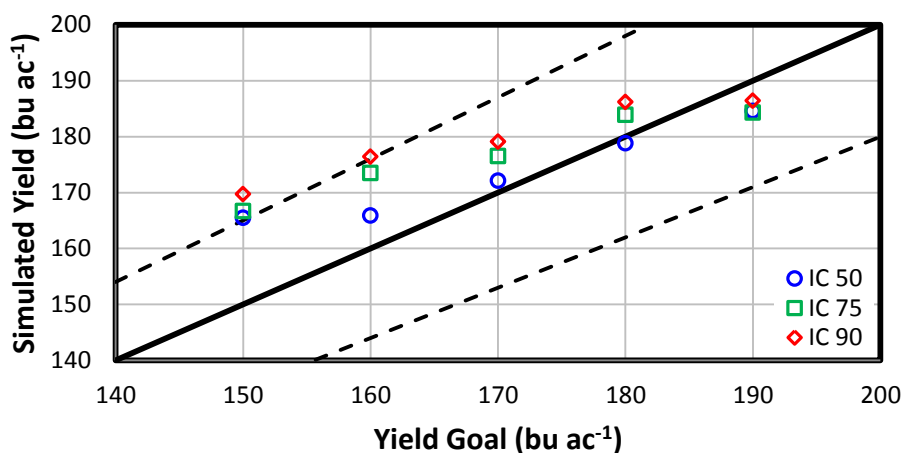


Figure 5.14. Regression results for the year 2005, showing the predicted yield vs. yield goal.

Table 5.11. Comparison between regression model and optimized irrigation distribution for the year 2005.

Simulated Scenario			Regression Model			Optimized Irrigation Distribution		
Year	SWC _i (%)	Yield Goal (bu ac ⁻¹)	Yield (bu ac ⁻¹)	ET (in)	Irr (in)	Yield (bu ac ⁻¹)	ET (in)	Irrigation (in)
2005	50	150	165.5	21.3	6	158.5	20.7	5
2005	50	160	165.9	21.5	6	168.8	21.7	6
2005	50	170	172.1	22.1	7	177.8	22.4	7
2005	50	180	178.8	23.0	8	185.9	23.2	8
2005	50	190	184.6	25.2	9	189	24.0	9
2005	75	150	166.7	21.7	3	156	21.0	2
2005	75	160	173.5	22.3	4	170.3	22.0	3
2005	75	170	176.5	22.6	4	170.3	22.0	3
2005	75	180	183.9	23.5	5	179.5	22.7	4
2005	75	190	184.3	23.6	5	195.1	24.4	6
2005	90	150	169.7	22.0	3	162.7	21.4	2
2005	90	160	176.4	22.6	4	162.7	21.4	2
2005	90	170	179.1	22.9	4	173.3	22.3	3
2005	90	180	186.2	23.7	5	182.2	23.1	4
2005	90	190	186.4	23.8	5	190	23.9	5

High yield goal prediction

In 2007, 60% of the simulations were within 10% of the yield goal. The error was due to high levels of precipitation and extra irrigations applied late in the growing season.

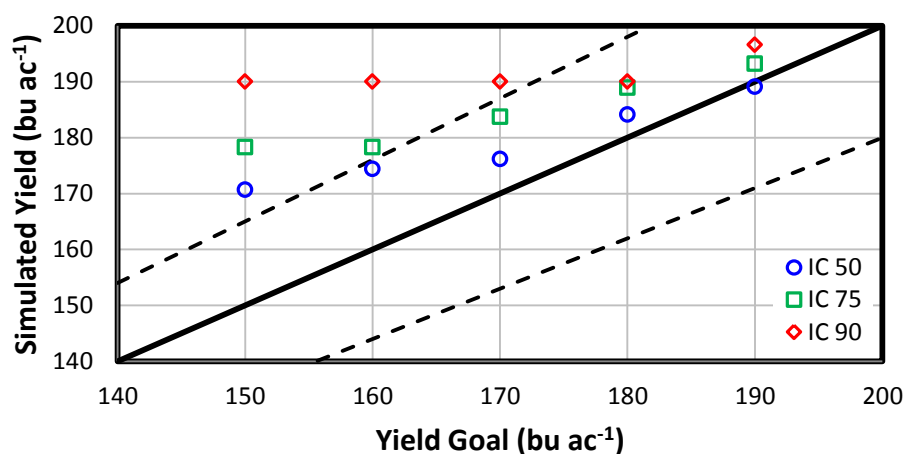


Figure 5.15. Regression results for the year 2007, showing the predicted yield vs. yield goal.

Table 5.12. Comparison between regression model and optimized irrigation distribution for 2007.

Simulated Scenario			Regression Model			Optimized Irrigation Distribution		
Year	SWC _i (%)	Yield Goal (bu ac ⁻¹)	Yield (bu ac ⁻¹)	ET (in)	Irr (in)	Yield (bu ac ⁻¹)	ET (in)	Irrigation (in)
2007	50	150	170.7	20.1	4	156.1	18.7	1
2007	50	160	174.4	20.4	4	164.8	19.5	2
2007	50	170	176.2	20.6	4	174.9	20.3	3
2007	50	180	184.1	21.4	5	183.1	21.0	4
2007	50	190	189.1	21.9	6	190.3	21.8	5
2007	75	150	178.3	20.9	0	Exceeded		
2007	75	160	178.3	20.9	0	Exceeded		
2007	75	170	183.7	21.4	1	Exceeded		
2007	75	180	188.9	21.8	2	187.3	21.6	1
2007	75	190	193.2	22.3	3	194.9	22.3	2
2007	90	150	190.0	22.0	0	Exceeded		
2007	90	160	190.0	22.0	0	Exceeded		
2007	90	170	190.0	22.0	0	Exceeded		
2007	90	180	190.0	22.0	0	Exceeded		
2007	90	190	196.6	22.6	2	190	22.0	0

High yield goal prediction

Regression Validation

The regression model was able to accurately predict yields and irrigation amounts for the scenarios used during calibration. To test robustness, the model was tested to investigate how it performed in scenarios outside of the calibration set. This included using different years, locations, system capacities, and soils.

Validating the Regression Model: Curtis

The regression model was applied at Curtis, NE for the years 1999-2008, excluding the years 2002, 2003, 2005, and 2007 that were used in the calibration process. Ten random years were chosen from the range, with a random initial soil water content between 50% to 90% and a random yield goal of 150-190 bu ac⁻¹ with discrete 10 bu ac⁻¹ increments each year (Table 5.13).

Once again the model predicted yield goals with a high level of accuracy, i.e. within 10%. When predicting the yield goal at 180 bu ac⁻¹ for 2004 and 2008, the regression model predicted low. Inspection of the well-watered crop results showed that the maximum yield that was achieved for those two years was 186 and 197 bu ac⁻¹ respectively. The reduction in potential maximum yield results in a reduction of predicted yields. The two 150 bu ac⁻¹ simulations still scheduled irrigation events during the 110-120 DAP time period. This occurred in conjunction with precipitation occurring after the final irrigation. The results of the regression are presented in Table 5.13 and Figure 5.16. This shows that the model works well for Curtis, NE.

Validating the Regression Model: Geographical Transferability

The regression model was then applied using the weather data from the site in McCook, NE; conditioned using the PMET_{sz} program. McCook was chosen due to its

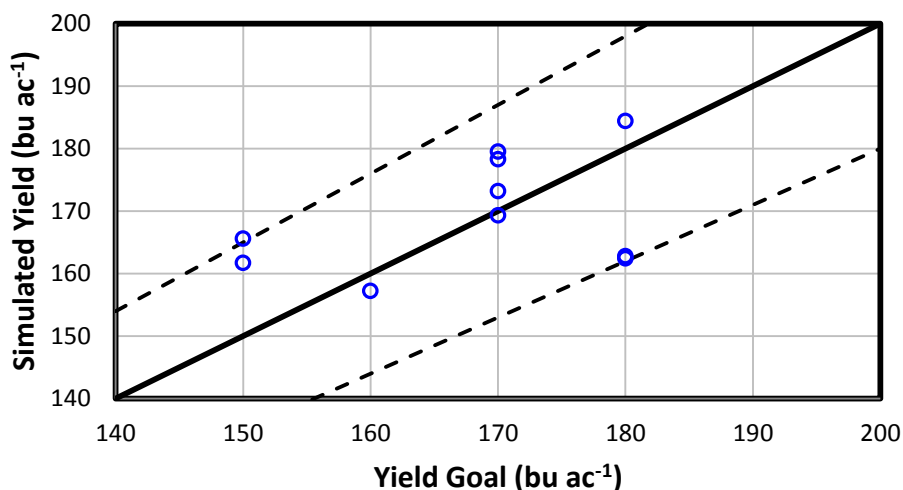


Figure 5.16. Regression results for Curtis, NE comparing predicted yield vs. yield goal.

Table 5.13. Regression results for Curtis, NE.

Simulated Scenario			Regression Model		
Year	SWC _i (%)	Yield Goal (bu ac ⁻¹)	Yield (bu ac ⁻¹)	ET (in)	Irr (in)
1999	78	180	184.4	23.0	3
1999	85	170	178.3	22.4	1
2000	61	150	165.6	22.6	10
2000	85	170	173.2	23.5	7
2001	85	170	169.3	23.4	7
2001	86	150	161.7	22.5	6
2004	75	160	157.2	21.3	0
2004	64	180	162.8	21.9	3
2006	72	170	179.5	23.2	8
2008	56	180	162.4	19.9	0

Low yield goal prediction

High yield goal prediction

location approximately due south of the station at Curtis, and experiences the same amount of seasonal precipitation. Geographical translation is an important characteristic that the regression model should possess. Ten random systems were chosen from range

of: years 1999-2008, initial soil water content 50-90%, and yield goal 150-190 bu ac⁻¹ using discreet steps (Table 5.14).

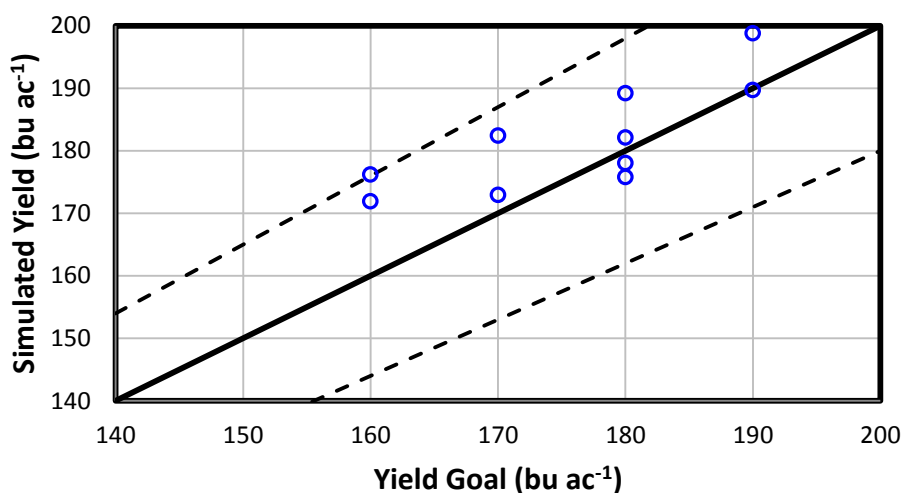


Figure 5.17. Regression results for McCook, NE comparing predicted yield vs. yield goal.

Table 5.14. Regression results for McCook, NE.

Simulated Scenario			Regression Model		
Year	SWC _i (%)	Yield Goal (bu ac ⁻¹)	Yield (bu ac ⁻¹)	ET (in)	Irr (in)
2000	71	160	176.2	23.9	13
2001	70	160	171.9	24.3	9
2002	57	180	175.8	27.0	17
2002	76	180	182.1	27.5	14
2003	53	180	178	25.7	11
2004	76	170	172.9	21.9	1
2005	63	190	189.7	26.0	10
2006	65	170	182.4	24.4	9
2006	83	190	198.8	26.1	8
2007	60	180	189.2	21.3	6

High yield goal prediction

The regression model predicted yields within 10% of the yield goal (Figure 5.17 and Table 5.14). The simulation in 2000 was the only year when the yield that was not

within 10% of the yield goal. A couple of late season precipitation events occurred after the last irrigation in 2000.

The strong north-south geographical translation of the model leads to the possibility of an east-west adaptation. To test the application of the model for varying longitudes, the regression model was then applied using the weather data from the sites in Dickens, NE and Holdrege, NE; conditioned using the PMET_{sz} program. Dickens was chosen due to its location approximately 24 miles west of the station at Curtis. In Nebraska, traveling 25 miles east to west one can expect a one inch reduction in average seasonal precipitation. Ten random systems were chosen from a range of: years 1999-2008, initial soil water content 50-90%, and yield goal 150-190 bu ac⁻¹ using discrete intervals (Table 5.15).

The regression model predicted the yields within 10% (Figure 5.18 and Table 5.15). The simulation in 1999 experienced precipitation after applying irrigation causing it to exceed the yield goal. In 2007 enough precipitation fell to meet and exceed the yield goal.

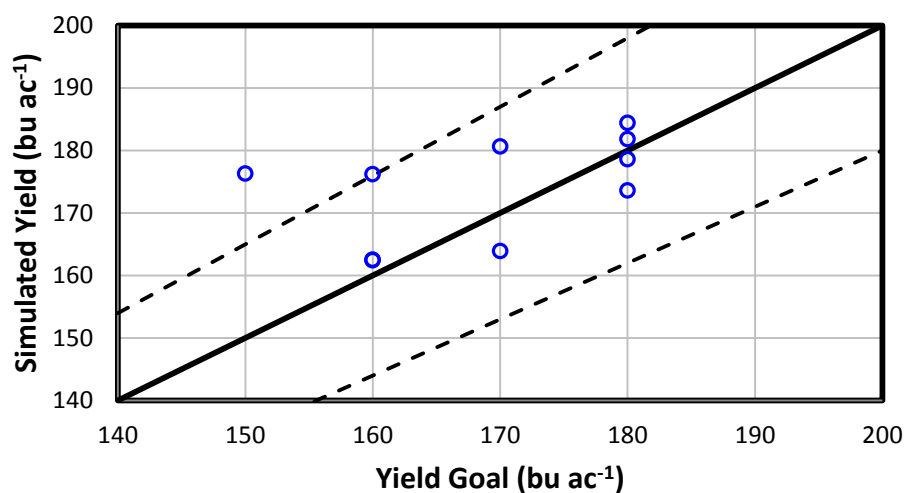


Figure 5.18. Regression results for Dickens, NE comparing predicted yield vs. yield goal.

Table 5.15. Regression results for Dickens, NE.

Simulated Scenario			Regression Model		
Year	SWC _i (%)	Yield Goal (bu ac ⁻¹)	Yield (bu ac ⁻¹)	ET (in)	Irr (in)
1999	67	160	176.2	22.1	5
1999	74	170	180.6	22.6	4
2000	85	180	184.4	25.0	10
2001	57	180	173.6	23.5	9
2002	56	160	162.4	25.9	17
2003	85	180	178.6	24.4	9
2003	59	160	162.5	22.9	11
2005	60	180	181.8	22.7	2
2006	56	170	163.9	20.8	15
2007	80	150	176.3	21.0	0

High yield goal prediction

Holdrege was chosen due to its location approximately 60 miles east of the station at Curtis, which averages about 2.5 inches more of seasonal precipitation than Curtis. Ten random systems were chosen from range of: years 1999-2008, initial soil water content 50-90%, and yield goal 150-190 bu ac⁻¹ using discreet steps (Table 5.16).

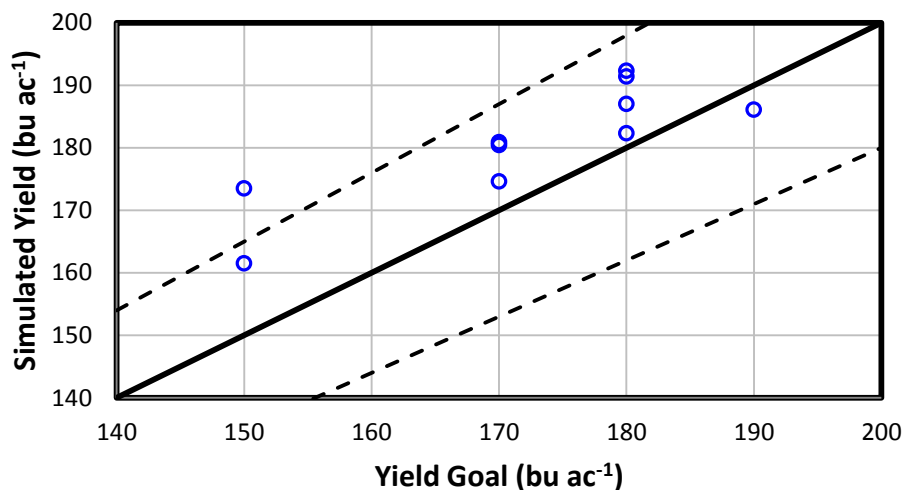


Figure 5.19. Regression results for Holdrege, NE comparing predicted yield vs. yield goal.

Table 5.16. Regression results for Holdrege, NE.

Simulated Scenario			Regression Model		
Year	SWC _i (%)	Yield Goal (bu ac ⁻¹)	Yield (bu ac ⁻¹)	ET (in)	Irr (in)
1999	63	190	186.1	23.1	1
2000	72	170	180.4	22.2	9
2001	60	170	180.9	22.9	7
2001	78	180	191.4	24.0	6
2002	57	170	174.6	25.2	13
2003	56	180	182.3	23.9	10
2004	72	150	161.5	20.7	2
2005	84	180	192.3	24.3	4
2006	70	150	173.5	21.7	3
2008	87	180	187.0	22.2	2

High yield goal prediction

The regression model accurately predicted the yield results (within 10%; Figure 5.19 and Table 5.16). The simulations in 2006 experienced enough precipitation that after applying some irrigation the yield goal was met and exceeded.

The regression model showed strong ability to adapt to other geographical location around the region, however, the model still exhibited the same error experienced during calibration.

Validating the Regression Model: System Capacity

System capacity controls the rate at which a producer can apply water to the crop. As the system capacity is reduced, it can become the limiting factor for irrigation management. The regression model was built using a capacity of one inch net irrigation applied every 3 days. It is important to know if a system with reduced capacity can apply water quickly enough to keep up with the model's recommendations.

The regression model was then applied using the weather data from the site in Curtis, NE; conditioned using the PMET_{sz} program. Using a capacity of one inch of net irrigation applied every four days, ten random systems were chosen from range of: years 1999-2008, initial soil water content 50-90%, and yield goal 150-190 bu ac⁻¹ using discreet steps. This process was repeated for a capacity of one inch of net irrigation applied every five days.

The regression model predicted the yield results with a high level of accuracy, the majority within 10% (Figure 5.20 and Table 5.17). Similar to what occurred for the higher capacity; extra irrigations are applied at the end of the growing season increased the yields beyond the yield goal for low yield goal simulations. In 2008, a reduced maximum potential yield of the crop limits the efficacy of the regression model.

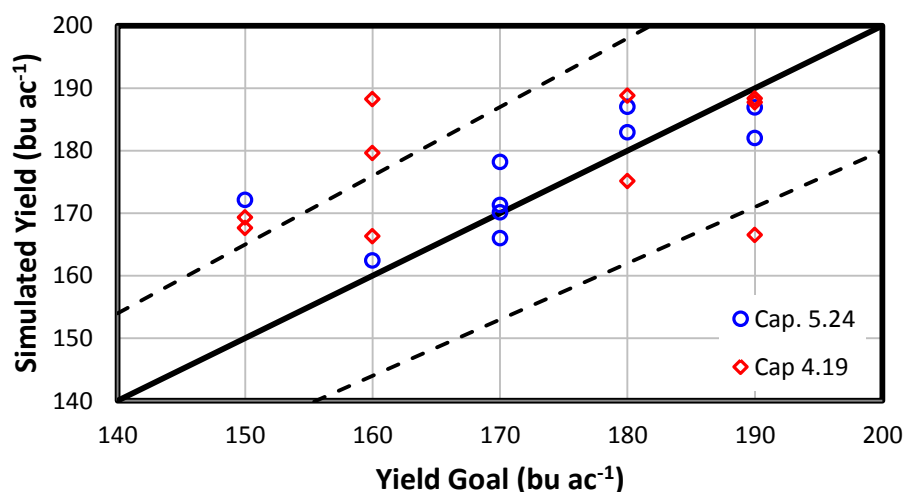


Figure 5.20. Regression results for reduced capacity tested at Curtis, NE comparing predicted yield vs. yield goal.

Table 5.17. Regression results for reduced capacity systems tested at Curtis, NE.

Simulated Scenario				Regression Model		
Year	SWC _i (%)	Yield Goal (bu ac ⁻¹)	Capacity (gal min ⁻¹ ac ⁻¹)	Yield (bu ac ⁻¹)	ET (in)	Irr (in)
2000	78	170	5.24	178.2	23.9	9
2000	86	150	5.24	172.1	23.2	7
2001	95	190	5.24	182	24.9	8
2003	62	170	5.24	170.1	24.2	11
2003	97	180	5.24	182.9	25.3	7
2003	74	170	5.24	171.3	24.2	9
2004	84	170	5.24	166	22.2	0
2005	95	190	5.24	186.9	23.8	5
2006	79	180	5.24	187	24.0	8
2008	56	160	5.24	162.4	19.9	0
1999	90	190	4.19	188.3	23.5	2
1999	68	150	4.19	167.6	21.1	2
2002	92	150	4.19	169.3	26.1	10
2003	65	160	4.19	166.3	23.7	10
2004	95	180	4.19	175.1	23.1	0
2006	74	160	4.19	179.6	23.1	8
2006	72	190	4.19	187.7	24.1	10
2007	56	180	4.19	188.8	21.8	5
2007	84	160	4.19	188.2	21.8	0
2008	59	190	4.19	166.5	20.3	0

 Low yield goal prediction

 High yield goal prediction

Validating the Regression Model: Fine Sandy Loam

The ability of the model to accurately predict yield goals should not be limited to a single soil type. A fine sandy loam was chosen to test the model for a different soil class. The soil properties used for the fine sandy loam soil were: field capacity 0.22, permanent wilting point 0.11, saturation 0.41, bulk density 85.5 lb ft⁻³, and saturated

hydraulic conductivity of 0.82 in hr^{-1} . The regression model was then applied using the weather data from the site in Curtis, NE; conditioned using the PMET_{sz} program.

The regression model was unable to predict yields with a suitable degree of accuracy. Yield results were under predicted for all simulations (Figure 5.21 and Table 5.18).

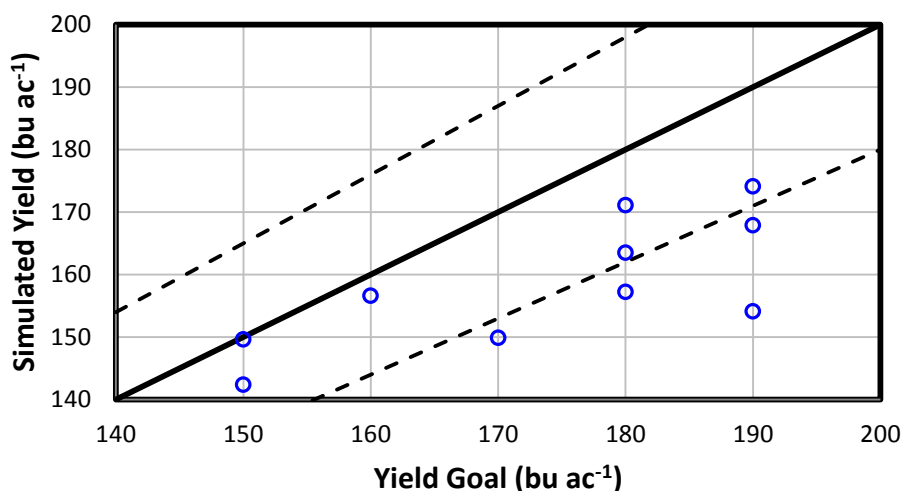


Figure 5.21. Regression results for fine sandy loam soil tested at Curtis, NE comparing predicted yield vs. yield goal.

Table 5.18. Regression results for a fine sandy loam soil tested at Curtis, NE.

Simulated Scenario			Regression Model		
Year	SWC _i (%)	YG (bu ac ⁻¹)	Yield (bu ac ⁻¹)	ET (in)	Irr (in)
2000	69	150	149.6	20.5	8
2002	75	170	149.9	23.6	12
2002	88	180	157.2	24.4	12
2003	80	150	142.4	20.4	7
2004	77	190	154.1	20.4	3
2005	71	180	163.5	20.9	7
2005	52	160	156.6	20.0	6
2006	66	190	174.1	22.4	10
2007	59	180	171.1	20.2	3
2008	53	190	167.9	20.2	4

Low yield goal prediction

The regression model includes a term for initial soil water content as a percentage of the water holding capacity of the maximum root zone. The Holdrege silt loam soil has a water holding capacity of 13.45 inches in a 5.9 foot root zone while the fine sandy loam can only hold 7.78 inches. The initial soil water content was adjusted from the fine sandy loam to what it would be equivalent for the Holdrege silt loam. The regression model was retested with the adjusted soil water content. Once again the model failed to accurately predict yield goal (Figure 5.21 and Table 5.15). The model tended to over predict yields when using the adjusted initial soil water content. In 2008, the maximum yield potential of a fully watered crop was limited and the regression model underestimated the yield goal.

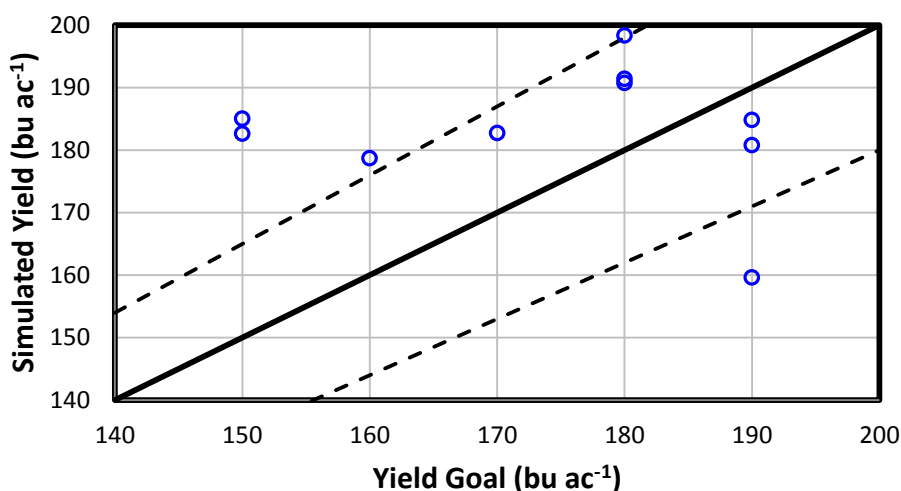


Figure 5.22. Regression results for fine sandy loam soil with adjusted initial soil water content tested at Curtis, NE comparing predicted yield vs. yield goal.

Table 5.19. Regression results for fine sandy loam soil with initial soil water content adjusted to a Holdrege silt loam tested at Curtis, NE.

Simulated Scenario				Regression Model		
Year	SWC _i (%)	Yield Goal (bu ac ⁻¹)	Adjusted SWC _i (%)	Yield (bu ac ⁻¹)	ET (in)	Irr (in)
2000	69	150	40	182.6	24.2	13
2002	75	170	43	182.7	28.0	17
2002	88	180	51	191.4	29.0	17
2003	80	150	46	185	25.4	13
2004	77	190	45	180.8	23.3	7
2005	71	180	41	190.7	24.1	10
2005	52	160	30	178.7	22.8	9
2006	66	190	38	184.8	23.7	14
2007	59	180	34	198.3	22.5	8
2008	53	190	31	159.6	19.4	3

 Low yield goal prediction

 High yield goal prediction

A possible explanation of the failure to accurately predict yields using the fine sandy loam could be due to how the stresses are modeled. Stresses are computed using relative soil water depletion. There are different amounts of water available to the plant for different soils at the same relative depletion. A more accurate method might be to exchange relative depletion to soil water tension. The crop should react similarly when it has to expend the same amount of work to extract water from the soil. Making this adjustment should improve the transferability of the model across soil types.

Conclusions

Using the data developed in the optimized irrigation distribution, a regression model was formed to predict the necessary field water supply (FWS) throughout the growing season for a desired yield goal. The model was tested for four locations with a silt loam soil in southwest and south central Nebraska. The model was accurate within

10% of the yield goal for a majority of the simulations with a tendency to err with a higher yield than the yield goal. Furthermore, the model accurately accounts for system capacity.

There are four sources of error for the regression model. The first is from failing to start applying irrigation early enough in the growing season for a year that experiences high ET, lower than usual spring precipitation, and low initial soil water content. This error produces a reduced yield. The second source of error comes from applying additional irrigations late in the growing season for a low yield goal. This error tends to use more water than is necessary to meet the yield goal, but tends to produce a higher yield. These two errors have the potential to be corrected with refinement of the range over which the model is applied.

The next two sources of error are climatic and weather related. The third source of error comes from large amounts of effective precipitation. The amount of effective precipitation has the potential to exceed what is necessary to meet the yield goal. If a growing season has a dry stretch prior to the precipitation, the regression model may prescribe irrigations that may be unnecessary after investigation of the entire season. However, predicting future rainfall is not reliable. Following the model during an early dry stretch would keep producers from falling behind on irrigation if the precipitation does not occur. This type of error leads to higher irrigation levels and high yields. The final type of error occurs during cooler and low ET years where the maximum yield potential simulated in AquaCrop was reduced. The regression model under predicts yields under these circumstances. There is little that can be done to mitigate effects of the last two error types.

The investigation into the transferability of the model to different soil classes remains questionable. Under the tested conditions the model was unable to predict yields accurately for a fine sandy loam. Further testing is necessary to discover the range of soil classes for which the model is accurate, if the model can be improved by adjusting the stress coefficient parameters, or if the model is incapable of being transferred between soil classes.

In comparison to the Water Miser strategy, the regression model covers an earlier portion (50-64 DAP) of the growing season than is covered by the Water Miser strategy. Furthermore, the regression model has initiated a stopping date (120 DAP) for irrigation. The model also incorporates a yield goal to reduce water usage. Finally the regression model is easier to implement than the Water Miser strategy. The Water Miser strategy requires constant measurement of the soil water content. The regression model requires a single soil water content measurement at the beginning of the year, and keeping track of effective precipitation, net irrigation and well-watered ET during the growing season.

The ability of the regression model to accurately predict yield goals makes the regression model a strong complement to the Water Optimizer suite of programs. Water Optimizer provides a target yield for an average year for a supply of irrigation water. The regression model is able to adjust the irrigation requirement for seasonal differences from the average to meet the targeted yield goal.

Suggested Improvements for the AquaCrop Model

The AquaCrop model tended to be cumbersome and tedious to use, especially when running a multitude of simulations. Calibrating the model required manually searching through input files, manually changing the desired parameter, and then individually running all of the simulations. An update to AquaCrop (AquaCrop 3.1) introduced the ability to simulate crops over a period of time; however, this does not allow the user to change crop, soil, irrigation or field management files. Making adjustments to the input file outside of the program requires reloading the AquaCrop program for the change to take affect. A recommendation would be to make the code open source or at least allow the model to be called using an outside program. A user could build the necessary input files, specify combinations of inputfiles to be simulated, and name the output files. This would greatly increase the speed the model can be used.

The growing degree day model used in AquaCrop also has its limitations. As temperatures cools late in the growing season the number of GDD accumulated each day decreases. This frequently leads to an extended growing season, sometime into the next growing season. The implementation of a frost-kill subroutine has the potential to improve the robustness of the model.

Currently the stress algorithms are a crop parameter based upon soil water depletion. An improvement can be made by utilizing matric potential. The same depletion in different soils will have different matric potential. Stress is tied to how much work is required by the plant to extract water from the soil, thus matric potential.

Plant population effect the speed the canopy cover achieves its maximum level. However, the maximum crop coefficient is not changed by a change in population. A

lower plant population indicates a lower number of potential stomata; and thereby a lower rate of transpiration. An adjustment to the crop coefficient for plant population could improve the robustness of the model.

The current irrigation algorithm is very simple. Several system characteristics could be added to the model to improve the range of scenarios the model can accommodate. System capacity, application efficiency, and irrigation uniformity are three irrigation system characteristics that should improve the efficacy of the model. A system capacity limits how often irrigation water can be applied to the crop and is important in simulating irrigation strategies. Application efficiency ties net irrigation to gross irrigation. Currently the AquaCrop model directly infiltrates the net irrigation into the soil profile. Finally uniformity describes the equal access of plants to irrigation water. Uniformity allows the user to simulate how different areas of the field would respond to differences in irrigation levels caused by differences in uniformity.

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A. Appendix Penman-Monteith Standardization Program

Figure A.1. User interface for the PMETsz program.

Site 1 in figure A.1 pulls up a dialog box in which the `AWDNStationFormat.csv` file is found. The file is then shown at site 2. Site 3 pulls up a dialog box to locate the specific station's raw hourly data file. When selected the raw hourly file name will appear at site 4. Site 5 pulls up a dialog box to locate the specific station's raw daily data file. When selected the raw daily file name will appear at site 6. Site 7 allows the user to input a date to check the calculation undertaken in the program. Several intermediate values for each hour will be written to a verification file. Site 8 initiates program by opening a dialog box double checking the weather station desired. *Note:* there are several weather stations on the Automated Weather Data Network (AWDN) that have the same name.

Automated weather stations have been set up to record various weather data across the upper great plain. However, neither the data that was collected nor was the output format which it was presented was consistent for all stations. Several clusters of stations do have consistent weather measurements and output formats. Each weather station on either the Automated Weather Data Network or CoAgMet networks was assigned to a cluster that exhibited similar output formats. All of the weather stations and classifications are recorded in a single file *AWDNStationFormat.csv*.

The Penam-Monteith Standardization program converts weather data from various weather stations into a standard output format. In addition it calculates various reference ET values. The general procedure is visible in Figure A.2.

Three input files are needed to run *PMETsz* for a station:

AWDNStationFormat.csv, the raw daily data file (*station.rda*), and the raw hourly file (*station.rhr*). Weather stations keep track of various errors experienced during the measurement process and appear as flags in the hourly and daily data files. *PMETsz* counts the number of flags that are associated with air temperature, relative humidity, soil temperature, wind speed, wind vector, wind vector standard deviation, and solar radiation. The total number of flags experienced before and including a given hour in a day was recorded in the hourly output file, while the daily total was recorded in the daily output file.

The hourly input data file is used to develop both the hourly and a majority of the daily output files. The daily input file is used to check the quality of hourly data.

PMETsz utilizes the ASCE Standardized Reference Evapotranspiration Equation manual (Allan 2005) to calculate the hourly ET_o and ET_r . Daily values for average temperature,

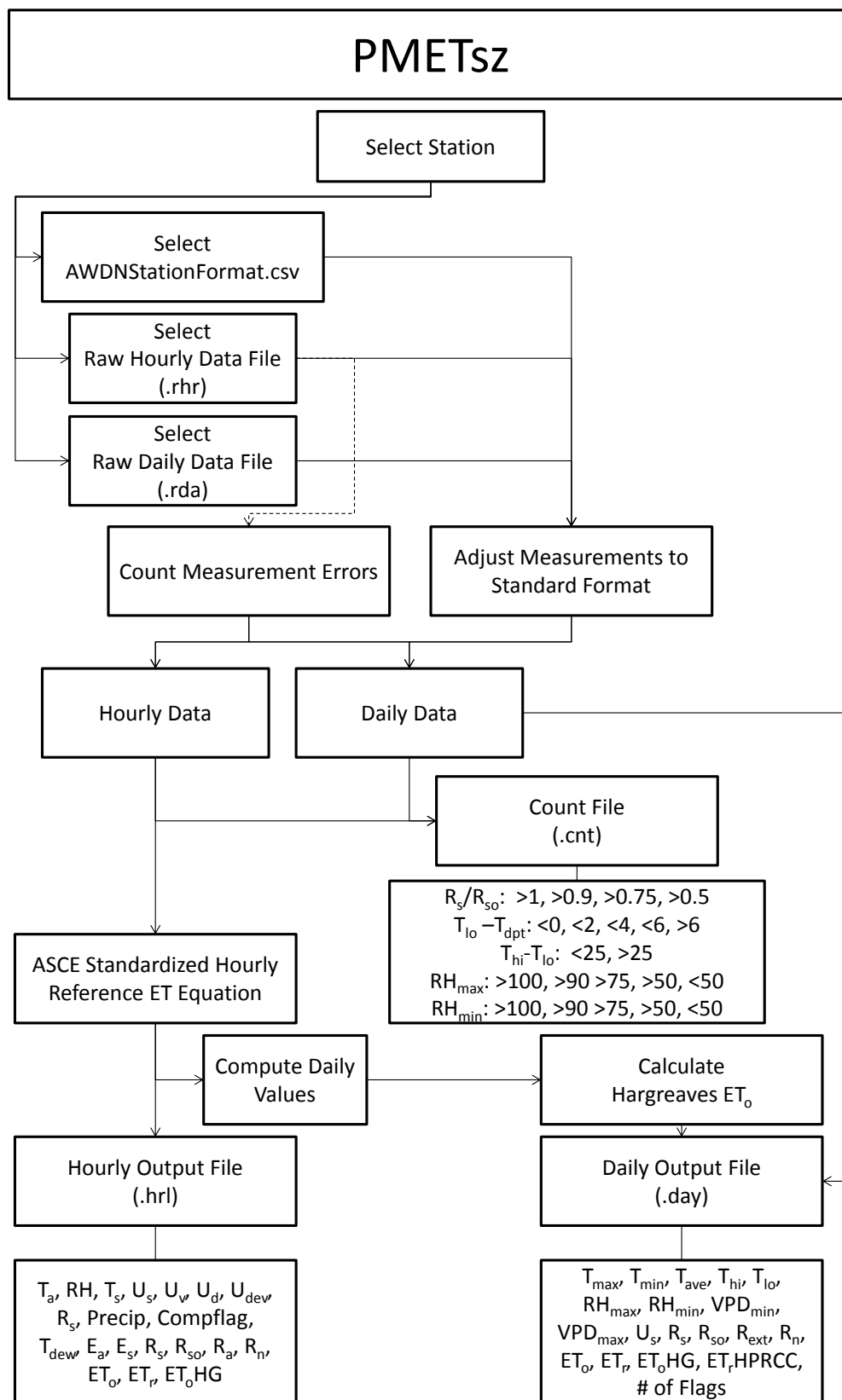


Figure A.2. Flow diagram for PMETSz program.

dew point temperature, and wind speed are calculated using the average of the hourly values. The daily solar radiation, clearsky radiation, and net radiation are calculated using the sum of the hourly values. Hargreave ET (Hargreaves and Samani, 1985) is calculated using the average hourly temperature, minimum and maximum hourly temperature, and the sum of the hourly external radiation.

The daily input does provide a few values to the daily output file. A list of output parameters for the daily and hourly data is available in Tables A.1-A.2.

Table A.1. Parameter in the hourly output file

Parameter	Symbol	Units
Month		
Day		
Year		
Hour		
Day of Year	DOY	C
Air Temperature	T_a	C
Relative Humidity	RH	%
Soil Temperature	T_s	C
Wind Speed	U_s	$m s^{-1}$
Wind Velocity	U_v	$m s^{-1}$
Wind Vector	U_d	rad
Wind Vector Standard Deviation	U_{dev}	rad
Solar Radiation	Solar	$W m^{-2}$
Precipitation	Precip	mm
Hourly Data Flags	Compflag	
Dew Point Temperature	T_{dew}	C
Actual Vapor Pressure	E_a	kPa
Saturated Vapor Pressure	E_s	kPa
Solar Radiation	R_s	$MJ m^{-2} h^{-1}$
Clear Sky Radiation	R_{so}	$MJ m^{-2} h^{-1}$
Extraterrestrial Radiation	R_a	$MJ m^{-2} h^{-1}$
Net Radiation	R_n	$MJ m^{-2} h^{-1}$
Short-Crop Reference ET	ET_o	$mm h^{-1}$
Tall-Crop Reference ET	ET_r	$mm h^{-1}$
Hargreaves Reference ET	ET_oHG	$mm h^{-1}$

Table A.2. Parameters in the daily output file.

Parameter	Symbol	Units	Calculation Process
Month			
Day			
Year			
Day of Year	DOY		
Maximum Temperature	Tmax	C	sum hourly
Minimum Temperature	Tmin	C	sum hourly
Average Temperature	Tave	C	average hourly
Hi Temperature	Thi	C	from daily file
Low Temperature	Tlow	C	from daily file
Maximum Relative Humidity	RHmax	%	max hourly
Minimum Relative Humidity	RHmin	%	min hourly
Minimum Vapor Pressure Deficit	VPDmin	kPa	max hourly
Maximum Vapor Pressure Deficit	VPDmax	kPa	min hourly
Wind Speed	Us	m s ⁻¹	average hourly
Solar Radiation	Rn	MJ m ⁻² d ⁻¹	sum hourly
Clear Sky Radiation	Rso	MJ m ⁻² d ⁻¹	sum hourly
Extraterrestrial Radiation	Rext	MJ m ⁻² d ⁻¹	sum hourly
Net Radiation	Rn	MJ m ⁻² d ⁻¹	sum hourly
Short-Crop Reference ET	ETo	mm d ⁻¹	sum hourly
Tall-Crop Reference ET	ETr	mm d ⁻¹	sum hourly
Hargreaves Reference ET	EToHG	mm d ⁻¹	Use Tmax, Tmin, Tave, Rext
Number of Data Flags	NumDataFlags		sum hourly

B. Appendix AWDNForm.vb Program

```
Imports System
Imports System.IO
Imports System.Text

Public Class AWDNform

    '-----
    ' Define Daily and Hourly AWDN file and station names
    Public AWDNdirectory As String, AWDNStationname As String
    Public AWDNHourRawFile As String, AWDNHourFilename As String
    Public AWDNDayRawFile As String, AWDNDayFilename As String
    Public AWDNHourFileInfo As System.IO.FileInfo
    Public AWDNDayFileInfo As System.IO.FileInfo
    Public ofdAWDNHour As New OpenFileDialog(), ofdAWDNDay As New OpenFileDialog()
    '-----

    '-----
    ' Define parameters for the information about the weather station
    Public StationID As String, StationName As String, StationInfoFile As String
    Public Lat_min As Double, Lat_deg As Double, Long_min As Double
    Public Long_deg As Double, Elev As Double, Lat_dec As Double, Long_dec As Double
    Public WindHt As Double, TempHt As Double, VegHt As Double
    Public Uratio1 As Double, Uratio2 As Double

    Public StationCode As Integer, NumFormat As Integer, NumColumns As Integer
    Public StationState As String, StationStateAB As String, StationTimeZone As String
    '-----

    ' Define hourly weather data variables
    Public Row As Long, Mon As Integer, Mday As Integer, Year As Integer
    Public Hour As Integer, nvalid As Integer
    Public Ta As Double, Tdew As Double, RH As Double, Ts As Double, Us As Double
    Public Uv As Double, Ud As Double, Udev As Double, Solar As Double
    Public Precip As Double
    '-----

    ' Define daily weather data variables
    Public DayThi As Double, DayTlo As Double, DayRH As Double
    Public DaySoilT As Double, DayUZ As Double
    Public DaySolar As Double, DayPrecip As Double, DayETrHPRC As Double
    Public DayMon As Integer, DayMday As Integer, DayYear As Integer
    Public DayHour As Integer
    '-----

    ' Define variable for computing Penman-Monteith reference ET from hourly data

    Public Cd As Double, Lat_rad As Double

```

```

Public Lz As Double, P As Double, PC As Double, slope As Double
Public Es As Double, Ea As Double, G As Double
Public dr As Double, Sd As Double, Timep As Double, b As Double, Sc As Double
Public w As Double, w1 As Double, w2 As Double, ws As Double, beta As Double
Public Ra As Double, Rs As Double, Rso As Double, Rn As Double, Rnl As Double
Public fcd As Double, fcdok As Double, U2 As Double
Public Rns As Double, ETrs As Double, ETos As Double

'-----
' Coefficient for hourly Penman-Monteith - grass (...o) and alfalfa (...r)
Public Gnightr As Double = 0.2, Gdayr As Double = 0.04, Cddayr As Double = 0.25
Public Cdnightr As Double = 1.7, Cnr As Double = 66

Public Gnighto As Double = 0.5, Gdayo As Double = 0.1, Cddayo As Double = 0.24
Public Cdnigho As Double = 0.96, Cno As Double = 37

Public Gsc As Double = 4.92, Pi As Double = Math.PI
'-----

Public aryRecord(50) As Object
Public FlagforReadingDailyData As Integer

'-----
' Define sum and average of hourly data for daily values
Public Tmax As Double, Tmin As Double, Tavg As Double, Tdpt As Double
Public Rnday As Double, Rsdas As Double, Rsdas As Double, Raday As Double
Public EToday As Double, ETrday As Double, EToHG As Double
Public RHmax As Double, RHmin As Double, Uday As Double
Public NumDataFlags As Integer
'-----

Public Datenow As Date, Firstdate As Date, DateOfReading As Date
Public PreviousDate As Date

Public NewFN As Object, Response As Object
Public sw As StreamWriter

Public NeedToReadLine As Boolean, DayDataError As Boolean

Public City As String, State As String
Public COAGMetsite As String
Public OutputDirectory As String, OutputFileName As String
Public File7Exists As Integer, File8Exists As Integer, File9Exists As Integer
Public DayColumns(25) As Integer, NumDayColumns As Integer
Public HourColumns(25) As Integer, NumHourColumns As Integer

Public VPDmax As Double, VPDmin As Double, VP As Double
Public Ts5cm As Double, DayTavg As Double
Public Ts5cmflg As String

Public RScnt(5) As Integer, TDcnt(5) As Integer, TRcnt(5) As Integer
Public RHmaxcnt(5) As Integer, RHmincnt(5) As Integer
Public DaysPerMonth As Integer, LastDayofMonth As Integer

```

```
Public FlagForStart As Integer, LastYear As Integer, HrCount As Integer
```

```
' Flags for the hourly weather variables
```

```
Public Taflg As String, RHflg As String, Tsflg As String, Usflg As String
Public Uvflg As String, Udflg As String, Udevflg As String, Rsflg As String
Public Precipflg As String, Blank As String, Compflg As String
```

```
' Flags and input array for the day AWDN file
```

```
Public DayaryRecord(50) As Object
```

```
Public Thidflg As String, Tlodflg As String, RHdflg As String, Tsdflg As String
Public Usdflg As String, Rsdflg As String, Precipdflg As String
```

```
' Verification parameters
```

```
Public Verify As Boolean = False
```

```
Public VerMon As Integer, VerDay As Integer, VerYear As Integer
```

```
'=====
```

```
Public Sub pickAWDNHourFile_Click(ByVal sender As Object, _
    ByVal e As System.EventArgs) Handles pickAWDNHourFile.Click
```

```
Dim myStream As Object = ""
```

```
Dim Periodspc As Integer, nspace As Integer
```

```
ofdAWDNHour.InitialDirectory = "g:\weather\"
ofdAWDNHour.Filter = ".rhr files (*.rhr)|*.rhr|All files (*.*)|*.*"
ofdAWDNHour.FilterIndex = 2
ofdAWDNHour.RestoreDirectory = True
```

```
If ofdAWDNHour.ShowDialog() = System.Windows.Forms.DialogResult.OK Then
```

```
Try
```

```
myStream = ofdAWDNHour.OpenFile()
```

```
If (myStream IsNot Nothing) Then
```

```
AWDNHourRawFile = ofdAWDNHour.FileName
```

```
End If
```

```
Catch Ex As Exception
```

```
MessageBox.Show("Cannot read file from disk. Error: " & Ex.Message)
```

```
Finally
```

```
' Check to make sure no exceptions on open.
```

```
If (myStream IsNot Nothing) Then
```

```
myStream.Close()
```

```
End If
```

```
End Try
```

```
Else
```

```
MsgBox(" You need to select an AWDN Hourly raw data file ")
```

```
Stop
```

```
End If
```

```
'-----
```

```

AWDNHourFileInfo = My.Computer.FileSystem.GetFileInfo(AWDNHourRawFile)

' AWDNdirectory = (AWDNFileInfo.DirectoryName)
AWDNdirectory = My.Computer.FileSystem.GetParentPath( _
    My.Computer.FileSystem.GetParentPath(AWDNHourRawFile))

Periodspc = InStr(AWDNHourFileInfo.Name, ".")
AWDNHourFilename = Microsoft.VisualBasic.Left(AWDNHourFileInfo.Name, _
    Periodspc - 1).ToUpper.Trim(" ")

AWDNHourlyFileBox.Text = AWDNHourFileInfo.Name
AWDNHourlyFileBox.Show()

'-----
' Determine the name for the AWDN station

nspc = InStr(AWDNHourFilename, "_") - 1
If (nspc > 0) Then
    AWDNStationname = AWDNHourFilename.Substring(0, nspc)
Else
    AWDNStationname = AWDNHourFilename
End If

End Sub

'-----

Private Sub pickAWDNDayFile_Click1(ByVal sender As Object, _
    ByVal ByRefByVal As System.EventArgs) Handles pickAWDNDayFile.Click

    Dim myStream As Object
    Dim Periodspc As Integer

    ofdAWDNDay.InitialDirectory = "g:\weather\"
    ofdAWDNDay.Filter = "rda files (*.rda)|*.rda|All files (*.*)|*.*"
    ofdAWDNDay.FilterIndex = 2
    ofdAWDNDay.RestoreDirectory = True

    myStream = ""

    If ofdAWDNDay.ShowDialog() = System.Windows.Forms.DialogResult.OK Then
        Try
            myStream = ofdAWDNDay.OpenFile()

            If (myStream IsNot Nothing) Then
                AWDNDayRawFile = ofdAWDNDay.FileName

            End If
        Catch Ex As Exception
            MessageBox.Show("Cannot read file from disk. Error: " & Ex.Message)
        Finally
            ' Check to make sure no exceptions on open.

```

```

        If (myStream IsNot Nothing) Then
            myStream.Close()
        End If
    End Try

Else
    MsgBox(" You need to select an AWDN Daily raw data file ")
    Stop
End If

AWDNDayFileInfo = My.Computer.FileSystem.GetFileInfo(AWDNDayRawFile)

Periodspc = InStr(AWDNDayFileInfo.Name, ".")
AWDNDayFilename = Microsoft.VisualBasic.Left(AWDNDayFileInfo.Name, _
    Periodspc - 1).ToUpper.Trim(" ")

AWDNDayFileBox.Text = AWDNDayFileInfo.Name
AWDNDayFileBox.Show()

End Sub

'=====

Public Sub AWDNproperties_Click(ByVal sender As Object, _
    ByVal e As System.EventArgs) Handles AWDNproperties.Click

    ' Subroutine to select file that contains information about AWDN stations

    Dim myStream As Object = ""
    Dim StationFileDialog As New OpenFileDialog()

    StationFileDialog.InitialDirectory = "g:\weather\"
    StationFileDialog.Filter = "AWDNcsv file (*.csv) | *.csv"
    StationFileDialog.FilterIndex = 1
    StationFileDialog.RestoreDirectory = True

    StationInfoFile = ""

    If StationFileDialog.ShowDialog() = System.Windows.Forms.DialogResult.OK Then
        Try
            myStream = StationFileDialog.OpenFile()
            If (myStream IsNot Nothing) Then
                StationInfoFile = StationFileDialog.FileName
            End If
        Catch Ex As Exception
            MessageBox.Show("Cannot read file from disk. - Error: " & Ex.Message)
            Stop
        Finally
            If (myStream IsNot Nothing) Then myStream.Close()
        End Try
    End If

    StationInfoBox.Text = StationFileDialog.SafeFileName.Trim(" ")

```

```
StationInfoBox.Show()
```

```
End Sub
```

```
'=====
```

```
Private Sub SelectStation()
```

```
Dim Response As MsgBoxResult
Dim dzeroa As Double, dzeror As Double, zoma As Double
Dim zomr As Double, Ze As Double
Dim StatString As String
```

```
FileOpen(2, StationInfoFile, OpenMode.Input)
StatString = LineInput(2)
```

```
Do While Not EOF(2)           ' Loop until end of file.
```

```
    StatString = LineInput(2)
    aryRecord = Split(StatString, ",")
```

```
    StationID = aryRecord(0)
    StationName = aryRecord(1)
    Lat_min = aryRecord(2)
    Lat_deg = aryRecord(3)
    Long_min = aryRecord(4)
    Long_deg = aryRecord(5)
    Elev = aryRecord(6)
    StationCode = aryRecord(7)
    StationState = aryRecord(8)
    StationStateAB = aryRecord(9)
    Lat_dec = aryRecord(10)
    Long_dec = aryRecord(11)
    StationTimeZone = aryRecord(12)
    NumFormat = aryRecord(13)
    NumColumns = aryRecord(14)
    WindHt = aryRecord(15)
    TempHt = aryRecord(16)
    VegHt = aryRecord(17)
```

```
    Long_dec = -Long_dec
    Lat_dec = FormatNumber(Lat_dec, 2)
    Long_dec = FormatNumber(Long_dec, 2)
```

```
    StationName.Trim(" ")
```

```
    If (AWDNStationname = StationName.Trim(" ") Or _
        (AWDNStationname = StationID)) Then
```

```
        Response = MsgBox(" Is this the right Station? " & StationName & " " _
            & StationStateAB, MsgBoxStyle.YesNo, "Found Station Information")
```

```
        If Response = MsgBoxResult.Yes Then GoTo Lend
```

```
    End If
```

```
Loop
```

```

Lerr:
  MsgBox("Error Loading Station File, Process Ending", MsgBoxStyle.OkOnly, _
    "Station Load Error")
End

Lend:
If Trim(StationTimeZone.ToUpper) = "CENTRAL" Then
  Lz = 90.0
Else
  Lz = 105.0
End If

' Atmospheric Pressure, kPa
P = FormatNumber(101.3 * ((293 - 0.0065 * Elev) / 293) ^ 5.26, 2)

PC = FormatNumber(0.000665 * P, 4)    ' Psychrometric constant, kPa/C

Lat_rad = Lat_dec * Pi / 180.0      ' Latitude in radians

'-----
' Compute parameters to adjust wind speeds to 2 m and for reference surface
' Parameter for actual vegetation height in meters

dzeroa = 0.67 * VegHt
zoma = 0.123 * VegHt

' Parameters for reference surface of 0.12 m grass
dzeror = 0.67 * 0.12
zomr = 0.123 * 0.12

' Set height of the internal boundary layer (Ze) in meters

Ze = 5

Uratio1 = Math.Log((2.0 - dzeror) / zomr) / Math.Log((WindHt - dzeroa) / zoma)
Uratio2 = Math.Log((Ze - dzeroa) / zoma) / Math.Log((Ze - dzeror) / zomr)

If (Verify) Then

  WriteLine(10, AWDNHourRawFile)
  WriteLine(10)
  WriteLine(10, "Lz", "Pc", "Lat_rad", "VegHt", "dzeroa", "zoma", "dzeror", "zomr", "Ze", _
    "WindHt", "Uratio1", "Uratio2")

  WriteLine(10, Lz, PC, Lat_rad, VegHt, dzeroa, zoma, dzeror, zomr, Ze, WindHt, Uratio1, _
    Uratio2)

  WriteLine(10, "")

  WriteLine(10, "Mon", "Day", "Year", "Hour", "Ta", "RH", "Solar", "Wind", _
    "slope", "Es", "Ea", "Tdew", "dr", "Sd", "Timep", "b", "Sc", "w", "w1", "w2", "ws", _
    "Ra", "Rso", "Rs", "Rns", "beta", "fcdok", "fcd", "Rnl", "Rn", "U2", "Gnightr", _

```

```
"Gdayr", "Cdnightr", "Cddayr", "Gnighto", "Gdayo", "Cdnigho", "Cddayo", _
"G for grass", "Cd for grass", "Cnr", "ETrs", "Cno", "ETos")
```

```
End If
```

```
'-----
```

```
FileClose(2)
```

```
'-----
```

```
' Stop processing if the format for the station is not defined
```

```
If (NumColumns < 0) Then
```

```
  MsgBox("Number of Data Columns is Negative", MsgBoxStyle.Information, _
    "Data Format Error ")
```

```
  End
```

```
End If
```

```
'-----
```

```
' Set column numbers for checking if missing essential data in hourly file
```

```
' NumHourColumns = number of essential data columns in the hourly file
```

```
Select Case NumFormat
```

```
  Case 1
```

```
    NumHourColumns = 8
```

```
    HourColumns(1) = 0
```

```
    HourColumns(2) = 1
```

```
    HourColumns(3) = 2
```

```
    HourColumns(4) = 3
```

```
    HourColumns(5) = 4
```

```
    HourColumns(6) = 6
```

```
    HourColumns(7) = 10
```

```
    HourColumns(8) = 12
```

```
  Case 2
```

```
    NumHourColumns = 8
```

```
    HourColumns(1) = 0
```

```
    HourColumns(2) = 1
```

```
    HourColumns(3) = 2
```

```
    HourColumns(4) = 3
```

```
    HourColumns(5) = 4
```

```
    HourColumns(6) = 6
```

```
    HourColumns(7) = 10
```

```
    HourColumns(8) = 12
```

```
  Case 3
```

```
    NumHourColumns = 8
```

```
    HourColumns(1) = 0
```

```
    HourColumns(2) = 1
```


HourColumns(3) = 2
 HourColumns(4) = 3
 HourColumns(5) = 4
 HourColumns(6) = 6
 HourColumns(7) = 10
 HourColumns(8) = 18

Case 4

NumHourColumns = 8

HourColumns(1) = 0
 HourColumns(2) = 1
 HourColumns(3) = 2
 HourColumns(4) = 3
 HourColumns(5) = 4
 HourColumns(6) = 6
 HourColumns(7) = 10
 HourColumns(8) = 20

Case 5

NumHourColumns = 8

HourColumns(1) = 0
 HourColumns(2) = 1
 HourColumns(3) = 2
 HourColumns(4) = 3
 HourColumns(5) = 4
 HourColumns(6) = 6
 HourColumns(7) = 10
 HourColumns(8) = 12

Case 6 ' COAGMet format

NumHourColumns = 6

HourColumns(1) = 0
 HourColumns(2) = 1
 HourColumns(3) = 2
 HourColumns(4) = 3
 HourColumns(5) = 5
 HourColumns(6) = 6

End Select

'-----
 ' Set column numbers for checking if there is missing data in daily file
 ' NumDayColumns = number of data columns in the daily file

Select Case NumFormat

Case 1 To 5

NumDayColumns = 10

DayColumns(1) = 0

```

DayColumns(2) = 1
DayColumns(3) = 2
DayColumns(4) = 3
DayColumns(5) = 4
DayColumns(6) = 6
DayColumns(7) = 8
DayColumns(8) = 12
DayColumns(9) = 14
DayColumns(10) = 18

```

Case 6

```
NumDayColumns = 8
```

```

DayColumns(1) = 0
DayColumns(2) = 1
DayColumns(3) = 2
DayColumns(4) = 3
DayColumns(5) = 5
DayColumns(6) = 7
DayColumns(7) = 12
DayColumns(8) = 13

```

End Select

End Sub

```
'=====
```

```
Private Sub ProcessData_Click(ByVal sender As Object, ByVal e As _
    System.EventArgs) Handles ProcessData.Click
```

```
' Subroutine to process the hourly data from AWDN files
```

```
Dim Dstring As String, DataString As String, FileString As String
Dim Doy As Integer, TimeDiff As Integer
Dim OldTime As DateTime, NewTime As DateTime
```

```
'-----
```

```
' Initialize Parameters
```

```

fcdok = 0.1
Tmax = -100.0
Tmin = 100.0
Tavg = 0.0
Tdpt = 0.0
RHmax = -100.0
RHmin = 200.0
Uday = 0.0
VPDmax = -100.0
VPDmin = 100.0
Rsdoy = 0.0
Rsoday = 0.0

```

```

Rnday = 0.0
EToday = 0.0
ETrday = 0.0
NumDataFlags = 0

Dstring = ""
Taflg = ""
RHflg = ""
Tsflg = ""
Usflg = ""
Uvflg = ""
Udfg = ""
Udevflg = ""
Rsflg = ""
Precipflg = ""

LastYear = 1980
HrCount = 0
DayDataError = False

'-----
' Open Input Files and Define Output Directory and Filename

FileOpen(1, AWDNHourRawFile, OpenMode.Input)
FileOpen(3, AWDNDayRawFile, OpenMode.Input)

OutputDirectory = Directory.CreateDirectory(AWDNdirectory & _
                                           "\Results\").FullName
OutputFileName = OutputDirectory & AWDNStationname

PMETszOutputBox.Text = OutputFileName
PMETszOutputBox.Show()

If (Verify) Then
    FileOpen(10, OutputDirectory & "Verify", OpenMode.Append)
    Write(10, "          VERIFICATION RESULTS")
    WriteLine(10, "")
End If

'-----
' Check the hourly input string to see if the line has No Valid Data message

Do While Not EOF(1)
    DataString = LineInput(1)
    nvalid = InStr(DataString, "Valid Data")

    If (nvalid = 0) Then
        GoTo L1
    End If
Loop

MsgBox("No Data in AWDN raw file", MsgBoxStyle.OkOnly, "AWDN File Error:")
End

```

```

'-----
' NeedToReadLine represents that first line of data has or has not been read

L1: NeedToReadLine = True

If (DataString.Substring(0, 7) = "CoAgMet") Then
  AWDNStationname = DataString.Substring(16, 5).Trim(" ").ToUpper
  NeedToReadLine = False
Else
  AWDNStationname = DataString.Substring(0, 20).Trim(" ")
  Dstring = LineInput(1) ' Read HPRCC header
End If

' Get parameters from AWDNStationInfo file for weather station

Call SelectStation()

Call OpenOutputFiles()

'-----
' Setup the progress bar
' Set the maximum year for the progress bar
pbar1.Maximum = 2008
pbar1.Step = 1
pbar1.Visible = True
'-----
' Set the flag for the start of weather data to initial value of "-999"
FlagForStart = "-999"

PreviousDate = Date.Parse("1/1/1900")
OldTime = DateTime.Parse("1/1/1990 1:00:00")

'-----
' Read hourly data - Loop until end of file.

Do While Not EOF(1)
  On Error GoTo Lend

  ' Have already Read the First line of COAGMet file
  If (NeedToReadLine) Then DataString = LineInput(1)

  aryRecord = Split(DataString, ",")

  Debug.Print(aryRecord(0))

  NeedToReadLine = True

'-----
' Determine the time for the current line of data

If NumFormat = 6 Then
  Dstring = aryRecord(1)

```

```

NewTime = DateTime.Parse(Dstring)

Else

    Mon = aryRecord(0)
    Mday = aryRecord(1)
    Year = aryRecord(2)
    Hour = aryRecord(3)

    NewTime = DateTime.Parse(Mon & "/" & Mday & "/" & Year)
    NewTime = NewTime.AddHours(Hour / 100.0)

End If

'-----
' Check if there is a skip in the hourly data. If hourly record is
' missing print message to hourly output file for each missing record

If (OldTime > DateTime.Parse("1/1/1990 1:00:00")) Then
    TimeDiff = DateAndTime.DateDiff(DateInterval.Hour, OldTime, NewTime)
    If (TimeDiff > 1) Then
        For j = 1 To (TimeDiff - 1)
            OldTime = OldTime.AddHours(1.0)

            WriteLine(7, OldTime.Month, OldTime.Day, _
                OldTime.Year, 100 * OldTime.Hour, _
                OldTime.DayOfYear, " Missing hourly record")
        Next j
    End If
End If

'-----
' Check if essential data are missing in the hourly record

For j = 1 To NumHourColumns
    If (aryRecord(j).ToString = "") Then
        WriteLine(7, DateValue(Dstring).Month, DateValue(Dstring).Day, _
            DateValue(Dstring).Year, 100 * TimeValue(Dstring).Hour, _
            DateValue(Dstring).DayOfYear, " Missing essential data")
        GoTo Loop1
    End If
Next

'-----
' Assign variables to the data read from the hourly file

Call AssignHourly()

'-----

Datenow = DateSerial(Year, Mon, Mday)
Doy = DateSerial(Year, Mon, Mday).DayOfYear

```

```

'-----
' Use flag for start and the hour to begin on first hour of the day
' Start processing for the first full day

If (FlagForStart < 0 And Hour <> 100) Then GoTo Loop1

If (FlagForStart < 0) Then

'-----
' Read data from day file until it equals yesterday from hour file
' Set flag for first day of reading from the daily file

' FlagforReadingDailyData = -1 hourly starts earlier daily file
' FlagforReadingDailyData = 0 hourly = daily date for first time
' FlagforReadingDailyData = 1 hourly = daily after first match

Call readAWDNDayToYesterday()

If FlagforReadingDailyData = -1 Then
  GoTo Loop1
End If

' Set the first day of data for the form
FirstMonthBox.Text = Str(Mon)
FirstMonthBox.Show()
FirstDayBox.Text = Str(Mday)
FirstDayBox.Show()
FirstYearBox.Text = Str(Year)
FirstYearBox.Show()

' Set FlagForStart to zero once first full day of data was found
FlagForStart = 0

' Set PreviousDate once appropriate date has been determined
If (PreviousDate = Date.Parse("1/1/1900")) Then
  PreviousDate = Database.AddDays(-1.0)
End If

LastYear = Year
pbar1.Minimum = Year
pbar1.Value = Year

End If

'-----
' Increment the ProgressBar

If (Year > LastYear) Then
  pbar1.Value = Year
  LastYear = Year
  pbar1.Update()
End If
'-----

```

```
' Set empty flags to * and concatenate major flags into compound flag
```

```
If (Taflg = " ") Then Taflg = "*"
If (RHflg = " ") Then RHflg = "*"
If (Tsflg = " ") Then Tsflg = "*"
If (Usflg = " ") Then Usflg = "*"
If (Uvflg = " ") Then Uvflg = "*"
If (Udflg = " ") Then Udflg = "*"
If (Udevflg = " ") Then Udevflg = "*"
If (Rsflg = " ") Then Rsflg = "*"
If (Precipflg = " ") Then Precipflg = "*"
```

```
Compflg = Taflg & RHflg & Tsflg & Usflg & Uvflg & Udflg & Udevflg & Rsflg
```

```
NumDataFlags = InStr(Compflg, "E") + InStr(Compflg, "e") + _
  InStr(Compflg, "M") + InStr(Compflg, "R") + NumDataFlags
```

```
'-----
' If there are no errors in the weather data
' Call Penman-Monteith subroutine to compute hourly reference ET
```

```
If (Ta = -999 Or RH = -999 Or Solar = -999 Or Us = -999) Then
  Tdew = -999.0
  Ea = -999.0
  Es = -999.0
  Rs = -999.0
  Rso = -999.0
  Ra = -999.0
  Rn = -999.0
  U2 = -999.0
  ETos = -999.0
  ETrs = -999.0
```

```
Else
  Call Penman_Monteith()
End If
```

```
'-----
' Print the hourly results to file 7 using the given formats
```

```
WriteLine(7, Mon, Mday, Year, Hour, Doy, _
  FormatNumber(Ta, 2), FormatNumber(RH, 2), FormatNumber(Ts, 2), _
  FormatNumber(Us, 2), FormatNumber(Uv, 2), FormatNumber(Ud, 0), _
  FormatNumber(Udev, 2), FormatNumber(Solar, 2), FormatNumber(Precip, 2), _
  Compflg, FormatNumber(Tdew, 2), FormatNumber(Ea, 3), _
  FormatNumber(Es, 3), FormatNumber(Rs, 2), FormatNumber(Rso, 2), _
  FormatNumber(Ra, 2), FormatNumber(Rn, 2), FormatNumber(ETos, 2), _
  FormatNumber(ETrs, 2), NumDataFlags)
```

```
' Print Verification Results
If (Verify) Then
  If (DateSerial(Year, Mon, Mday) = DateSerial(VerYear, VerMon, VerDay)) Then
```

```

WriteLine(10, Mon, Mday, Year, Hour, Ta, RH, Solar, Us, slope, Es, Ea, _
    Tdew, dr, Sd, Timep, b, Sc, w, w1, w2, ws, Ra, Rso, Rs, Rns, beta, _
    fcdok, fcd, Rnl, Rn, U2, Gnightr, Gdayr, Cdnightr, Cddayr, Gnightr, _
    Gdayo, Cdnightr, Cddayo, G, Cd, Cnr, ETrs, Cno, ETos)

    End If
End If

'-----
' Update daily totals or averages with latest hourly data for day
' And add 1 to the hourly counter

Tmax = Math.Max(Tmax, Ta)
Tmin = Math.Min(Tmin, Ta)
RHmax = Math.Max(RHmax, RH)
RHmin = Math.Min(RHmin, RH)
Tavg = Tavg + Ta
Tdpt = Tdpt + Tdew
Uday = Uday + U2
VPDmax = Math.Max(VPDmax, (Es - Ea))
VPDmin = Math.Min(VPDmin, (Es - Ea))
Rsday = Rsday + Rs
Rsoday = Rsoday + Rso
Rnday = Rnday + Rn

EToday = EToday + Math.Max(0.0, ETos)
ETrday = ETrday + Math.Max(0.0, ETrs)

HrCount = HrCount + 1

'-----
' If it is the end of the day compute the daily averages and
' read the corresponding data for the current day from the daily file,
' compute Hargreaves ETo using daily maximum and minimum temperatures
' and then print the daily results

If Hour = 2400 Then

    Call CheckDailyData()

'-----
' Reset the daily average and total variables for daily results

Tmax = -100.0
Tmin = 100.0
RHmin = 200
RHmax = -100
Tavg = 0.0
Tdpt = 0.0
Uday = 0.0
VPDmax = -100.0

```



```

VPDmin = 100.0
Rsd day = 0.0
Rsod ay = 0.0
Rnd ay = 0.0
ETod ay = 0.0
ETrd ay = 0.0
NumDataFlags = 0
HrCount = 0
DayDataError = False

'-----
' Print statistics and zero the counters at the end of the month

DaysPerMonth = Date.DaysInMonth(Year, Mon)

If (Mday = DaysPerMonth) Then

    WriteLine(9, Mon, Year, _
        RScnt(0), RScnt(1), RScnt(2), RScnt(3), RScnt(4), _
        TDcnt(0), TDcnt(1), TDcnt(2), TDcnt(3), TDcnt(4), _
        TRcnt(0), TRcnt(1), TRcnt(2), TRcnt(3), TRcnt(4), _
        RHmaxcnt(0), RHmaxcnt(1), RHmaxcnt(2), RHmaxcnt(3), _
        RHmaxcnt(4), RHmincnt(0), RHmincnt(1), RHmincnt(2), _
        RHmincnt(3), RHmincnt(4))

    ' Reset the statistical counters
    For j = 0 To 4
        RScnt(j) = 0
        TDcnt(j) = 0
        TRcnt(j) = 0
        RHmaxcnt(j) = 0
        RHmincnt(j) = 0
    Next
End If

End If
'-----

Loop1:
    OldTime = NewTime

Loop

'-----
' End of the hourly data file.

Lend:
    On Error Resume Next
    MsgBox(" File Finished", , "AWDN File Processing")

    FileClose(1)

```

```

FileClose(3)
FileClose(7)
FileClose(8)
FileClose(9)
FileClose(10)

```

```
End Sub
```

```

'=====
Private Sub Penman_Monteith()

'////////////////////////////////////
'///                                     ///
'/// Hourly estimate of Reference Crop ET using ASCE Penman-Monteith Method  ///
'///                                     ///
'////////////////////////////////////

Dim Doy As Integer

' slope of saturation vapor pressure curve, kPa/C
slope = 2503.0 * (Math.Exp((17.27 * Ta) / (Ta + 237.3))) / ((Ta + 237.3) ^ 2.0)

Es = 0.6108 * Math.Exp((17.27 * Ta) / (Ta + 237.3)) ' Saturation Vapor Pressure, kPa
Ea = Es * (Math.Min(100.0, RH) / 100.0)           ' Actual Vapor Pressure ea, kPa
Tdew = (237.3 * Math.Log(Ea) + 116.91) / (16.78 - Math.Log(Ea)) ' Dew Point Temp, C
Doy = DateSerial(Year, Mon, Mday).DayOfYear      ' Day of Year

' Doy = Mday(-32.0 + Int(275.0 * Mon / 9.0) + 2.0 * Int(3.0 / (Mon + 1)) _
' + Int((Mon / 100.0 - (Year - Int(Year / 4.0) * 4.0) / 4.0 + 0.975))

dr = 1.0 + 0.033 * Math.Cos(2.0 * Doy * Pi / 365.0) ' Inverse Relative Distance
Sd = 0.409 * Math.Sin(2.0 * Doy * Pi / 365.0 - 1.39) ' Solar declination Sd
Timep = Hour / 100.0 - 0.5                          ' Standard clock time
b = 2.0 * Pi * (Doy - 81.0) / 364.0

' Seasonal correction for solar time Sc
Sc = 0.1645 * Math.Sin(2 * b) - 0.1255 * Math.Cos(b) - 0.025 * Math.Sin(b)

'-----
' Solar time angle at midpoint w
w = (Pi / 12.0) * (Timep + 0.06667 * (Lz - Long_dec) + Sc - 12.0)

w1 = w - Pi / 24.0
w2 = w + Pi / 24.0
ws = Math.Acos(-Math.Tan(Lat_rad) * Math.Tan(Sd))

If w1 < -ws Then w1 = -ws
If w2 < -ws Then w2 = -ws
If w1 > ws Then w1 = ws
If w2 > ws Then w2 = ws
If w1 > w2 Then w1 = w2

```

```

'-----
' Extraterrestrial radiation - hourly
Ra = (12.0 / Pi) * dr * Gsc * ((w2 - w1) * Math.Sin(Lat_rad) * Math.Sin(Sd) _
+ Math.Cos(Lat_rad) * Math.Cos(Sd) * (Math.Sin(w2) - Math.Sin(w1)))

If w < -ws Then Ra = 0.0
If w > ws Then Ra = 0.0

Rso = (0.75 + 0.00002 * Elev) * Ra      ' Clear sky radiation
Rs = Solar * 3600.0 / 1000000.0      ' Solar Radiation, MJ/m2-hr

'-----
' Check limits on solar radiation
If (Rs > Rso) Then                    ' Check Max value of Rs
  Rs = Rso
  NumDataFlags = NumDataFlags + 1
End If

If (Rs < 0) Then                      ' Check Min value of Rs
  Rs = 0
  NumDataFlags = NumDataFlags + 1
End If

Rns = 0.77 * Rs                      ' Net Shortwave Radiation, MJ/m2-hr

beta = Math.Asin(Math.Sin(Lat_rad) * Math.Sin(Sd) + _
  Math.Cos(Lat_rad) * Math.Cos(Sd) * Math.Cos(w))

'-----
' Compute cloudiness factor

' If beta < 0.3 set fcd to last good value of fcd

If beta < 0.3 Then
  fcd = fcdok
Else
  fcd = Math.Min(1.0, (1.35 * (Rs / Rso) - 0.35))
  fcd = Math.Max(0.05, fcd)
  fcdok = fcd
End If

' Net long wave radiation

Rnl = (2.042 * 10.0 ^ -10.0) * (Ta + 273.16) ^ 4.0 * (0.34 - 0.14 * Ea ^ 0.5) * fcd
Rn = Rns - Rnl                      ' Net solar radiation

'-----
' Adjust wind speed to 2-m reference height for a reference grass surface

U2 = Us * Uratio1 * Uratio2

'-----

```

```

' Compute reference crop ET for alfalfa reference crop

If Rn < 0.0 Then          ' Compute soil heat flux
    G = Gnightr * Rn
Else
    G = Gdayr * Rn
End If

If Rn <= 0.0 Then        ' Set the Cd parameter
    Cd = Cdnightr
Else
    Cd = Cddayr
End If

ETrs = (0.408 * slope * (Rn - G) + (PC * Cnr * U2 * (Es - Ea)) / (Ta + 273.0)) _
        / (slope + PC * (1 + Cd * U2))

'-----
' Compute reference crop ET for grass reference crop

If Rn < 0.0 Then          ' Compute soil heat flux
    G = Gnightr * Rn
Else
    G = Gdayo * Rn
End If

If Rn <= 0.0 Then        ' Set the Cd parameter
    Cd = Cdnightr
Else
    Cd = Cddayo
End If

ETos = (0.408 * slope * (Rn - G) + (PC * Cno * U2 * (Es - Ea)) / (Ta + 273.0)) _
        / (slope + PC * (1 + Cd * U2))

'-----
End Sub

'=====

Private Sub AWDNform_Load(ByVal sender As System.Object, _
    ByVal e As System.EventArgs) Handles MyBase.Load

End Sub

'=====

Private Sub readAWDNDayToYesterday()

    Dim Dstring As String
    Dim NotFirstTime As Boolean

'-----
' Check the input string to see if the date is valid

```

```

Do While Not EOF(3)          ' Loop until end of file.
  Dstring = LineInput(3)    ' Read data
  nvalid = InStr(Dstring, "Valid Data")

  If (nvalid = 0) Then
    GoTo L1
  End If
Loop

MsgBox("No Data in AWDN day file", MsgBoxStyle.OkOnly, "AWDN File Error:")
End

```

L1:

```

' Read the header and first line from AWDNDay file for HPRCC format
Select Case NumFormat
  Case 1 To 5
    Dstring = LineInput(3)
    Dstring = LineInput(3)
End Select

' Already read the first line of data for all formats so set to false
NotFirstTime = False

'-----
' Begin the loop to read the weather data one day at a time.

Do Until EOF(3)

  If (NotFirstTime) Then Dstring = LineInput(3)

  DayaryRecord = Split(Dstring, ",")
  NotFirstTime = True

  Call AssignDaily()

  '-----
  ' Check if daily date equals hourly date

  DateOfReading = DateSerial(DayYear, DayMon, DayMday)
  If (Datenow <= DateOfReading) Then GoTo L2
Loop

MsgBox(" Reached End of Daily Data File", , " Error Reading Daily File:")
End

```

L2:

```

If (Datenow = DateOfReading) Then
  FlagforReadingDailyData = 0
  Return
Else

  ' Hour file starts before day file

```

```

    FlagforReadingDailyData = -1
End If

End Sub

'=====
Private Sub CheckDailyData()

'-----
' Read the weather data from the day file
' FlagforReadingDailyData = 1 for the first day of data,
' so that data has been read already then skip reading.

Dim Dstring As String
Dim Doy As Integer, DayDiff As Integer

Ladj:
If (FlagforReadingDailyData < 1) Then
    FlagforReadingDailyData = 1
Else
    Dstring = LineInput(3)
    DayaryRecord = Split(Dstring, ",")
End If

If NumFormat = 6 Then
    DateOfReading = DayaryRecord(1)
    DayMon = DateOfReading.Month
    DayMday = DateOfReading.Day
    DayYear = DateOfReading.Year

Else
    DayMon = DayaryRecord(0)
    DayMday = DayaryRecord(1)
    DayYear = DayaryRecord(2)
    DateOfReading = DateSerial(DayYear, DayMon, DayMday)
End If

Doy = DateSerial(DayYear, DayMon, DayMday).DayOfYear

'-----
' Check to see if there is a skip in the daily records in the file
' If record is missing print message to daily output file
' for each missing record

DayDiff = DateDiff(DateInterval.Day, PreviousDate, DateOfReading)
If (DayDiff > 1) Then
    For j = 1 To (DayDiff - 1)
        PreviousDate = PreviousDate.AddDays(1.0)

        WriteLine(8, PreviousDate.Month, PreviousDate.Day, _
            PreviousDate.Year, PreviousDate.DayOfYear, " Missing Daily Record")
    Next j
End If

```

```

'-----
' Check hourly date (Datenow) and date of reading for daily data
' If date from daily file is less than date from the hourly date, need to
' read daily records until matches the hourly date. Print missing label.

If (DateOfReading < Datenow) Then
  WriteLine(8, DayMon, DayMday, DayYear, Doy, "Missing Hourly Data")
  PreviousDate = DateSerial(DayYear, DayMon, DayMday)
  GoTo Ladj
Elseif (DateOfReading > Datenow) Then
  ' There is a skip in the daily file so that hourly file is now earlier than
  ' the daily file.
  FlagforReadingDailyData = -1
  Return
End If

'-----
' Check to see if essential data are missing
For j = 1 To NumDayColumns
  If (DayaryRecord(DayColumns(j)).ToString = "") Then
    DayDataError = True
    GoTo Lend
  End If
Next

'-----
' Good to Process Data

Call AssignDaily()

'-----
If (HrCount <> 24) Then
  DayDataError = True
Else
  Tavg = Tavg / 24.0
  Tdpt = Tdpt / 24.0
  Uday = Uday / 24.0

'-----
' Compute the Hargreaves ETo (mm/day) for grass reference crop
' Extraterrestrial radiation - daily

Raday = (24.0 / Pi) * dr * Gsc * (ws * Math.Sin(Lat_rad) * _
  Math.Sin(Sd) + Math.Cos(Lat_rad) * Math.Cos(Sd) * Math.Sin(ws))

EToHG = 0.0023 * Math.Sqrt(Math.Abs(DayThi - DayTlo)) * _
  (0.5 * (DayThi + DayTlo) + 17.8) * Raday / 2.45

'-----
' Compute statistics for selected parameters

If (Rsday >= Rsoday) Then RScnt(0) = RScnt(0) + 1

```

```

If (0.9 <= Rsday / Rsoday And Rsday / Rsoday < 1.0) Then RScnt(1) = RScnt(1) + 1
If (0.75 <= Rsday / Rsoday And Rsday / Rsoday < 0.9) Then RScnt(2) = RScnt(2) + 1
If (0.5 <= Rsday / Rsoday And Rsday / Rsoday < 0.75) Then RScnt(3) = RScnt(3) + 1
If (Rsday / Rsoday < 0.5) Then RScnt(4) = RScnt(4) + 1

If (Tdpt >= DayTlo) Then TDcnt(0) = TDcnt(0) + 1
If (0 < (DayTlo - Tdpt) And (DayTlo - Tdpt) <= 2.0) Then TDcnt(1) = TDcnt(1) + 1
If (2.0 < (DayTlo - Tdpt) And (DayTlo - Tdpt) <= 4.0) Then TDcnt(2) = TDcnt(2) + 1
If (4.0 < (DayTlo - Tdpt) And (DayTlo - Tdpt) <= 6.0) Then TDcnt(3) = TDcnt(3) + 1
If ((DayTlo - Tdpt) > 6.0) Then TDcnt(4) = TDcnt(4) + 1

If ((DayThi - DayTlo) <= 10) Then TRcnt(0) = TRcnt(0) + 1
If (10 < (DayThi - DayTlo) And (DayThi - DayTlo) <= 15.0) Then TRcnt(1) = TRcnt(1) + 1
If (15.0 < (DayThi - DayTlo) And (DayThi - DayTlo) <= 20.0) Then TRcnt(2) = TRcnt(2) + 1
If (20.0 < (DayThi - DayTlo) And (DayThi - DayTlo) <= 25.0) Then TRcnt(3) = TRcnt(3) + 1
If ((DayThi - DayTlo) > 25.0) Then TRcnt(4) = TRcnt(4) + 1

If (RHmax >= 100.0) Then RHmaxcnt(0) = RHmaxcnt(0) + 1
If (90.0 < RHmax And RHmax <= 100.0) Then RHmaxcnt(1) = RHmaxcnt(1) + 1
If (75.0 < RHmax And RHmax <= 90.0) Then RHmaxcnt(2) = RHmaxcnt(2) + 1
If (50.0 < RHmax And RHmax <= 75.0) Then RHmaxcnt(3) = RHmaxcnt(3) + 1
If (RHmax <= 50.0) Then RHmaxcnt(4) = RHmaxcnt(4) + 1

If (RHmin >= 100.0) Then RHmincnt(0) = RHmincnt(0) + 1
If (75.0 < RHmin And RHmin <= 100.0) Then RHmincnt(1) = RHmincnt(1) + 1
If (50.0 < RHmin And RHmin <= 75.0) Then RHmincnt(2) = RHmincnt(2) + 1
If (25.0 < RHmin And RHmin <= 50.0) Then RHmincnt(3) = RHmincnt(3) + 1
If (RHmin <= 25.0) Then RHmincnt(4) = RHmincnt(4) + 1
End If

```

Lend:

```

'-----
' Print to the daily file

If (DayDataError) Then
  Doy = DateSerial(DayYear, DayMon, DayMday).DayOfYear
  WriteLine(8, DayMon, DayMday, DayYear, Doy, "Missing or Bad Data")
Else

  WriteLine(8, DayMon, DayMday, DayYear, Doy, _
    FormatNumber(Tmax, 2), FormatNumber(Tmin, 2), _
    FormatNumber(Tavg, 2), FormatNumber(Tdpt, 2), FormatNumber(DayThi, 2), _
    FormatNumber(DayTlo, 2), FormatNumber(RHmax, 2), FormatNumber(RHmin, 2), _
    FormatNumber(VPDmin, 3), FormatNumber(VPDmax, 3), _
    FormatNumber(Uday, 3), FormatNumber(Rsday, 2), _
    FormatNumber(Rsoday, 2), FormatNumber(Raday, 2), FormatNumber(Rnday, 2), _
    FormatNumber(EToday, 2), FormatNumber(ETrday, 2), FormatNumber(EToHG, 2), _
    FormatNumber(DayETrHPRC, 2), NumDataFlags)

' Print Verification Results
If (Verify) Then

```



```

If (DateSerial(Year, Mon, Mday) = DateSerial(VerYear, VerMon, VerDay)) Then

    WriteLine(10, "")
    WriteLine(10, "DOY", "Tmax", "Tmin", "DayThi", "DayTlo", "Raday", _
        "EToHG", "EToday", "ETrday")

    WriteLine(10, Doy, Tmax, Tmin, DayThi, DayTlo, Raday, EToHG, EToday, _
        ETrday)

    End If
End If

End If

PreviousDate = DateOfReading
DayDataError = False

End Sub

'=====

Private Sub OpenOutputFiles()

    Dim FileString As String

    ' Open output files as new if they don't exist and append if they do exist

    If File.Exists(OutputFileName & ".hrl") Then
        FileOpen(7, OutputFileName & ".hrl", OpenMode.Append)
    Else
        FileOpen(7, OutputFileName & ".hrl", OpenMode.Output)

        WriteLine(7, StationName, StationStateAB, StationID, Lat_dec, Long_dec, _
            Lz, Elev, P, PC, StationTimeZone)

        FileString = " Month, Day, Year, Hour, DOY, AirTemp_C, RelHum_%, SoilTemp_C, " _
            & " WindSp_m/s, WindV_m/s, WindDir_rad, WDirDev_rad, Solar_W/m2, Precip_mm, " _
            & " CompFlag, Tdew_C, Ea_kPa, Es_kPa, Rs_MJ/m2-h, Rso_MJ/m2-h, Ra_MJ/m2-h, " _
            & " Rn_MJ/m2-h, ETos_mm/h, ETrs_mm/h, NumDataFlags"

        PrintLine(7, FileString)
    End If

    If File.Exists(OutputFileName & ".day") Then
        FileOpen(8, OutputFileName & ".day", OpenMode.Append)
    Else
        FileOpen(8, OutputFileName & ".day", OpenMode.Output)

        WriteLine(8, StationName, StationStateAB, StationID, Lat_dec, Long_dec, _
            Lz, Elev, P, PC, StationTimeZone)
    End If

```

```

FileString = " Month, Day, Year, DOY, Tmax_C, Tmin_C, Tavg_C, Tdew_C, Thi_C, " _
& " Tlo_C, RHmax_%, RHmin_%, VPDmin_kPa, " _
& " VPDmax_kPa, Wind_m/s, Solar_MJ/m2-d, Rso_MJ/m2-d, Rext_MJ/m2-d, " _
& " Rn_MJ/m2-d, ETo_mm/d, ETr_mm/d, EToHG_mm/d, ETrHPRCC_mm/d, NumDataFlags"

PrintLine(8, FileString)
End If

If File.Exists(OutputFileName & ".cnt") Then
FileOpen(9, OutputFileName & ".cnt", OpenMode.Append)
Else
FileOpen(9, OutputFileName & ".cnt", OpenMode.Output)

WriteLine(9, StationName, StationStateAB, StationID, Lat_dec, Long_dec, _
Lz, Elev, P, PC, StationTimeZone)

FileString = " Mon, Year, RS>Rso, Rs/Rso>0.9, Rs/Rso>0.75, Rs/Rso>0.5, " _
& " Rs/Rso<0.5, Tlo-Td<0, Tlo-Td<2, Tlo-Td<4, Tlo-Td<6, Tlo-Td>6, " _
& " Thi-Tlo<10, Thi-Tlo<15, Thi-Tlo<20, Thi-Tlo<25, Thi-Tlo>25, " _
& " RHmax>100, RHmax>90, RHmax>75, RHmax>50, RHmax<50, " _
& " RHmin>100, RHmin>75, RHmin>50, RHmin>25, RHmin<25"

PrintLine(9, FileString)
End If

End Sub
'=====
Private Sub AssignHourly()

' Subroutine to assign variable to data read from hourly weather data file
' Select the format for the input data based on the NumFormat

Select Case NumFormat
Case 1
' month day year hour AIR TEMP C Rel Hum %
' SOIL TMP C-S10CM RAD W/M2 WIND SP M/SEC WIND VEC M/S
' Wind vector Vector std dev PRECIP MM TOT RAD KJ/M2

For j = 0 To 21
If (aryRecord(j) = "") Then aryRecord(j) = "-999"
Next

Mon = aryRecord(0)
Mday = aryRecord(1)
Year = aryRecord(2)
Hour = aryRecord(3)
Ta = aryRecord(4)
Taflg = aryRecord(5)
RH = aryRecord(6)
RHflg = aryRecord(7)
Ts = aryRecord(8)
Tsflg = aryRecord(9)

```

```

Solar = aryRecord(10)
Rsflg = aryRecord(11)
Us = aryRecord(12)
Usflg = aryRecord(13)
Uv = aryRecord(14)
Uvflg = aryRecord(15)
Ud = aryRecord(16)
Udflg = aryRecord(17)
Udev = aryRecord(18)
Udevflg = aryRecord(19)
Precip = aryRecord(20)
Precipflg = aryRecord(21)

```

Case 2

```

' month   day   year   hour   AIR TEMP C   Rel Hum %
' SOIL TMP C-S10CM  WIND SP M/SEC   WIND VEC M/S  Wind vector
' Vector std dev   RAD W/M2   PRECIP MM

```

```

For j = 0 To 21
  If (aryRecord(j) = "") Then aryRecord(j) = "-999"
Next

```

```

Mon = aryRecord(0)
Mday = aryRecord(1)
Year = aryRecord(2)
Hour = aryRecord(3)
Ta = aryRecord(4)
Taflg = aryRecord(5)
RH = aryRecord(6)
RHflg = aryRecord(7)
Ts = aryRecord(8)
Tsflg = aryRecord(9)
Us = aryRecord(10)
Usflg = aryRecord(11)
Uv = aryRecord(12)
Uvflg = aryRecord(13)
Ud = aryRecord(14)
Udflg = aryRecord(15)
Udev = aryRecord(16)
Udevflg = aryRecord(17)
Solar = aryRecord(18)
Rsflg = aryRecord(19)
Precip = aryRecord(20)
Precipflg = aryRecord(21)

```

Case 3

```

' month   day   year   hour   AIR TEMP C   Rel Hum %
' SOIL TMP C-S10CM  5CM SOIL TEMP C   WIND SP M/SEC
' WIND VEC M/S   Wind vector   Vector std dev
' RAD(w / M2)   PRECIP MM   SH BAND DIFFUSE
' PAR uE/m**2   PAR #2

```

```

For j = 0 To 21
  If (aryRecord(j) = "") Then aryRecord(j) = "-999"
Next

```

```

Mon = aryRecord(0)
Mday = aryRecord(1)
Year = aryRecord(2)
Hour = aryRecord(3)
Ta = aryRecord(4)
Taflg = aryRecord(5)
RH = aryRecord(6)
RHflg = aryRecord(7)
Ts = aryRecord(8)
Tsflg = aryRecord(9)
Ts5cm = aryRecord(10)
Ts5cmflg = aryRecord(11)
Us = aryRecord(10)
Usflg = aryRecord(11)
Uv = aryRecord(12)
Uvflg = aryRecord(13)
Ud = aryRecord(14)
Udflg = aryRecord(15)
Udev = aryRecord(16)
Udevflg = aryRecord(17)
Solar = aryRecord(18)
Rsflg = aryRecord(19)
Precip = aryRecord(20)
Precipflg = aryRecord(21)

```

Case 4

```

' month   day   year   hour   AIR TEMP C   Rel Hum %
' SOIL TMP C-S10CM WIND SP M/SEC   WIND VEC M/S   Wind vector
' Vector std dev   PRECIP MM   RAD W/M2   SOIL TEM TUR 10CM
' TOT RAD KJ/M2   TRAD ASE KJ/M2   TRAD AS KJ/M2   TRAD ASW KJ/M2

```

```

For j = 0 To 21
  If (aryRecord(j) = "") Then aryRecord(j) = "-999"
Next

```

```

Mon = aryRecord(0)
Mday = aryRecord(1)
Year = aryRecord(2)
Hour = aryRecord(3)
Ta = aryRecord(4)
Taflg = aryRecord(5)
RH = aryRecord(6)
RHflg = aryRecord(7)
Ts = aryRecord(8)
Tsflg = aryRecord(9)
Us = aryRecord(10)
Usflg = aryRecord(11)
Uv = aryRecord(12)

```

```

Uvflg = aryRecord(13)
Ud = aryRecord(14)
Udflg = aryRecord(15)
Udev = aryRecord(16)
Udevflg = aryRecord(17)
Precip = aryRecord(18)
Precipflg = aryRecord(19)
Solar = aryRecord(20)
Rsflg = aryRecord(21)

```

Case 5

```

' Format for Kansas data

' month day year hour AIR TEMP C-S Samp RH %
' Wind avg dir WIND SP M/SEC Rad Flux MJ/m**2 PRECIP MM
' SOIL TEM C-S10CM

```

```

For j = 0 To 17
  If (aryRecord(j) = "") Then aryRecord(j) = "-999"
Next

```

```

Mon = aryRecord(0)
Mday = aryRecord(1)
Year = aryRecord(2)
Hour = aryRecord(3)
Ta = aryRecord(4)
Taflg = aryRecord(5)
RH = aryRecord(6)
RHflg = aryRecord(7)
Ud = aryRecord(8)
Udflg = aryRecord(9)
Us = aryRecord(10)
Usflg = aryRecord(11)
Solar = aryRecord(12)
Rsflg = aryRecord(13)
Precip = aryRecord(14)
Precipflg = aryRecord(15)
Ts = aryRecord(16)
Tsflg = aryRecord(17)

```

```

Solar = Solar * 277.78 ' Convert from MJ/m2-hr to W/m2

```

Case 6

```

' COAGMet hourly data format: Station Code,
' Datetime (in the format YYYY-MM-DD HH:MM:SS),
' Mean(Temperature(Celsius)), Relative(Humidity(Fraction)),
' Vapor(Pressure(kPa)), Solar(Radiation(kJ / m ^ 2 * min)),
' Mean Wind Speed (m/s), Vector Average Wind Direction
' (in Degrees, 0 and 360 being north),
' Standard Deviation of Wind Direction (Degrees),
' Precipitation(millimeters), Mean Soil Temp at 5cm (Celsius),
' Mean Soil Temp at 15cm (Celsius), Wind(Gust(m / s)),
' Wind Gust Time (minutes into day), Wind Gust Direction (Degrees)

```

```

'-----
' COAGMet treats midnight as start of next day, i.e. hour = 0:00,
' while HPRCC treats midnight as hour = 24:00. To be consistent if
' hour = 0:00 then the hour is changed to 2400 and the date is
' set to the previous day

COAGMetsite = aryRecord(0).ToString.ToUpper

DateOfReading = aryRecord(1)
Hour = DateOfReading.Hour
If Hour = 0 Then
    DateOfReading = DateOfReading.AddMinutes(-1.0)
    Hour = 24
End If

Hour = Hour * 100

Mon = DateOfReading.Month
Mday = DateOfReading.Day
Year = DateOfReading.Year
'-----

For j = 0 To 14
    If (aryRecord(j) = "") Then aryRecord(j) = "-999"
Next

Ta = aryRecord(2)
RH = aryRecord(3)
VP = aryRecord(4)
Solar = aryRecord(5)
Us = aryRecord(6)
Ud = aryRecord(7)
Udev = aryRecord(8)
Precip = aryRecord(9)
Ts5cm = aryRecord(10)
Ts = aryRecord(11)

RH = RH * 100          ' Conver to percentage
Solar = Solar * 1000.0 / 60.0 ' Convert from KJ/min-m2 to W/m2

End Select

'-----
' Check hourly data for quality

If (RH <> -999) Then
    If (RH > 100.0) Then
        RH = 100.0
        NumDataFlags = NumDataFlags + 1
    End If

```

```

If (RH < 10.0) Then
  RH = 10.0
  NumDataFlags = NumDataFlags + 1
End If
End If

```

```

If (Ta <> -999) Then
  If (Ta > 50) Then
    Ta = 38
    NumDataFlags = NumDataFlags + 1
  End If
  If (Ta < -40) Then
    Ta = -40.0
    NumDataFlags = NumDataFlags + 1
  End If
End If

```

```

If (Us <> -999) Then
  If (Us > 30) Then
    Us = 30
    NumDataFlags = NumDataFlags + 1
  End If
End If

```

```

'-----

```

```

End Sub

```

```

'-----

```

```

Private Sub AssignDaily()

```

```

  ' Assign daily records to daily variables for HPRCC (1-5) and COAGMet (6)

```

```

  Select Case NumFormat

```

```

    Case 1 To 5

```

```

      For j = 0 To 18

```

```

        If (DayaryRecord(j) = "") Then DayaryRecord(j) = "-999"

```

```

      Next

```

```

      DayMon = DayaryRecord(0)

```

```

      DayMday = DayaryRecord(1)

```

```

      DayYear = DayaryRecord(2)

```

```

      DayHour = DayaryRecord(3)

```

```

      DayThi = DayaryRecord(4)

```

```

      Thidflg = DayaryRecord(5)

```

```

      DayTlo = DayaryRecord(6)

```

```

      Tlodflg = DayaryRecord(7)

```

```

      DayRH = DayaryRecord(8)

```

```

      RHdflg = DayaryRecord(9)

```

```

      DaySoilT = DayaryRecord(10)

```

```

      Tsdflg = DayaryRecord(11)

```

```

      DayUZ = DayaryRecord(12)

```

```

Usdflg = DayaryRecord(13)
DaySolar = DayaryRecord(14)
Rsdfg = DayaryRecord(15)
DayPrecip = DayaryRecord(16)
Precipdflg = DayaryRecord(17)
DayETrHPRC = DayaryRecord(18)

```

Case 6

```

'-----
' Read daily data for COAGMet format: COAGMet Site Code,
' Datetime (in the format YYYY-MM-DD), Mean(Temperature(Celsius))
' Maximum(Temperature(Celsius)), Time Maximum Temperature (HH:MM:SS),
' Minimum(Temperature(Celsius)), Time Minimum Temperature (HH:MM:SS),
' Vapor(Pressure(kPa)), Maximum Relative Humidity (Fraction),
' Time Maximum Relative Humidity (HH:MM:SS), Minimum Relative Humidity
' (Fraction), Time of Minimum Relative Humidity (HH:MM:SS),
' Solar(Radiation(MJ / m ^ 2)), Wind_Run(km / Day),
' Precipitation(millimeters),
' Maximum Soil Temperature at 5cm (Celsius),
' Time of Maximum Soil Temperature at 5cm (HH:MM:SS),
' Minimum Soil Temperature at 5cm (Celsius)
' Time of Minimum Soil Temperature at 5cm (HH:MM:SS),
' Maximum Soil Temperature at 15cm (Celsius),
' Time of Maximum Soil Temperature at 15cm (HH:MM:SS)
' Minimum Soil Temperature at 15cm (Celsius),
' Time of Minimum Soil Temperature at 15cm (HH:MM:SS),
' Battery(Voltage), Year of data, Maximum daily wind gust (m/s),
' Time maximum daily wind gust (min into day NOT HH:MM as other),
' Direction of maximum daily wind gust (deg)
'-----

```

```

For j = 0 To 27
  If (DayaryRecord(j) = "") Then DayaryRecord(j) = "-999"
Next

```

```
COAGMetsite = DayaryRecord(0)
```

```

DateOfReading = DayaryRecord(1)
DayMon = DateOfReading.Month
DayMday = DateOfReading.Day
DayYear = DateOfReading.Year

```

```

DayTavg = DayaryRecord(2)
DayThi = DayaryRecord(3)
DayTlo = DayaryRecord(5)
DaySolar = DayaryRecord(12)
DayUZ = DayaryRecord(13)
DayPrecip = DayaryRecord(14)

```

```
DayUZ = DayUZ * 1000.0 / 86400.0 ' Convert to average speed m/s
```

```
DayETrHPRC = -99.0
```


End Select

End Sub

'=====

Private Sub radVerify_CheckedChanged(ByVal sender As System.Object, ByVal e As _
System.EventArgs) Handles radVerify.CheckedChanged

' Set the verification parameters

If radVerify.Checked Then

Verify = True

VerMon = boxVerifyMonth.Text

VerDay = boxVerifyDay.Text

VerYear = boxVerifyYear.Text

Else

Verify = False

VerMon = 1

VerDay = 1

VerYear = 1900

End If

End Sub

'=====

End Class

Appendix 2. PMETsz.vb Program

Imports System.IO

Public Class AWDNform

Public AWDNrawfile As String, AWDNdirectory As String, AWDNFilename As String
 Public AWDNFileInfo As System.IO.FileInfo
 Public ofdStation As New OpenFileDialog()

Public StationID As String, StationName As String
 Public Lat_min As Double, Lat_deg As Double, Long_min As Double, Long_deg As Double, Elev As
 Double, _
 Lat_dec As Double, Long_dec As Double
 Public StationCode As Integer
 Public StationState As String, StationStateAB As String, StationTimeZone As String

Public Row As Long, Mon As Integer, Mday As Integer, Year As Integer, Hour As Integer, nvalid As
 Integer, Doy As Integer

Public Ta As Double, Tdew As Double, RH As Double, Ts As Double, Us As Double, Uv As Double, Ud As
 Double
 Public Udev As Double, Solar As Double, Precip As Double

Public Cd As Double, Lat_rad As Double
 Public Lz As Double, P As Double, PC As Double, slope As Double, Es As Double, Ea As Double
 Public dr As Double, Sd As Double, Timep As Double, b As Double, Sc As Double
 Public w As Double, w1 As Double, w2 As Double, ws As Double, beta As Double
 Public Ra As Double, Rs As Double, Rso As Double, Rn As Double, Rnl As Double, Rns As Double
 Public fcd As Double, fcdok As Double, U2 As Double

Public G As Double, ETrs As Double, ETos As Double

Public Jday As Integer

Public Gsc As Double = 4.92, Pi As Double = Math.PI

Public Gnightr As Double = 0.2, Gdayr As Double = 0.04, Cddayr As Double = 0.25
 Public Cdnightr As Double = 1.7, Cnr As Double = 66

Public Gnighto As Double = 0.5, Gdayo As Double = 0.1, Cddayo As Double = 0.24
 Public Cdnigho As Double = 0.96, Cno As Double = 37

Public Dstring As String, StationInfoFile As String

Public Tmax As Double, Tmin As Double, Tavg As Double, Tdpt As Double, Uday As Double, Rnday As
 Double
 Public Rsday As Double, Rsoday As Double, Raday As Double, EToday As Double, ETrday As Double,
 EToHG As Double

'=====

```
Public Sub pickAWDNfile_Click(ByVal sender As Object, ByVal e As System.EventArgs) Handles
pickAWDNfile.Click
```

```

Dim myStream As Object
Dim Periodspc As Integer

ofdStation.InitialDirectory = "c:\"
ofdStation.Filter = "txt files (*.txt)|*.txt|All files (*.*)|*.*"
ofdStation.FilterIndex = 2
ofdStation.RestoreDirectory = True

myStream = ""

If ofdStation.ShowDialog() = System.Windows.Forms.DialogResult.OK Then
Try
myStream = ofdStation.OpenFile()

If (myStream IsNot Nothing) Then
AWDNrawfile = ofdStation.FileName

End If
Catch Ex As Exception
MessageBox.Show("Cannot read file from disk. Original error: " & Ex.Message)
Finally
' Check to make sure no exceptions on open.
If (myStream IsNot Nothing) Then
myStream.Close()
End If
End Try

Else
MsgBox(" You need to select an AWDN raw data file ")
Stop
End If

MsgBox(AWDNrawfile, MsgBoxStyle.OkOnly, Title:="Weather File is:")
AWDNFileInfo = My.Computer.FileSystem.GetFileInfo(AWDNrawfile)
AWDNdirectory = (AWDNFileInfo.DirectoryName)

Periodspc = InStr(AWDNFileInfo.Name, ".")
AWDNFilename = Microsoft.VisualBasic.Left(AWDNFileInfo.Name, Periodspc - 1).ToUpper.Trim("
").Replace(" ", "-")

AWDNFileBox.Text = AWDNrawfile
AWDNFileBox.Show()

End Sub

'=====

Public Sub AWDNproperties_Click(ByVal sender As Object, ByVal e As System.EventArgs) Handles
AWDNproperties.Click
```

```

' Subroutine to select the file that contains information about the AWDN stations

Dim myStream As Object
Dim StationFileDialog As New OpenFileDialog()

StationFileDialog.InitialDirectory = "c:\\"
StationFileDialog.Filter = "AWDNcsv file (*.csv)|*.csv"
StationFileDialog.FilterIndex = 1
StationFileDialog.RestoreDirectory = True

myStream = ""
StationInfoFile = ""

If StationFileDialog.ShowDialog() = System.Windows.Forms.DialogResult.OK Then
  Try
    myStream = StationFileDialog.OpenFile()

    If (myStream IsNot Nothing) Then

      StationInfoFile = StationFileDialog.FileName
      '   Debug.Print(StationInfoFile)
    End If

  Catch Ex As Exception
    MessageBox.Show("Cannot read file from disk. --- Original error: " & Ex.Message)
    Stop

  Finally
    ' Check this again, since we need to make sure we didn't throw an exception on open.
    If (myStream IsNot Nothing) Then
      myStream.Close()
    End If
  End Try
End If

StationInfoBox.Text = StationInfoFile
StationInfoBox.Show()

End Sub

Private Sub SelectStation()

  Dim aryRecord(13) As Object

  FileOpen(2, StationInfoFile, OpenMode.Input)

  Dstring = LineInput(2)

  'StationID   Name   Lat_Min Lat_deg Long_min      Long-deg      Elev_m  State_Code
    State_Name   State_Abbr   Lat_dec Long_dec

  Do While Not EOF(2)          ' Loop until end of file.
    Dstring = LineInput(2)

```

```

'      Debug.Print(Dstring)

aryRecord = Split(Dstring, ",")

StationID = aryRecord(0)
StationName = aryRecord(1)
Lat_min = aryRecord(2)
Lat_deg = aryRecord(3)
Long_min = aryRecord(4)
Long_deg = aryRecord(5)
Elev = aryRecord(6)
StationCode = aryRecord(7)
StationState = aryRecord(8)
StationStateAB = aryRecord(9)
Lat_dec = aryRecord(10)
Long_dec = aryRecord(11)
Long_dec = -Long_dec
StationTimeZone = aryRecord(12)

' Debug.Print(" Station: " & StationID & " " & StationName & " " & Elev)
' Debug.WriteLine(" Station info : " & " " & StationCode & " " & StationState & " " &
StationStateAB)
' Debug.WriteLine(" Location: " & " " & Lat_dec & " " & Long_dec)

StationName.Trim(" ").Replace(" ", "-")

Debug.Print(AWDNFilename & " and " & StationName.Trim(" ").Replace(" ", "-"))

If (AWDNFilename = StationName.Trim(" ").Replace(" ", "-")) Then
' file matches station list
MsgBox(" File and Station Names Match", MsgBoxStyle.OkOnly, "Found Station Information")
GoTo Lend
End If

Loop

Lerr:
MsgBox("Error Loading Station File, Process Ending", MsgBoxStyle.OkOnly, "Station Load Error")
Stop

Lend:
If Trim(StationTimeZone.ToUpper) = "CENTRAL" Then
Lz = 90
Else
Lz = 105
End If

P = 101.3 * ((293 - 0.0065 * Elev) / 293) ^ 5.26 ' Atmospheric Pressure, kPa
PC = 0.000665 * P ' Psychrometric constant, kPa/C
Lat_rad = Lat_dec * Pi / 180.0 ' Latitude in radians

FileClose(2)

```

End Sub

'=====

```
Private Sub Finished_Click(ByVal sender As Object, ByVal e As System.EventArgs) Handles Finished.Click
    End
End Sub
```

'=====

```
Private Sub ProcessData_Click(ByVal sender As Object, ByVal e As System.EventArgs) Handles
ProcessData.Click
```

```
    ' Process the AWDN file
```

```
    '-----
```

```
    ' Define the local variables
```

```
    Dim Datenow As Date, Firstdate As Date
```

```
    Dim aryRecord(22) As Object
```

```
    Dim NewFN As Object, Response As Object
```

```
    Dim Dstring As String, City As String, State As String
```

```
    Dim OutputDirectory As String, OutputFileName As String
```

```
    Dim FlagForStart As Integer
```

```
    ' Dimension flags for weather variables
```

```
    Dim Taflg As String, RHflg As String, Tsflg As String, Usflg As String, Uvflg As String, Udflg As String
```

```
    Dim Udevflg As String, Rsflg As String, Precipflg As String, Blank As String, Compflg As String
```

```
    '-----
```

```
    ' Open input and output files
```

```
    FileOpen(1, AWDNrawfile, OpenMode.Input)
```

```
    OutputDirectory = Directory.CreateDirectory(AWDNdirectory & "\Results\").FullName
```

```
    OutputFileName = OutputDirectory & AWDNFilename
```

```
    ETrefOutputBox.Text = OutputFileName
```

```
    ETrefOutputBox.Show()
```

```
    FileOpen(7, OutputFileName & ".hrl", OpenMode.Output)
```

```
    FileOpen(8, OutputFileName & ".day", OpenMode.Output)
```

```
    '-----
```

```
    ' Initialize Parameters
```

```
    fcdok = 0.1
```

```
    Tmax = -100.0
```

```
    Tmin = 100.0
```

```
    Tavg = 0.0
```

```
    Tdpt = 0.0
```

```
    Uday = 0.0
```

```
    Rsday = 0.0
```

```
    Rsoday = 0.0
```

```
    Raday = 0.0
```

```

Rnday = 0.0
EToday = 0.0
ETrday = 0.0
Dstring = ""
'-----
' Search the AWDN Station Info file to get station parameters

Call SelectStation()

Debug.Print("Processing: " & AWDNrawfile)

' Check the input string to see if the date is valid

Do While Not EOF(1)      ' Loop until end of file.
  Dstring = LineInput(1) ' Read data
  nvalid = InStr(Dstring, "Valid Data")

  If (nvalid = 0) Then
    GoTo L1
  End If

Loop

L1:

' Print the location information and the headers for the output files

WriteLine(7, StationName, StationStateAB, StationID, Lat_dec, Long_dec, Lz, Elev, P, PC,
StationTimeZone)
WriteLine(8, StationName, StationStateAB, StationID, Lat_dec, Long_dec, Lz, Elev, P, PC,
StationTimeZone)

Dstring = LineInput(1)      ' Read header

Dstring = " Month, Day, Year, Hour, DOY, AirTemp_C, RelHum_%, SoilTemp_C, WindSp_m/s, " _
& "WindV_m/s, WindDir_rad, WDirDev_rad, Solar_W/m2, Precip_mm, CompFlag, " _
& "Tdew_C, Ea_kPa, Es_kPa, Rs_MJ/m2-h, Rso_MJ/m2-h, Ra_MJ/m2-h, Rn_MJ/m2-h, ETos_mm/h,
ETrs_mm/h"

PrintLine(7, Dstring)

Dstring = " Month, Day, Year, DOY, Tmax_C, Tmin_C, Tavg_C, Tdew_C, " _
& " Wind_m/s, Solar_MJ/m2-d, Rso_MJ/m2-d, Rext_MJ/m2-d, Rn_MJ/m2-d, ETo_mm/d,
ETr_mm/d, EToHG_mm/d"

PrintLine(8, Dstring)

'-----
' Read hourly data
'-----

FlagForStart = -999

```

```

Do While Not EOF(1)          ' Loop until end of file.
  On Error GoTo Lend

  Dstring = LineInput(1)
  aryRecord = Split(Dstring, ",")

  '   For Each itm In aryRecord
  '     Debug.Print(itm)
  '   Next itm

  Mon = aryRecord(0)
  Mday = aryRecord(1)
  Year = aryRecord(2)
  Hour = aryRecord(3)
  Ta = aryRecord(4)
  Taflg = aryRecord(5)
  RH = aryRecord(6)
  RHflg = aryRecord(7)
  Ts = aryRecord(8)
  Tsflg = aryRecord(9)
  Us = aryRecord(10)
  Usflg = aryRecord(11)
  Uv = aryRecord(12)
  Uvflg = aryRecord(13)
  Ud = aryRecord(14)
  Udflg = aryRecord(15)
  Udev = aryRecord(16)
  Udevflg = aryRecord(17)
  Solar = aryRecord(18)
  Rsflg = aryRecord(19)
  Precip = aryRecord(20)
  Precipflg = aryRecord(21)

  If (FlagForStart < 0 And Hour <> 100) Then GoTo Loop1

  If (FlagForStart < 0) Then

    Datenow = DateSerial(Year, Mon, Mday)
    Firstdate = DateSerial(Year - 1, 12, 31)
    Doy = DateDiff(DateInterval.DayOfYear, Firstdate, Datenow)

    DOYbox.Text = Str(Doy)
    DOYbox.Show()
    YearBox.Text = Str(Year)
    YearBox.Show()

    FlagForStart = 1
  End If

  If (Taflg = " ") Then Taflg = "*"

```



```

If (RHflg = " ") Then RHflg = "*"
If (Tsflg = " ") Then Tsflg = "*"
If (Usflg = " ") Then Usflg = "*"
If (Uvflg = " ") Then Uvflg = "*"
If (Udflg = " ") Then Udflg = "*"
If (Udevflg = " ") Then Udevflg = "*"
If (Rsflg = " ") Then Rsflg = "*"
If (Precipflg = " ") Then Precipflg = "*"

```

```
Compflg = Taflg & RHflg & Tsflg & Usflg & Uvflg & Udflg & Udevflg & Rsflg & Precipflg
```

```
Call Penman_Monteith()
```

```
WriteLine(7, Mon, Mday, Year, Hour, Doy, Ta, RH, Ts, Us, Uv, Ud, Udev, Solar, Precip, Compflg, _
    Tdew, Ea, Es, Rs, Rso, Ra, Rn, ETos, ETrs)
```

```

Tmax = Math.Max(Tmax, Ta)
Tmin = Math.Min(Tmin, Ta)
Tavg = Tavg + Ta
Tdpt = Tdpt + Tdew
Uday = Uday + U2
Rsday = Rsday + Rs
Rsoday = Rsoday + Rso
Raday = Raday + Ra
Rnday = Rnday + Rn
EToday = EToday + Math.Max(0.0, ETos)
ETrday = ETrday + Math.Max(0.0, ETrs)

```

```

If Hour = 2400 Then
    Tavg = Tavg / 24.0
    Tdpt = Tdpt / 24.0
    Uday = Uday / 24.0

```

```
EToHG = 0.0023 * Math.Sqrt(Tmax - Tmin) * (Tavg + 17.8) * Raday / 2.45
```

```
WriteLine(8, Mon, Mday, Year, Doy, Tmax, Tmin, Tavg, Tdpt, Uday, Rsday, _
    Rsoday, Raday, Rnday, EToday, ETrday, EToHG)
```

```

Tmax = -100.0
Tmin = 100.0
Tavg = 0.0
Tdpt = 0.0
Uday = 0.0
Rsday = 0.0
Rsoday = 0.0
Raday = 0.0
Rnday = 0.0
EToday = 0.0
ETrday = 0.0

```

```
End If
```

```
Dstring = Str(Doy) & " / " & Str(Year)
Debug.Print(Dstring)
```

```
Loop1:
```

```
Loop
```

```
Lend:
```

```
On Error Resume Next
MsgBox(" File Finished", , "AWDN File Processing")
```

```
FileClose(1)
```

```
FileClose(7)
```

```
FileClose(8)
```

```
End Sub
```

```
'=====
==
```

```
Private Sub Penman_Monteith()
```

```
'////////////////////////////////////
```

```
'///                               ///
```

```
'/// Hourly estimation of Reference Crop ET usin ASCE Penman-Monteith Method ///
```

```
'///                               ///
```

```
'////////////////////////////////////
```

```
Rs = Solar * 3600.0 / 1000000.0           ' Solar Radiation, MJ/m2-hr
```

```
' slope of saturation vapor pressure curve, kPa/C
```

```
slope = 2503.0 * (Math.Exp((17.27 * Ta) / (Ta + 237.3))) / ((Ta + 237.3) ^ 2.0)
```

```
Es = 0.6108 * Math.Exp((17.27 * Ta) / (Ta + 237.3)) ' Saturation Vapor Pressure, kPa
```

```
Ea = Es * (RH / 100.0)                   ' Actual Vapor Pressure ea, kPa
```

```
Tdew = (237.3 * Math.Log(Ea) + 116.91) / (16.78 - Math.Log(Ea)) ' Dew Point Temp, C
```

```
Rns = 0.77 * Rs                           ' Net Shortwave Radiation, MJ/m2-hr
```

```
Jday = Mday - 32.0 + Int(275.0 * Mon / 9.0) + 2.0 * Int(3.0 / (Mon + 1)) _
      + Int((Mon / 100.0 - (Year - Int(Year / 4.0) * 4.0) / 4.0 + 0.975) * 365.25) ' Julian day
```

```
dr = 1.0 + 0.033 * Math.Cos(2.0 * Jday * Pi / 365.0) ' Inverse Relative Distance factor
```

```
Sd = 0.409 * Math.Sin(2.0 * Jday * Pi / 365.0 - 1.39) ' Solar declination Sd
```

```
Timep = Hour / 100.0 - 0.5                ' Standard clock time
```

```
b = 2.0 * Pi * (Jday - 81.0) / 364.0
```

```

' Seasonal correction solar time Sc
Sc = 0.1645 * Math.Sin(2 * b) - 0.1255 * Math.Cos(b) - 0.025 * Math.Sin(b)

'solar time angle at midpoint w
w = (Pi / 12.0) * (Timep + 0.06667 * (Lz - Long_dec) + Sc - 12.0)

w1 = w - Pi / 24.0
w2 = w + Pi / 24.0

ws = Math.Acos(-Math.Tan(Lat_rad) * Math.Tan(Sd))

If w1 < -ws Then w1 = -ws
If w2 < -ws Then w2 = -ws
If w1 > ws Then w1 = ws
If w2 > ws Then w2 = ws
If w1 > w2 Then w1 = w2

Ra = (12.0 / Pi) * dr * Gsc * ((w2 - w1) * Math.Sin(Lat_rad) * Math.Sin(Sd) +
  + Math.Cos(Lat_rad) * Math.Cos(Sd) * (Math.Sin(w2) - Math.Sin(w1)))

If w < -ws Then Ra = 0.0
If w > ws Then Ra = 0.0

Rso = (0.75 + 0.00002 * Elev) * Ra      ' Clear sky radiation

beta = Math.Asin(Math.Sin(Lat_rad) * Math.Sin(Sd) +
  + Math.Cos(Lat_rad) * Math.Cos(Sd) * Math.Cos(w))

If beta < 0.3 Then      ' Compute cloudiness factor
  fcd = fcdok
Else
  fcd = (1.35 * (Rs / Rso) - 0.35)
  fcd = Math.Min(Math.Max(0.05, fcd), 1.0)
  fcdok = fcd
End If

' Net long wave radiation

Rnl = (2.042 * 10.0 ^ -10.0) * (Ta + 273.16) ^ 4.0 * (0.34 - 0.14 * Ea ^ 0.5) * fcd

Rn = Rns - Rnl      ' Net solar radiation

U2 = Us * 0.9209      ' Wind speed at 2 m height

'-----
' Compute reference crop ET for alfalfa reference crop

If Rn < 0.0 Then      ' Compute soil heat flux
  G = Gnightr * Rn
Else
  G = Gdayr * Rn
End If

```

```

If Rn <= 0.0 Then                                ' Set the Cd parameter
    Cd = Cdnightr
Else
    Cd = Cddayr
End If

ETrs = (0.408 * slope * (Rn - G) + (PC * Cnr * U2 * (Es - Ea)) / (Ta + 273.0)) _
        / (slope + PC * (1 + Cd * U2))

'-----
' Compute reference crop ET for grass reference crop

If Rn < 0.0 Then                                ' Compute soil heat flux
    G = Gnighto * Rn
Else
    G = Gdayo * Rn
End If

If Rn <= 0.0 Then                                ' Set the Cd parameter
    Cd = Cdnightr
Else
    Cd = Cddayo
End If

ETos = (0.408 * slope * (Rn - G) + (PC * Cno * U2 * (Es - Ea)) / (Ta + 273.0)) _
        / (slope + PC * (1 + Cd * U2))

End Sub

Private Sub DoneButton_Click()
    End
End Sub

Private Sub StationInfoBox_TextChanged(ByVal sender As System.Object, ByVal e As System.EventArgs)
Handles StationInfoBox.TextChanged

    End Sub

    Private Sub Label1_Click(ByVal sender As System.Object, ByVal e As System.EventArgs) Handles
Label1.Click

        End Sub
End Class

```