THESIS

EVAPOTRANSPIRATION-BASED IRRIGATION SCHEDULING TOOLS FOR USE IN EASTERN COLORADO

Submitted by

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ABSTRACT

EVAPOTRANSPIRATION-BASED IRRIGATION SCHEDULING IN EASTERN COLORADO

Accurate evapotranspiration (ET) information can be used to improve irrigation water management in eastern Colorado. Crop ET information can be used to help an irrigation manager make decisions on when to initiate irrigation and to determine how much water should be applied. ET information can be obtained through the use of specialized equipment, estimated using models, or obtained from sources such as Colorado Agricultural Meteorological Network (CoAgMet) (http://climate.colostate.edu/~coagmet/).

This study has one main focus, the testing of tools for use in ET-based irrigation scheduling. The purpose of the first part of this study was to develop and test two irrigation scheduling tools, one for use with annual crops (Colorado Irrigation Scheduler: Annual (CIS-A)) and the other for use with forage crops (Colorado Irrigation Scheduler: Forage (CIS-F)). The tools use ET information calculated using the ASCE Standardized Reference ET equation to track the daily soil water balance in a crop's root zone and make recommendations on irrigation timings and amount of water to be applied. The second part of this study tested the accuracy of a Model E atmometer (ETgage Company, Loveland, CO, USA) in providing estimates of reference ET in southeastern Colorado.

In the first part of the study the CIS-A was tested at two sites (north and south) during the 2010 – 2012 growing season in a corn (*Zea mays* L.) field located near Greeley, Colorado. The results of the study indicated that the performance of the tool was acceptable based on the relatively small magnitude of errors in the estimated deficits compared to total available water (TAW) in the soil profile. RMSE was at most 15.3% of TAW, as was the case in 2012 at the north site, and was as low as 8.6% of TAW in 2011 at the north site. The CIS-A tended to overestimate the observed deficit during all years of the study and across all sites (relative error, RE = 13.58% and mean bias error MBE = -3.41 mm). Overall average error indicated that the CIS-A was within 15.92 mm (root mean square error, RMSE) and 12.61 mm (mean absolute error, MAE) of the observed deficit for the entire study. Satisfactory performance of the CIS-A was observed in all years and across all sites with the exception of 2012 at the north site. In 2012 the performance of the CIS-A was less than acceptable (RMSE = 22.89 mm, MBE = -12.86 mm, MAE = 18.01 mm, and RE = 30.85%). Evaluations of the CIS-F during the 2010 and 2011 growing seasons showed mixed results. The CIS-F was tested on two weighing lysimeters in two different alfalfa (*Medicago sativa* L.) fields located at the Arkansas Valley Research Center (AVRC) near Rocky Ford, Colorado. During both years of the study the CIS-F tended to overestimate the observed deficit. The CIS-F performed best in 2011(RMSE = 22.02 mm, MBE = -16.95 mm, MAE = 17.65 mm, and RE = 18.73%) with a RMSE within 6.6% of TAW. In 2010 poorer results were obtained (RMSE = 38.21 mm, MBE = -32.84 mm, MAE = 32.94 mm, and RE = 34.11%). However, in 2010 RMSE was still within 11.5% of TAW. Upon further analysis it was found that much of the error encountered during the evaluation of the CIS-F occurred early in each growing season. It was determined that during this period, crop ET (ET_c) estimated using the scheduler was higher than lysimeter measured ET. The difference between lysimeter measured ET and ET_c estimated using the ASCE (2005) hourly guidelines for a tall crop and crop coefficients developed using data from the lysimeters was determined to be the major source of the error experienced during both growing seasons. ET_c was found to be significantly higher than lysimeter measured ET during the initial part of the alfalfa growing season causing the CIS-F to estimate a deficit greater than what was observed.

The objective of the second part of this study was to determine if an ETgage Model E atmometer, equipped with a canvas #54 cover, could be used to effectively estimate alfalfa reference ET. The ASCE Standardized Alfalfa Reference ET Equation (ASCE ET_{rs}) was used as the standard for comparison of atmometer ET values to determine atmometer performance. Four years of alfalfa ET, as determined by an atmometer (ET_{gage}), were compared to ASCE ET_{rs}. Daily as well as 2, 3, 5, and 7 day sums of daily ET_{gage} and ASCE ET_{rs} were compared using simple least-squares linear regression. Coefficients of determination (R^2) between daily ET_{gage} and ASCE ET_{rs} for all years were greater than or equal to 0.80. Throughout the study, the atmometer tended to underestimate ASCE ET_{rs}. Average seasonal underestimation of ASCE ET_{rs} measured by the atmometer ranged from 9.06% to 18.9%. Root Mean Square Error (RMSE) and Mean Bias Error (MBE) ranged from 1.14 to 1.82 mm d^{-1} and -0.66 to -1.51 mm d^{-1}, respectively. The atmometer underestimated daily ASCE ET_{rs} 88% of the time, with an average underestimation of 1.30 mm d^{-1}. Under estimation of ASCE ET_{rs} measured by the atmometer occurred most often on days when mean daily horizontal wind speeds were greater than 2 m s^{-1} or when mean daily air temperatures were below 20 °C. The atmometer performed best when the alfalfa was at reference condition. Localized calibration equations for reference and non-reference conditions with a temperature correction were developed to improve accuracy, with average magnitude of MBE reduced from -0.97 mm d^{-1} to 0.13 mm d^{-1}.

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CHAPTER 1: INTRODUCTION

Evapotranspiration (ET) is a combination of two processes, evaporation of water from soil surfaces and transpiration of water from plant materials (Allen et al., 1998 and Davis and Dukes, 2010). Just after planting, nearly 100% of ET is from evaporation. As crops grow and the canopy closes transpiration makes up the largest fraction of ET. Once full canopy is achieved greater than 90% of ET is from transpiration (Allen et al., 1998). In areas where crop production is primarily limited by lack of precipitation it is important for an irrigation manager to know the rate of ET. In order to meet crop water requirements the water lost through the processes of ET must be replaced, either through precipitation or irrigation. ET-based irrigation scheduling is a method of irrigation scheduling that can be used by irrigation managers to ensure crop water requirements are met while also ensuring over-irrigation does not occur. Both under-irrigation and over-irrigation have unintended consequences. Under-irrigation causes a reduction in quality and quantity of yield. Over-irrigation can have the same effect on quality and quantity of yield, but more importantly over-irrigation can result in off farm transport of nutrients, pesticides, and other agro-chemicals and increases operating costs, wastes energy and water (Irmak et al., 2006).

ET information can be used by an irrigation manager to help make more sound irrigation scheduling decisions (Bauder, 2005). Knowing when and how much irrigation water to apply is an important component of crop production in areas that require irrigation to meet crop water requirements (Irmak et al., 2005). There are two classes of methods used to obtain ET information. The first class is referred to as direct methods. Direct measurements of ET estimates include eddy covariance, Bowen ratio, and weighing lysimeters. Direct measurements of ET are considered to be the best methods of obtaining ET information because they are a direct measure of actual crop ET (ET_c). However, they are expensive and the equipment requires regular maintenance and extensive training in order to obtain accurate ET information. Direct methods are typically used to calibrate the second and more practical class of methods used to obtain ET information (Allen et al., 2007).

The second class of methods used to obtain ET information is referred to as indirect. The term indirect is applied to these types of methods because no direct measurements of ET are made, but rather ET is modeled or evaporation from a surface other than a plant canopy is measured. Indirect methods include a variety of weather based equations used to estimate ET from a vegetated surface. The list is extensive, but some of the more popular equations used in Colorado include the 1985 Hargreaves (Hargreaves and Allen, 2003), 1982 Kimberly-Penman (ASCE-EWRI, 2005), Blaney-Criddle (Brower and Heibloem, 1986) and the ASCE-EWRI (2005) Standardized Penman-Monteith Reference Evapotranspiration Equation. The latter is considered to be one of the best methods available to estimate ET using indirect methods (Allen et al., 2007). Also, in 2003 the United States Supreme Court recommended its use to determine reference crop ET (ET_{ref}) and crop consumptive use for compliance with the Arkansas River Compact in the case of Kansas v. Colorado (Ley et al. 2010; Montgomery, 2003). As a result the Standardized Reference ET equation has been more widely adopted as the preferred method to estimate ET.

Other types of indirect methods include devices like evaporative pans and atmometers. The evaporative pan measures the rate of evaporation from a water-filled container with a known surface area that is open to the atmosphere. An atmometer is a little more complex than the evaporative pan, yet it is still a simple and inexpensive device. An atmometer consists of a water filled reservoir capped with a water filled porous ceramic cup (Alam and Trooien, 2001, and Altenhofen, 1985). The ceramic cup is connected to the water reservoir by a small plastic tube.

As water evaporates from the ceramic cup it is replaced by water from the reservoir through suction. Water that evaporates from the atmometer can be measured electronically using a data logger or manually, depending on the type of atmometer used. Covers made of different types of fabrics are typically placed over the ceramic cup to control vapor diffusion rates, protect the ceramic cup from contamination, and help shed rain or irrigation water. The different types of fabrics are designed to mimic different rates of ET, typically grass or alfalfa reference ET.

All of the indirect methods provide ET information in a form that is referred to as reference ET (ET_{ref}). ET_{ref} is defined by the ASCE-EWRI (2005) as being the rate of ET from a hypothetical vegetated surface having a dense, uniform, actively growing canopy with a specified height and surface resistance, is not short of soil moisture, and representing a minimum expanse of 100 m with the same or similar vegetation type. In Colorado the use of an alfalfa-based, also referred to as a tall reference, ET_{ref} estimate is more common (Al-Kaisi and Broner, 2009). The ASCE-EWRI Standardized Reference ET Equation (ET_{rs}) for a tall crop is calculated using Equation (1) for an hourly time step:

$$\mathrm{ET_{rs}} = \frac{0.408\,\Delta\,(\mathrm{R_n} - \mathrm{G}) + \gamma\,\frac{\mathrm{C_n}}{\mathrm{T} + 273}\,\mu_2\,(\mathrm{e_s} - \mathrm{e_a})}{\Delta + \gamma\,(1 + \mathrm{C_d}\mu_2)} \qquad \text{Eq. (1)}$$

where: ET_{rs} is the standardized reference crop ET for a tall crop (mm/h), R_n is calculated net radiation at the crop surface ($MJ/m^2/h$), G is the soil heat flux density at the soil surface ($MJ/m^2/h$), T is the mean hourly air temperature measured at 1.5 to 2 m above the soil surface (°C), μ_2 is the mean hourly wind speed at 2 m, e_s is the saturation vapor pressure at 1.5 to 2.5 m above soil surface (kPa), e_a is the mean actual vapor pressure 1.5 to 2.5 m above the soil surface (kPa), Δ is the slope of the saturation vapor pressure-temperature curve (kPa/°C), γ is the psychrometric constant (kPa/°C), C_n is a numerator constant specific to reference crop type and calculation time step (equal to 66 (K mm s^3/Mg/h) for tall reference and hourly time step calculations), C_d is the denominator constant that changes with reference crop type and calculation time step (equal to 0.25 (s/m) during daytime and 1.7 (s/m) during nighttime for tall reference and hourly time step calculations), and where the coefficient 0.408 is in m^2 mm/MJ. Measurements or estimates of solar radiation, wind speed, air temperature, and humidity are required variables, and calculation procedures for the terms used in the Standardized Reference ET equation for a tall reference crop are described in detail in the ASCE-EWRI (2005) publication.

In order to obtain an estimate of actual crop ET (ET_c), similar to that obtained using direct methods, a crop coefficient must be used to transform ET_{ref}. The method of using a crop coefficient to estimate ET_c is the most common procedure used to calculate ET_c (Irmak et al. 2005). Crop coefficients have been developed to incorporate the effects of conditions experienced by a crop in the field, including: changes in leaf area, plant height, crop specific characteristics, irrigation methods, the rate at which a crop develops, planting or sowing dates, degree of canopy cover, canopy resistance, soil and climate conditions, and management practices (Doorenbos and Pruitt, 1977 and Irmak et al., 2005). Crop coefficients have been developed for specific use with each indirect method and crop type for both the equation style ET_{ref} calculations, and evaporation measuring devices. Caution should be used when selecting crop coefficients from previous literature. An irrigation manager or researcher must ensure that the crop coefficient selected is appropriate for the method being used to estimate ET_{ref}.

This thesis is a compilation of two scientific articles that study two indirect methods of estimating ET. The first objective was to develop, demonstrate, and evaluate an ET-based irrigation scheduling spreadsheet tool for use by irrigators and water managers to track daily soil water deficit. The intent of the tool is to provide the necessary framework to simplify the tracking of a soil's daily water balance using ET_{ref} information. The use of the tool is intended to provide recommendations on the timing and amount of irrigation water to be applied in order to improve irrigation management. The scientific article that addresses the first objective is presented in Chapter 2 of this thesis. The second main objective was to determine if a Model E (ETgage Company, Loveland, CO, USA) atmometer equipped with a canvas #54 cover could be used to effectively estimate alfalfa reference ET as calculated by the ASCE Standardized Reference ET Equation (ET_{rs}) in southeast Colorado. Calibration equations were developed to improve ET_{rs} estimates made using an atmometer to more closely estimate that which is calculated using the Standardized Reference ET equation. The scientific article that addresses the second main objective is presented in Chapter 3 of this thesis.

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CHAPTER 2: DEVELOPMENT AND EVALUATION OF TWO EVAPOTRANSPIRATION-BASED IRRIGATION SCHEDULING TOOLS

SUMMARY

Proper irrigation management is vital to most crop production in arid and semi-arid regions. Precise irrigation scheduling techniques help ensure crop water requirements are met while also conserving fresh water resources and protecting the environment from off-farm transport of agro-chemicals. The objectives of this study were to develop, demonstrate, and evaluate an ET-based irrigation scheduling spreadsheet tool for use by producers and irrigation water managers to help facilitate improved irrigation management decisions. Two irrigation scheduling tools were developed using Microsoft Excel® spreadsheets to track daily soil water deficits, one for use with annual crops (CIS-A), and one for use with alfalfa (CIS-F). The performance of the scheduling tools was tested using observed field data. Three years of data (2010 – 2012) at two sites (north and south) obtained from a corn (*Zea mays* L.) field near Greeley, Colorado was used to test the CIS-A's ability to predict soil water deficits. Over the three years the CIS-A was evaluated, the tool tended to overestimate the observed deficit (mean bias error MBE = -3.41 mm and relative error RE = 13.58%). The best performance of the CIS-A observed during this study occurred in 2010 at the north site (root mean square error RMSE = 12.97 mm, MBE = -0.34 mm, mean absolute error MAE = 10.62 mm, and RE = 1.84 %). As for the CIS-F, two growing seasons of alfalfa (*Medicago sativa* L.) field data, from two lysimeters located at the Arkansas Valley Research Center in Rocky Ford, Colorado, were used to evaluate the performance of the tool. Results of the study indicated the CIS-F also tended to overestimate the deficit. The CIS-F performed best in 2011 when average error (MBE) was -16.95 mm and average overestimation (RE) of the deficit was 18.73%. Overall both schedulers performed well

and much of the error experienced throughout the study could be explained, indicating that the tool should prove to be an effective instrument in improving irrigation water management.

INTRODUCTION

Irrigation is an important element of crop production in rain deficient areas akin to eastern Colorado. In order to meet the water requirements of most crops in arid and semi-arid regions irrigation water must be applied. This is particularly true in areas where lack of precipitation usually limits crop growth and yield (Irmak et al. 2005). Because fresh water resources are typically in short supply in arid regions it is important to use the limited resource in a most efficient manner. Proper irrigation scheduling is becoming increasingly important, especially as growing populations place increased pressure on the transfer of water from agricultural uses to municipality uses (DeJonge et al., 2011). Environmental concerns over off farm transport of agro-chemicals have also raised awareness for the increased need for proper irrigation scheduling. Knowing when and how much irrigation water to apply is critical to conserve fresh water resources, meet crop water requirements, and protect the environment. Evapotranspiration (ET) based irrigation scheduling is a method that can be used to improve irrigation water management to conserve water resources (Bauder, 2005). A simple method of ET-based irrigation scheduling known as the water balance approach can be implemented to improve irrigation management practices.

The water balance approach to irrigation scheduling, also known as the check book method and/or accounting method, tracks the daily soil water balance in the rooting zone of a crop. Just as with a check book all deposits and withdrawals must be accounted for. In this case, the depth of water in the system is tracked. Deposits are made to the system through precipitation, irrigation, and upflux of ground water. Conversely, withdrawals are accounted for as ET, surface runoff, and deep percolation. For irrigation management, it is convenient to express the root zone water balance in terms of the soil water deficit (D). The soil water deficit is the difference between field capacity and current soil water content. The deficit is zero if the current soil water content is greater than or equal to field capacity. The concept of field capacity is discussed later in this section. The daily soil water balance, or daily soil water deficit, can be tracked using Equation 1, adapted from equation (85) of FAO Irrigation and Drainage Paper No. 56 (Allen et al., 1998):

$$D_c = D_p + ET_c - P - Irr - U + SRO + DP \qquad \text{Eq. (1)}$$

where D_c is the soil water deficit at the end of the current day, D_p is the soil water deficit from the previous day, ET_c is the actual crop ET for the current day, P is gross precipitation on the current day, Irr is the net irrigation amount applied on the current day, U is current days upflux, SRO is the surface runoff on the current day, and DP is deep percolation on the current day, with all units being expressed as a depth of water (mm). Figure 1 depicts a graphical model of a hypothetical soil water balance.

Initiation of the water balance requires an initial estimate or measurement of soil water content in the root zone (Allen et al., 1998). Soil sampling techniques can be used to obtain accurate estimates of soil water content, or the deficit can be estimated as zero following heavy precipitation or irrigation events early in the growing season when crop rooting depths are shallow. Once the initial soil water content is known daily additions and subtractions of water from the root zone can be obtained and the soil water balance calculation can commence.

Precipitation and Irr amounts are usually the easiest variables for an irrigation manager to obtain. For the highest precision to be achieved an irrigator should have accurate measurements of the amount of water being applied to their field through irrigation. Measurements of P can be obtained easily from the use of onsite rain gages or from nearby weather networks that provide precipitation measurements. Once P and Irr values are obtained the other variables necessary to complete the calculation of a soil water balance are $ET_{c,}$ U, SRO, and DP. Andales et al. (2011) have indicated that it is difficult to measure U, SRO, and DP in most instances. Furthermore, in many areas the ground water table which contributes to U is significantly deeper than the root zone of most crops. In these instances the contribution of ground water is negligible. SRO and DP can also be accounted for in a simple manner. In the event that SRO or DP is observed D_c can be set to zero. Taking all this into consideration Andales et al. (2011) have proposed simplifying Equation (1) to $D_c = D_p + ET_c – P – Irr$. From the simplified equation, it can be assumed that SRO or DP will occur if (P + Irr) exceeds (Dp + ETc), which results in a negative value for Dc. When this happens, Dc can be set to zero and it is assumed that the soil profile is at field capacity. This assumption does not consider rainfall or irrigation intensity and soil infiltration rates, but is acceptable for approximating the soil water deficit in semi-arid environments, especially if mid-season corrections are made using observed moisture contents of the root zone. With the simplification of the water balance equation proposed by Andales et al. (2011) the only remaining variable needed to complete the calculation is ET_c.

Actual crop evapotranspiration (ET_c) is a little more difficult to obtain. In order to acquire ET_c, reference ET (ET_{ref}) must first be computed or obtained from another source. If ET_{ref} is computed it is recommended that the ASCE-EWRI (2005) guidelines be used to do so as it is considered to be the best method available to calculate ET_{ref} when all necessary weather data are available (Allen et al., 2007). The minimum variables required to calculate ET_{ref} following the ASCE-EWRI (2005) guidelines include daily minimum and maximum air temperature, solar radiation, average wind speed, and average humidity (ASCE-EWRI 2005). ET_{ref} data can also be obtained from a variety of sources such as the Colorado Agricultural Meteorological Network (CoAgMet). CoAgMet provides daily values of ET_{ref} following the ASCE-EWRI hourly guidelines for computing ET_{ref} on their website (http://ccc.atmos.colostate.edu). No matter how ET_{ref} is obtained it is a requirement that the data comes from a reliable source (Bauder, 2005).

In Colorado, the use of an alfalfa-based ET_{ref} (ET_{rs}) estimate is more suitable over that of a grass-based ET_{ref} (ET_{os}) estimate. According to Al-Kaisi and Broner (2009) this is because alfalfa has a deep rooting system making it less susceptible to water stress in the dry climate of eastern Colorado. Once ET_{rs} estimates have been computed or obtained, a crop coefficient approach can be used to estimate ET_c. The method of using a crop coefficient to estimate ET_c is the most common procedure used to calculate ET_c (Irmak et al., 2005). Using this approach ET_c is calculated by multiplying ET_{ref} by a crop coefficient. The equation to calculate ET_c takes the form $ET_c = ET_{rs} \times K_{cr}$, adapted from Allen et al. (1998): where ET_c is actual crop ET as a depth (mm), ET_{rs} is alfalfa-based ET_{ref} as a depth (mm), and K_{cr} is an alfalfa-based crop coefficient specific to individual crops and is dimensionless.

The use of a crop coefficient integrates the effects of conditions experienced by a crop in the field, including; changes in leaf area, plant height, crop specific characteristics, irrigation methods, the rate at which a crop develops, planting or sowing dates, degree of canopy cover, canopy resistance, soil and climate conditions, and management practices (Doorenbos and Pruitt, 1977, and Irmak et al., 2005). Therefore, a K_{cr} is used to modify ET_{rs} to more accurately estimate ET_c. K_{cr} values typically range from 0.2 early in the growing season to 1.0 during peak vegetative stages when full ground cover has been achieved (Andales et al., 2011). K_{cr} values for specific crops can be obtained from a variety of reputable publications (Allen et al., 1998 and Allen et al., 2007) or from local County Extension Service. When selecting crop coefficients it is important to select ones that have been developed for the same method used to calculate ET_{ref}. If ET_{ref} was calculated using alfalfa-based procedures then only alfalfa-based crop coefficients should be used to calculate ET_c, or methods outlined by Allen et al. (1998) should be used to convert grass-based K_{co} values to alfalfa-based K_{cr} values.

The computation of the soil water balance equation has other constraints associated with it. There is an upper and lower limit to the amount of water available to crops within the root zone (Andales and Chávez, 2011). The upper limit occurs when there is no soil water deficit in the root zone. The upper limit is often referred to as field capacity (FC). FC is a term used to describe the water remaining in a soil profile one to two days after saturation has occurred and natural drainage, due to gravity, has removed excess water (Schwab et al., 1993). The lower limit of water available to crops is termed permanent wilting point (PWP) and is often associated with 1.5 MPa of tension in the soil. When soil moisture levels reach PWP plants are stressed to the point that they can no longer extract water from the soil causing plant death. Both FC and PWP are generalized as they vary between soil types and plant species (Schwab et al., 1993). Nevertheless, relatively accurate estimations of both FC and PWP can be made using field and laboratory methods. The total water available in a soil for plant uptake is termed total available water (TAW) and is calculated as the difference between FC and PWP (TAW = FC – PWP). A portion of TAW is termed readily available water (RAW). The RAW fraction of TAW makes up the portion of the water in the soil that plants can extract without experiencing soil water stress. Once TAW falls below RAW plant stress and potential yield loss begins to occur and progresses as water is further depleted.

When the soil water balance approach to irrigation scheduling is used to track daily soil water deficit, irrigation is typically initiated when the deficit approaches a threshold. The term often used to describe the threshold is management allowed depletion (MAD). MAD is based on management and economic factors and is normally slightly higher than RAW to avoid the possibility of water stress (Allen et al., 1998). MAD is typically expressed as a percent or fraction of TAW. Published crop specific values for MAD can be obtained from Allen et al. (1998) and Al-Kaisi and Broner (2009). MAD can also be expressed as a depth of water using Equation (2):

$$\mathrm{d_{MAD}} = \frac{\mathrm{MAD}}{100} \times \mathrm{TAW} \times \mathrm{D_{rz}} \qquad \text{Eq. (2)}$$

where MAD is management allowed depletion (percent), TAW is total plant available water (mm), and D_{rz} is root zone depth (mm).

In the event the soil moisture deficit exceeds MAD before irrigation or precipitation events occur, crops begin to experience stress. Once a plant begins to experience water stress due to lack of adequate soil moisture, ET_c is reduced. As a result, the concept of a water stress coefficient (K_s) has been introduced to account for the reduction of transpiration by a plant under water stressed conditions. The water stress coefficient is calculated using Equation (3):

$$\mathrm{K_s} = \frac{\mathrm{TAW} - \mathrm{D_p}}{(1 - \mathrm{MAD}) \times \mathrm{TAW}}, \quad \text{for } D_p > d_{MAD} \qquad \text{Eq. (3)}$$

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

where TAW is total plant available water (mm), D_p is the previous day’s soil water deficit (mm), and MAD is management allowed depletion (decimal fraction). With the introduction of the concept of K_s the ET_c is therefore computed using Equation (4):

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

Once the soil water content drops below MAD, ET_c decreases proportionally to the amount of water remaining in the crop root zone (Allen et al, 1998). Figure 2 provides a graphical representation of K_s and how ET_c is reduced when soil moisture exceeds MAD.

The use of a K_s and K_{cr} help to ensure more accurate estimations of ET_c are obtained. The water balance equation using alfalfa-based ET_{ref} and K_{cr} values can therefore be rewritten incorporating all components using Equation (5).

$$D_c = D_p + (ET_{rs} \times K_{cr} \times K_s) - P - Irr \quad \text{Eq. (5)}$$

where $D_c = 0$ if $(P + Irr)$ exceeds $(D_p + ET_c)$. Using Equation (5) and having accurate approximations of FC and PWP an irrigation manager can easily track a soil's daily water balance. Irrigation managers can use the daily soil water balance to more accurately estimate the amount and timing of irrigations. The recommended net amount of irrigation water to apply is simply the current day's deficit (D_c) and timing is based upon irrigation system capacity ensuring that the deficit does not exceed MAD.

Objectives

The objectives of this study were: (1) to develop and demonstrate an ET-based irrigation scheduling spreadsheet tool for use by irrigators and water managers to track daily soil water deficit; and (2) to evaluate the accuracy of the tool in estimating daily soil water deficits. The development of this tool aims to provide users with the information needed to make sound irrigation scheduling decisions. The tool provides the necessary framework to simplify the tracking of a soil's daily water balance. The use of the tool is intended to provide recommendations on the amounts and timing of irrigation water to improve irrigation efficiency.

MATERIALS AND METHODS

Development of irrigation scheduling tools

Two irrigation scheduling tools were developed using Microsoft Excel® spreadsheets to track daily soil water deficits, one for use with annual crops (Colorado Irrigation Scheduler: Annual (CIS-A)), and one for use with perennial forage crops (Colorado Irrigation Scheduler: Forage (CIS-F)). The irrigation scheduling tools track daily soil water deficit using Equation (5) (see Appendix III for Visual Basic for Applications source code). Each tool tracks the soil water deficit of a user specified depth of soil (control depth).

The first step in initiating the scheduling tools is to acquire soil physical properties. The soil physical properties needed for computation of the water balance are FC and TAW, both expressed in terms of depth of water. The soil properties can be entered for each individual soil layer for up to five layers. The soil properties for each layer can be manually entered or they can be queried from the United States Department of Agriculture Natural Resource Conservation Service – Web Soil Survey website: (http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm) using the "Collect Soils Data" tab located on the Introduction page (see Appendices for screen shots of scheduling tools).

The second step is to set up the farm by selecting the "Set Up Farm Using data from CoAgMet" tab (see Appendix I and II for screen shots of scheduling tools). This step allows the user to enter the remainder of the information required to calculate the water balance. For the CIS-A a planting date and an emergence date must be entered, and for the CIS-F a green up date must be entered. At this point a crop, irrigation method and application efficiency that corresponds with the irrigation system being used must be selected. Once this information has been selected all remaining parameters are queried from the Colorado Agricultural

Meteorological Network (CoAgMet). The user has the ability to choose which CoAgMet weather station to query data from. The station chosen will typically be the station located nearest to the field of interest. However, in some instances the nearest weather station may be located over a non-irrigated surface. In this instance the next closest station located over an irrigated surface should be selected. The CoAgMet website (http://ccc.atmos.colostate.edu) provides daily values of P, ET_{rs} (ET_{rs} is calculated following ASCE (2005) hourly guidelines for a tall reference crop), maximum air temperature (T_{max}), and minimum air temperature (T_{min}). A user can also manually enter P, ET_{rs}, T_{max}, and T_{min} information if the data were obtained from other sources. T_{max} and T_{min} are required for both the CIS-A and CIS-F because the K_{cr} used to calculate ET_c uses growing degree days to formulate crop coefficient curves. If any of the ET or weather data are manually entered the parameters must be entered using SI units only. The irrigation scheduling tools automatically calculate ET_c using an internal algorithm (Excel Visual Basic for Applications® macro) that incorporates crop coefficients (K_{cr}) and soil water stress coefficients (K_s) as shown in Equation (4).

The default value for D_c is zero for the initial start of the growing season. This value can also be entered manually if a deficit other than zero was obtained through soil sampling procedures. Values for Irr are always entered manually by the user. The Irr amount entered by the user should be the gross irrigation amount applied in depth of water. The schedulers automatically correct the gross irrigation amount to reflect the net irrigation amount based on previously selected irrigation application efficiency selected by the user for the appropriate irrigation method being used. Once the required fields have been populated the tool automatically calculates the daily water balance and provides the end of day deficit. The end of day deficit in turn is the net amount of water required to refill the root zone back to FC. Irrigation is typically initiated before the deficit exceeds MAD. Default values for MAD used in both versions of the tool were obtained from Allen et al., (1998) and Al-Kaisi and Broner (2009) but can also be adjusted to meet user needs. Two draft manuals have been created detailing the instructions for using the irrigation scheduling tools and are available in Appendix I and II of this thesis.

Research locations

Data collected from three field locations were used to evaluate the performance of the irrigation scheduling tools. The corn field used to evaluate the CIS-A tool is located in the South Platte River Basin near Greeley, Colorado (latitude N40.460545°, longitude W104.57894°, 1429 m above mean sea level). This field was planted to corn in early May of each year of the study from 2010 to 2012. Two field locations were used to evaluate the CIS-F tool. Both fields were located in the Arkansas River basin at The Colorado State University Arkansas Valley Research Center (AVRC) near Rocky Ford, Colorado. The first field, used in 2010, is referred to as the large lysimeter (LL) field (latitude N38.03779°, longitude W103.68941°, altitude 1274 m above sea level). The LL field was planted with alfalfa in the fall of 2007. The second field site was utilized in 2011 and is referred to as the reference lysimeter (RL) field (latitude N38.03851°, longitude W103.68702°, altitude 1274 m above sea level). The RL field was planted with alfalfa in the fall of 2010.

Irrigation management

The corn field was irrigated via a center pivot irrigation system. The irrigation system and irrigation water application was maintained and managed by a cooperative grower that participated in this study. Irrigation application efficiency of the system was estimated to be 90%, based off of guidelines outlined by Martin et al. (2007). The alfalfa fields used in this study were irrigated using furrow irrigation methods and were managed by the staff at the AVRC. However, the lysimeter monoliths from where the soil water content measurements were taken were irrigated manually to mimic the furrow irrigation of the surrounding field. An irrigation application efficiency of 100% was used for both years of the study because surface runoff from the lysimeters is prevented by the perimeter of the monolith tanks which protrude above the soil surface. Also, field capacity was never exceeded during either growing season of this study, thus no deep percolation was observed. Figures 3 and 4 show comparisons of irrigation amounts applied throughout the study in the corn field and alfalfa fields, respectively.

Leaf area index measurements

Several crop measurements were taken throughout the study in order to determine leaf area index (LAI) in the corn field. LAI information from the corn field was used to help formulate or validate crop coefficient curves used in the CIS-A. Two sites were selected in the southwest quarter of the field. Herein the sites will be referred to as the north site (latitude 40.45819°, longitude 104.58135°) and the south site (latitude 40.45809°, longitude 104.58134°). The two sites were separated by approximately 6 m and offset by one row. Two corn plants, one each in the north and south sites, were selected in the beginning of each growing season and weekly leaf area indices (LAI, m^2 of leaf surface area/ m^2 of soil) were taken manually throughout the 2010-2012 growing seasons. LAI was determined using methods described by Kang et al. (2003).

Soil properties

The soil type present in the corn field sites is classified as an Olney fine sandy loam (fine-loamy, mixed, superactive, mesic Ustollic Haplargids) (Soil Survey Staff, 2013). Soil bulk density in the corn field was determined using a Madera probe (Precision Machine Company

Inc., Lincoln, NE) and methods described by Evett (2008). Two samples were taken from each site location at the end of the 2011 growing season at depths of 0-15, 15-30, 30-45, 45-60, 60-90, and 90-105 cm and again at the beginning of the 2012 growing season at the same depths. PWP for each soil layer was determined using a WP4-T Dewpoint PotentiaMeter (Decagon Devices, Inc., Pullman WA). A soil moisture release curve was created to obtain gravimetric water content at 1.5 MPa of tension. Volumetric water content at PWP was then calculated using methods described by Evett (2008). FC for each soil layer was determined in situ by soil core sampling 24 hours after several deep irrigation/precipitation events in 2011. Gravimetric water content at FC determined in 2011 was used to calculate volumetric water content at FC for all years. Total plant available water content (TAW) was determined using the equation TAW = FC - PWP, and TAW was determined for each soil layer sampled. Values for soil properties used in the CIS-A are presented in Table 1-1.

The soil type present at the alfalfa field sites used for evaluation of the CIS-F is classified as a Rocky Ford silty clay loam (fine-silty, mixed, superactive, calcareous, mesic, Ustic Torriorthents) (Soil Survey Staff, 2013). Soil properties from the alfalfa fields used in the CIS-F were obtained during installation of the lysimeters. Berrada et al. (2008) and Al Wahaibi (2011) gave a detailed description of the methods used to obtain soil properties. Soil properties obtained from the alfalfa fields are presented in Table 1-2.

Soil water content measurements

Soil core samples were taken from the corn field on a weekly basis throughout each growing season using a JMC Backsaver handle and a “dry” sampling tube with a core diameter of 1.905 centimeters (Clements Associates Inc., Newton, IA). Soil samples were taken at depths of 0-15, 15-30, 30-45, 45-60, 60-90, and 90-105 cm within 1 m of each sampling site, for a total of two profile samples per field visit. The soil samples were weighed to obtain fresh mass and then oven dried at 105 °C until a constant mass was obtained. Gravimetric (g g^{-1}) and volumetric (cm^3 cm^{-3}) water content in the corn field was determined using methods described by Evett (2008).

Soil water content was measured in the alfalfa fields using neutron attenuation. Soil moisture readings were taken on a routine basis in 20 cm increments to a depth of 190 cm using a CPN 503 DR Hydroprobe (CPN International Inc., Concord, CA, USA). Berrada et al. (2008) provide a description of the methods used to calibrate the CPN 503 DR Hydroprobe and the methods used to convert readings to volumetric water content.

ET_c calculations

The hourly version of the ASCE-EWRI (2005) Standardized PM equation for a tall reference crop was used to calculate ET_{ref} (ET_{rs}) for all years of the study and for use in both versions of the scheduler. Hourly values of wind speed, solar radiation, humidity, and air temperature required to calculate ET_{rs} were obtained from CoAgMet. Data obtained from CoAgMet station GLY04 was used to calculate ET_{rs} used in the CIS-A. The GLY04 station (latitude 40.4487, longitude 104.638, 1427 m above mean sea level) is located 2.4 km north of the Greeley, CO airport and 5.2 km west of the corn field. On July 16, 2010 T_{max} and T_{min} values were missing from the GLY04 station and on June 10, to June 13, 2010 measured solar radiation values were out of range. These values were all replaced with values from nearby CoAgMet station KSY01.

CoAgMet station RFD01 was used to obtain weather parameters to calculate ET_{rs} for use in the CIS-F. The RFD01 station is located 4.0 km southeast of Rocky Ford, CO at the AVRC (latitude 38.0385°, longitude 103.695°, 1274 m above mean sea level). The RFD01 station is located 480.0 m west of the alfalfa field used in 2010 and 683.0 m west of the alfalfa field used in 2011. In 2011 data from RFD01 was unavailable for a portion of the growing season. RFD01 station was out of service from Aug. 12, 2011 to Nov. 5, 2011 due to technical problems. Data from a fully automated weather station located at the research site in the RL field was used to replace missing data from RFD01. CoAgMet site descriptions and weather station specifications can be found on the CoAgMet website.

Although CoAgMet provides daily values of ET_{rs} based on the ASCE-EWRI (2005) hourly guidelines for a tall reference crop, these values were not used in the evaluation of the schedulers. For reasons unknown at this time, ET_{rs} values from CoAgMet were found to be higher than that calculated using other calculators of the ASCE-EWRI standardized ET_{ref} equation. Therefore, REF-ET, a computer program developed by the University of Idaho was used to calculate ET_{rs} using the weather parameter data obtained from CoAgMet for each growing season and for each version of the scheduler. More information on REF-ET can be found at http://www.kimberly.uidaho.edu/ref-et/. ET_{rs} calculated using REF-ET was manually inputted into both the CIS-A and CIS-F. The schedulers then internally calculate ET_c automatically using Equation (4).

The default crop coefficients utilized in Equation (4) in the CIS-A to calculate ET_c for corn are based on mean crop coefficients obtained from Allen et al. (1998). The crop coefficient curve from Allen et al. (1998) is a grass based crop coefficient (K_{co}) but was converted to an alfalfa based crop coefficient (K_{cr}) using methods described by Allen et al. (1998). The K_{cr} curve developed for use in the CIS-A follows the FAO style curve with the four crop development stages. Allen et al. (2007) provide a detailed description on the construction of the FAO style K_c

curve and the four crop development stages used to define the curve. Figure 5 shows the general shape of the FAO style K_{cr} curve.

In addition to the conversion of the K_{co} to a K_{cr}, the curve used in the CIS-A incorporates a fraction of total growing degree (GDD, °C) required to reach maturity after emergence to define the cutoffs of the four crop development stages rather than using the number of days after planting to define the cutoffs similar to that outlined by Allen et al. (1998, 2007). GDDs were calculated using Equation (6):

$$\mathrm{GDD} = \frac{\mathrm{T_{max}} + \mathrm{T_{min}}}{2} - \mathrm{T_{base}} \qquad \text{Eq. (6)}$$

where, T_{max} is maximum daily air temperature °C, T_{min} is minimum daily air temperature °C, and T_{base} is base air temperature set at 10 °C for corn. Total GDD °C for corn to reach maturity from emergence was set at 1389 °C based on observation of crop maturity from observations during 2010 at the research site.

The default K_{cr} values utilized in the CIS-A were obtained from Allen et al. (2007), where $K_{c\ ini}$, $K_{c\ mid}$, and $K_{cr\ end}$ are 0.25, 1, and 0.4, respectively, and the default cutoffs marking the end of the initial period (seedling stage), the end of crop development period (rapid development), the beginning of senescence, and the end of season were determined by calculating the fraction of GDD °C accumulated after emergence for the crop to reach each stage based on observations made during the 2010 growing season. However, the K_{cr} used in the evaluation of the CIS-A was a modified version of the default K_{cr}. The $K_{c\ ini}$ and $K_{c\ mid}$ used in the evaluation of the CIS-A remained the same as the default, but the $K_{c\ end}$ (0.30) used in the evaluation of the CIS-A was set lower than the default $K_{c\ end}$ (0.40), yet still in range of the mean K_c values presented by Allen et al. (2007) that were developed for specific use with the ASCE Standardized Reference ET Equation for the end of season. The $K_{c\ end}$ was set near the lower end of the mean K_c values to improve end of season performance of the CIS-A. The cutoffs for the four crop development stages were also further modified. The default crop development stage cutoffs were modified for the evaluation of the CIS-A to incorporate observations made over the entire study. Cutoff 1, which corresponds with the end of the initial (seedling) crop growth stage was set at 20.0% of total GDD to reach maturity. Cutoff 2, which corresponds with the end of the development stage and the beginning of effective full cover, was set at 40.0% of total GDD required to reach maturity, and cutoff 3 which corresponds with the end of the mid-season period and the beginning of the late season period was set at 70.0% of GDD required to reach maturity. All adjustments to the K_{cr} curve used in the CIS-A over that presented by Allen et al. (2007) were made based off of observed LAI and observation of crop maturity. The K_{cr} curve used in the CIS-A to calculate ET_c is presented in Figure 1-5 and Table 1-3.

The K_{cr} used in Equation (4) to calculate alfalfa ET_c used in the CIS-F was developed using lysimeter data. Al Wahaibi (2011) provides a detailed description on the development of the crop coefficients used in the CIS-F. Because the alfalfa is harvested several times each season two crop coefficient curves were used, one for use prior to the first harvest date (first cutting cycle) and one for use with the remainder of the harvest periods individually (cutting cycles 2 – 4). The alfalfa K_{cr} curves used in the CIS-F to calculate ET_c are presented in Figure 1-6 and Table 1-4.

Evaluation of irrigation scheduling tools

The performance of the irrigation scheduling tools in estimating soil water deficit was tested by comparing the scheduler's predicted soil water deficits to observed soil water deficits over a control depth. The control depth used in the evaluation of the CIS-A was set at 105 cm and the control depth used in the evaluation of the CIS-F was set at 230 cm. The control depth of the CIS-F remains static throughout the season. However, the CIS-A incorporates an internal algorithm to model annual crop root development until the roots reach the user specified control depth. Initially the root depth is assumed to be 15.24 cm and remains so until emergence. Once emergence occurs, the modeled rooting depth increases linearly until the user specified control depth is reached. The modeled root depth is assumed to reach the user specified control depth once the crop reaches full canopy. The CIS-A uses Equation (7) to model crop rooting depths (see Appendix IV for Equation (7) code),

$$\mathrm{D_{rz}} = \frac{\mathrm{D_{max}} - 15.24}{\mathrm{GDD_M} \times \mathrm{GDD_2}} \times \mathrm{GDD_{cum}} + 15.24 \qquad \text{Eq. (7)}$$

where: D_{rz} = depth of modeled root zone (cm), D_{max} is the user specified control depth (cm), GDD_M is the total cumulative growing degree days required to reach maturity (°C) from emergence, GDD_2 is the fraction of total growing degree days required to reach maturity at cutoff 2 and GDD_{cum} is growing degree days (°C) accumulated after emergence on the current day. As a result of the implementation of Equation (7) only the modeled root zone deficit is tracked until the crop reaches full canopy and the roots extend to the control depth.

Evaluation of the tools was initialized starting with the first observed soil water deficit of each season at each site. This was done to ensure that the tools were initiated with an observed deficit. As stated previously the default initial deficit is zero unless otherwise corrected upon initiation of the tools. The predicted deficits from the tools were statistically compared to the observed deficits using methods recommended by Willmott (1982) and Willmott and Matsuura (2005) for evaluation of model performance for the remainder of the season for each year and site. The performance of the tools were analyzed using root mean square error (RMSE, Eq. 8), mean absolute error (MAE, Eq. 9), mean bias error (MBE, Eq. 10), and relative error (RE, Eq. 11):

$$\mathrm{RMSE} = \left[\mathrm{N}^{-1}\sum_{\mathrm{i}=1}^{\mathrm{N}}(\mathrm{P_i} - \mathrm{O_i})^2\right]^{0.5} \qquad \text{Eq. (8)}$$

$$\mathrm{MAE} = \mathrm{N}^{-1}\sum_{\mathrm{i}=1}^{\mathrm{N}}|\mathrm{P_i} - \mathrm{O_i}| \qquad \text{Eq. (9)}$$

$$\mathrm{MBE} = \mathrm{N}^{-1}\sum_{\mathrm{i}=1}^{\mathrm{N}}(\mathrm{P_i} - \mathrm{O_i}) \qquad \text{Eq. (10)}$$

$$\mathrm{RE}\ \% = \frac{\left(\overline{\mathrm{P}} - \overline{\mathrm{O}}\right)}{\overline{\mathrm{O}}} \times 100 \qquad \text{Eq. (11)}$$

where N is the number of observations, P and O are the predicted and observed values, respectively, and $\overline{\mathrm{P}}$ and $\overline{\mathrm{O}}$ are the mean of the predicted and observed values, respectively. All statistical comparisons were made using only the data obtained on days when observed soil water content measurements were available.

A final evaluation of the irrigation scheduling tools was made to determine the potential of the tool to be used to help save water. Two iterations of the CIS-A were run using data from 2011 at the north site. The first iteration was run using actual irrigation data and the second was run simulating recommended irrigation timings and amounts. Simulated irrigation timings were based off of CIS-A estimated deficits in order to maintain deficits above MAD while avoiding losses through runoff or deep percolation. The amount of simulated gross irrigation water applied during each irrigation event was representative of actual gross irrigation amounts applied in 2011 and within the capacity of the center pivot system. Irrigation timings were also simulated to ensure that the deficit did not drop below MAD. The actual amount of total gross irrigation water applied in 2011 was then compared to the amount of simulated gross irrigation water applied to determine if water savings could be achieved using the scheduler to make irrigation scheduling decisions.

RESULTS AND DISCUSSION

Evaluation of CIS-A

Comparisons made between the CIS-A predicted deficit and the observed deficit for the 105 cm control depth indicated that the CIS-A tended to overestimate the deficit in all years and across all sites throughout the study (Table 1-5). Across all years and sites throughout this study the CIS-A predicted a deficit larger than the observed deficit by an average of 13.58%. Average error (MBE) indicated that the CIS-A over predicted the deficit by an average of 3.41 mm for the entire study. Overall average error indicated that the CIS-A was within 15.92 mm (RMSE) and 12.61 mm (MAE) of the observed deficit for the entire study. The best performance of the CIS-A was observed in 2010 at the north site when average seasonal overestimation of the deficit was only 1.84%. The CIS-A's worst performance was observed during the 2012 growing season at the north site when an average seasonal overestimation of the deficit was 33.56% greater than the observed deficit.

The CIS-A predicted a deficit greater than the observed deficit on nearly 60% of all observations made throughout the study. On the days when overestimation of the deficit occurred the observed deficit was over predicted by an average of 13.70 mm. Conversely, when the CIS-A underestimated the deficit it was determined that the average underestimation of the deficit was 11.09 mm. The greatest error observed on a single day during this study occurred on September 7, 2012 at the north site when the CIS-A overestimated the deficit by 42.43 mm. The best single day performance of the CIS-A was observed during the same year at the south site on July 18.

On this date the CIS-A under predicted the observed deficit by 0.27 mm. Of the 94 observations made throughout the study the CIS-A predicted a deficit within 10 mm of the observed deficit 49% of the time and within 25 mm 86% of the time.

Further observation of the data indicated that the CIS-A tended to under predict the observed deficit the most in the beginning of each growing season and over predict the observed deficit most towards the end of each growing season (Figures 7 – 12). One possible scenario to explain this trend could be that the K_{cr} used in the initial crop growth stage causes an underestimation of ET_c and the K_{cr} used during the final crop development stage causes an overestimation of ET_c. Modifications to $K_{cr\ ini}$ were made to try and improve the overall performance of the CIS-A, however only slight improvement was observed in the overall error. When $K_{cr\ ini}$ was increased both RMSE and MAE decreased slightly, (< 1 mm), but MBE and MAE both increased substantially. When the $K_{cr\ end}$ was adjusted to try and correct for the overestimation of the deficit near the end of the season it was found that a $K_{cr\ end}$ value smaller than what was used during the evaluation of the tool improvement in all statistical measures was observed across each year and site.

Another possible causation specific to the overestimation of the deficit near the end of the season was also examined. As stated previously, water extraction predicted by the CIS-A is confined to the 105 cm control depth. Once dent occurs in corn their roots can extend to a depth greater than 180 cm (Melvin et al. 2005), well beyond the control depth. Howell et al. (1995) have also indicated that corn mainly extracts water from 0 – 150 cm range but water can also be extracted from depths below 150 cm. If the crop extracted water from a depth greater than the control depth, the CIS-A would not account for the additional water extracted from depths below 105 cm. The result would be an error in the water balance, much like what was observed. In

2011 and 2012 corn roots were observed in the deepest soil core samples (90 – 105 cm) near the end of each season. Observations of roots in the deepest soil core samples were not annotated in 2010 however it is likely that it occurred in 2010 as well. Also, as Hillel (2007) has indicated, water will spontaneously flow from areas where matric suction is lower to where it is higher. Unsaturated flow of water from depths below the control depth may have also contributed to the error observed near the end of each growing season. Again the CIS-A would not account for this addition of water and it would be nearly impossible to account for such movement in a normal field setting. If unsaturated flow did occur this could also explain why the end of season CIS-A predicted deficit was greater than the observed deficits. The addition of water to the system from depths below the control depth and plant extraction of water from below the control depth is the most likely cause of the error observed near the end of each season. If the crop did in fact extract water from depths greater than the control depth the CIS-A would not account for the additional water made available to the crop thus the CIS-A would predict a deficit greater than that which was observed.

Another possible contribution to the error observed between CIS-A predicted deficits and observed deficits could also be explained by the difference between actual field conditions at the field site and conditions at the CoAgMet GLY-04 station where data were collected for use in the CIS-A. As stated previously, the CoAgMet GLY-04 weather station is located approximately 5.2 km west of the field site. Spatial variation of precipitation was observed during the 2011 and 2012 growing seasons. Automated on-site rain gages indicated precipitation events occurred on Aug. 4, 2011 (approximately 9 mm), June 22, 2012 (approximately 16 mm) and again on June 25, 2012 (approximately 13 mm), whereas CoAgMet station GLY-04 did not indicate any precipitation on Aug. 4, 2011 or June 25, 2012 and less than 1 mm accumulation on June 22,

2012. Data from other weather stations within the same proximity to the field site as the GLY-04 station also confirmed the spatial variability of precipitation in the area surrounding the field site. On-site rain gage data was unavailable in 2010 and much of 2011, therefore other instances cannot be confirmed. In 2010 manual rain gages were used in the field and it was impossible to differentiate between irrigation and precipitation events, and in 2011 technical problems persisted for much of the season with the automated rain gages. However, observation of precipitation measurements from other weather networks in the area confirmed the spatial variability of precipitation.

Other weather variables such as air temperature, RH, and wind speed may have also varied between the field site and the GLY-04 station further introducing error. Unfortunately, because there were no on-site measurements of these variables it is impossible to confirm the effects of spatial variability. Therefore, further modifications to the crop coefficient curve used in the CIS-A were not made at this time.

In addition to the average over prediction of the deficit made by the CIS-A, considerable runoff and or deep percolation (RO/DP) was also predicted in all years and across all sites during this study. The CIS-A predicted the most RO/DP in 2011. At the north site the CIS-A predicted 209 mm of RO/DP and at the south site 220 mm. 2011 was also the wettest year receiving 224 mm of precipitation during the study period. In addition to 2011 being the wettest year the field sites also received the most irrigation, 561 mm gross. During 2012 the CIS-A predicted the least amount of RO/DP with 70 mm at the north site and 83 mm at the south site. In contrast to 2011, 2012 received the least amount of precipitation with 151 mm over the studied season. Gross irrigation in 2012 totaled 472 mm and was the second highest amount applied for a season throughout the entire study. 2010 fell in the middle with 121 mm and 118 mm of RO/DP predicted at the north and south sites, respectively. Precipitation in 2010 also fell between that of 2011 and 2012 with 216 mm. Of all of the years in this study 2010 received the least amount of gross irrigation water applied during the growing season. However, this may not be the case in fact. In 2011 and 2012 the field sites received 51 mm of gross irrigation prior to emergence whereas this did not occur in 2010. An irrigation record book used by the cooperating farmer to log irrigation timing and amounts did not indicate any irrigation events logged prior to June 27, 2010. However, the observed deficit on June 18, 2010 indicates that such an event likely occurred. Further evidence can also be seen by the number of days the CIS-A predicted a deficit greater than MAD. The CIS-A predicted a deficit exceeding MAD for 14 consecutive days between May 28, and June 10, 2010 at the north site (Fig. 7) and for 11 consecutive days at the south site (Fig. 8) from May 31, to June 10, 2010 yet the observed deficit did not reflect a deficit exceeding MAD. If an irrigation event was overlooked this would make the irrigation amount in 2010 higher than that which was reported and possibly increase the total amount of RO/DP predicted by the CIS-A as well. The actual amount of RO/DP in each year and at each site is nearly impossible to quantify in this instance because measurements of such were unavailable. Therefore, at this time the ability of the CIS-A to predict RO/DP cannot be properly evaluated.

However, one other possible explanation regarding the prediction of RO/DP estimated by the scheduler could be a result of inaccurate estimations of FC. As stated previously FC was estimated based off of soil water content measurements taken following deep irrigation/precipitation events in 2011. If errors were made in the estimates of FC this would result in an error in the estimate of TAW. If the actual FC was higher than what was estimated then TAW would be greater than what was estimated. If TAW was in fact higher then there would be a reduction in the amount of RO/DP. Also, if TAW was higher than what was estimated there would also be a reduction in the overestimation of the deficit that was observed near the end of each growing season.

Despite the average overestimation of the deficit (MBE = -3.41and RE = 13.58%) predicted by the CIS-A and the inability to quantify RO/DP at this field site, the tool performed well outside of the end of season in 2012 at the north site. One possible reason for the high over prediction of the deficit by the CIS-A during 2012 at the north site is that the location where soil water content measurements were taken may have been in a depression causing a concentration of water in the area. Although it was not documented, if this is in fact the case, it could help to explain why this is the only site/year that indicated that the CIS-A grossly underperformed. With the exclusion of the end of season performance of the CIS-A in 2012 at the north site, the overall performance of the CIS-A was considerably improved (RMSE = 13.81 mm, MAE = 11.10 mm, MBE = -1.47 mm and RE = 5.0%).

Considering all of the possibilities for error to be introduced, this simple model does a sufficient job of estimating soil water deficits. Overall, this study indicates that the CIS-A could serve as a tool to help facilitate improved irrigation scheduling decision making. Root mean square error over the entire study, with the exception of 2012 at the north site, was less than what could be applied in a single irrigation event. Furthermore, RMSE was at most 15.3% of TAW, as was the case in 2012 at the north site, and was as low as 8.6% of TAW in 2011 at the north site.

Evaluation of CIS-F

During both years of this study the deficit of the 230 cm control depth for alfalfa was consistently overestimated by the CIS-F. Comparison statistics for both alfalfa field sites are presented in Table 1-6. The CIS-F performed best in 2011 on the RL when average seasonal overestimation of the deficit was 18.73% greater than the observed deficit. Average error (MBE) indicated that the CIS-F overestimated the deficit by an average of 16.95 mm. Statistical comparisons using RMSE and MAE indicated that the overall average error between CIS-F predicted deficit and the observed deficit was an average of 22.02 mm and 17.65 mm, respectively. The performance of the CIS-F did not fare as well in 2010 on the LL. Average seasonal overestimation of the deficit in 2010 was 34.11% and RMSE, MBE, and MAE were 38.21 mm, -32.84 mm, and 32.94 mm, respectively.

In 2010 the CIS-F estimated a deficit greater than the observed on 13 out of the 14 observations made throughout the season (Figure 13). Similar results were observed in 2011 when the CIS-F overestimated the deficit on 15 out of the 16 observations (Figure 14). However, the magnitude of error was much less in 2011 than in 2010. To help illustrate this point, the largest and the smallest magnitudes of error were both observed in 2010. The CIS-F estimated a deficit 69.52 mm greater than the observed deficit on April 26, 2010 and a deficit 0.73 mm smaller than the observed deficit on August 18, 2010. The largest magnitude of error observed on any single observation date in 2011 occurred on June 3, 2011 when the CIS-F overestimated the deficit by 39.26 mm. The smallest error in 2011 occurred on September 1, 2011 when the CIS-F overestimated the deficit by 1.62 mm.

Unlike the CIS-A the CIS-F did not experience an increase in magnitude of error between the predicted and the observed deficit near the end of each season. Figures 13 and 14 show the end of season deficits predicted by the CIS-F were very close to the observed deficit. In fact, the end of season deficit predicted by the CIS-F was only 2.85 mm greater than the observed in 2010 and only 5.61 mm less than the observed in 2011. Most of the seasonal overestimation of the deficit occurred in the beginning of each growing season and the error diminished significantly by the end of each growing season.

In addition to the overestimation of the deficit, the CIS-F also estimated RO/DP during both years of the study. Because the lysimeter monoliths were used to evaluate the CIS-F, both RO and DP are easily accounted for in this instance. A lip (box edge) on the exterior of the monolith container extends 8 – 10 cm above the soil surface preventing any RO from the lysimeter monoliths. The lysimeters also have a built in feature to measure DP. In the event that DP may occur, it can be measured via a drainage system located at the bottom of the monolith. However, no DP was observed in either year of the study during the observation periods, yet the CIS-F estimated 53.80 mm of RO/DP in 2010, all of which occurred during cut 4. In 2011 the CIS-F estimated 122.09 mm of RO/DP over the growing season with 10.86 mm in cut 1, 39.03 mm in cut 2, 61.17 mm in cut 3, and 11.04 mm in cut 4.

In an attempt to explain why the CIS-F predicted RO/DP in each year of the study, comparisons were made between cumulative ET_c from the CIS-F and cumulative measured ET from the lysimeters. ET data from the lysimeters used in the comparisons was only available from March 30, of each year till the end of each growing season. Thus, 20 days at the start of cut 1 in each season was unavailable for comparison. However, the missing data was not an issue, because the schedulers were initialized with the first observed soil water deficit which coincided with the start of available lysimeter data in each year. The results of the comparison indicated there was a considerable difference between lysimeter measured ET (ET_{Lys}) and CIS-F estimated ET_c in each year of the study. For instance, in 2010 the CIS-F underestimated LL ET_{Lys} by 122.99 mm in total for the season (Figure 15), 4.52, 43.95, 41.15, and 33.37 mm during cuts 1, 2, 3, and 4, respectively.

Similar results were observed in 2011 as well. When cumulative ET_c from the CIS-F was compared to cumulative RL ET_{Lys} it was determined that ET_c was lower than RL ET_{Lys} during all cuts (Figure 16). Cumulative ET_c from the CIS-F was 1.88 mm lower than cumulative RL ET_{Lys} during cut 1, 52.02 mm lower during cut 2, 42.94 mm lower during cut 3, and 25.24 mm lower during cut 4. As stated previously the CIS-F estimated DP/RO during all cuts in 2011. The total amount of RO/DP estimated by the CIS-F during the entire season is very similar to the amount that the CIS-F underestimated RL ET_{Lys}. In fact, the amount of RO/DP predicted by the CIS-F (122.09 mm) is only 0.01 mm higher than the difference between CIS-F ET_c and RL ET_{Lys} (122.08 mm) for all cuts in 2011. Therefore, it was apparent that the RO/DP predicted by the CIS-F resulted from the underestimation of alfalfa ET_c.

Although most, if not all, of the RO/DP predicted by the CIS-F can be explained by the difference between ET_{Lys} and CIS-F ET_c, the fact still remains that the model tended to overestimate the deficit in both years of the study. Despite the detail that a portion of the lysimeter data was unavailable for the first part of the first cutting cycle during each year of the study, the charts for the first cutting cycles in Figures 15 and 16 paint a compelling picture. Cumulative ET_{Lys} from both years was slightly higher than CIS-F ET_c; however observation of the charts for cut 1 indicates that CIS-F ET_c was actually higher than ET_{Lys} for the majority of the cut 1 period when data was available. Ironically the greatest overestimation of the observed deficit predicted by the CIS-F was observed mainly during cut 1 in each year. In 2010 three out of the 4 highest overestimations of the observed deficit occurred during the first cut, and in 2011 all of the highest overestimation of the observed deficit occurred in cut 1. As stated previously, the greatest error observed in this study occurred in 2010 when the CIS-F overestimated the deficit by 69.52 mm on April 26, 2010. In 2010 the CIS-F also over predicted the deficit by 45.14 mm on May 4, 2010 and 54.44 mm on May 13, 2010 during cut 1. Coincidently, all of these observations fell on days when cumulative CIS-F ET_c was considerably higher than LL

ET_{Lys}. In fact on April 26, cumulative CIS-F ET_c was 32.93 mm higher than LL ET_{Lys}, 27.35 mm higher on May 13, and 26.66 mm higher on May 13. These observations help to explain much of the error observed in 2010 in the beginning of the season.

In 2011 the same trend as 2010 was also observed during cut 1; although the magnitude by which the CIS-F overestimated ET compared to RL ET_{Lys} was not as great, the difference still explains much of the error experienced during cut 1. By April 21, 2011, the second observation made during the season and the second highest overestimation of the observed deficit made by the CIS-F, cumulative CIS-F ET_c was 18.57 mm higher than cumulative RL ET_{Lys}. The error between the CIS-F predicted deficit and the observed deficit was -39.07 mm, nearly half of which can be explained by the different rates of ET. On the other observation dates in cut 1 the trend was similar where nearly half of the error can be explained by the difference between RL ET_{Lys} and CIS-F ET_c.

During this study the CIS-F also predicted a deficit exceeding MAD on several occasions. In 2010, on the LL, the CIS-F estimated a deficit exceeding MAD two times, once during the initial part of cutting cycle 2 and again at the beginning of cutting cycle 3. During cutting cycle 2 the CIS-F predicted a deficit exceeding MAD for four days prior to an irrigation event on June 10, 2010. However, observed soil water content measurements taken just prior to the irrigation indicated that the deficit did not exceed MAD. During cutting cycle 2 dMAD was 166.78 mm and the observed deficit just prior to the irrigation event on June 10, 2010 indicated a deficit of 132.96 mm, well above dMAD (Fig. 13). The second time the CIS-F predicted deficit exceeded MAD, observed soil water content measurements do in fact indicate that the deficit exceeded MAD. During cutting cycle 3 dMAD was 133.43 mm and the observed deficit just prior to the first irrigation during cut 3 was 142.88 mm. In 2011, on the RL, the CIS-F also predicted a deficit exceeding MAD on two occasions (Fig. 14). The first occurred at the start of cutting cycle 2 and the second occurred at the end of cutting cycle 3. Both times in 2011 the observed soil water content indicated that the deficit did exceed MAD.

Overall this study indicated that the CIS-F did tend to overestimate the observed deficit. Yet end of season deficits predicted by the CIS-F were very similar to that of the observed deficits and RMSE was within 6.6% of TAW in 2011 and 11.5% TAW in 2010. As indicated, much of the error occurred in the initial part of each growing season and much of the error encountered during this study can be explained by the difference between CIS-F estimated ET_c and lysimeter measured ET. In light of the difference observed between cumulative CIS-F estimated ET_c and cumulative lysimeter measured ET it is proposed that further improvements should be made to the K_{cr} values used to estimate ET_c in the CIS-F. The lack of observed deficits prior to March 30, of each growing season does not allow for the evaluation of $K_{c\ ini}$ during the first cutting cycle. However, data were available to evaluate $K_{c\ mid}$ for the first cutting cycle of 2010 and $K_{c\ mid}$ to $K_{c\ end}$ and $K_{c\ end}$ during each season of the first cutting cycle. Because the CIS-F tended to overestimate ET during much of this period (Figures 15 and 16) it is recommended that the $K_{c\ mid}$ and $K_{c\ end}$ values should be lowered. The lowering of $K_{c\ mid}$ and $K_{c\ end}$ during the first cutting cycle would help alleviate much of the discrepancy seen between CIS-F ET_c and lysimeter measured ET and reduce much of the error experienced during the first cutting cycle. It is also proposed that the value for $K_{c\ mid}$ during the remainder of the cutting cycles (2 – 4) be increased to help offset the discrepancies seen between CIS-F cumulative ET_c and cumulative lysimeter measured ET (Figures 15 and 16). As a result it is recommended that the $K_{c\ mid}$ and $K_{c\ end}$ be lowered to 0.80 and 0.75, respectively during the first cutting cycle, and the $K_{c\ mid}$ during cutting cycles 2 – 4 be increased to 1.15. This simple modification of the K_c values had a considerable impact on the overall performance of the CIS-F and improvement in all statistical analysis was seen in both 2010 and 2011 (Table 1-7). Nevertheless, this is a calibration of sorts and future tests should be conducted to validate the proposals.

Demonstration of the CIS as a tool to save water

In an attempt to further validate the usefulness of the CIS-A as an aid in irrigation scheduling, the potential of the tool to be used to help save water was also evaluated. Two iterations of the CIS-A were run using data from 2011 from the north site. The first iteration was run using actual irrigation data and the second was run simulating irrigation timings and amounts. Simulated irrigation timings were based off of CIS-A estimated deficits in order to maintain deficits that don't exceed MAD. The amount of simulated gross irrigation water applied during each irrigation event was representative of actual gross irrigation amounts applied in 2011 and within system capacities. As stated previously the actual gross amount of irrigation water applied in 2011 was 561 mm over the growing season. When the iteration of the CIS-A was run simulating irrigation, the total amount of gross irrigation water applied for the growing season was 423 mm; 138 mm less than what was actually applied. The number of irrigation events required to maintain a deficit not exceeding MAD in the simulated irrigation iteration was also reduced. The number of irrigation events (24) was decreased by ten over that which actually occurred (34). In addition to the water savings and reduction in the number of applications, CIS-A predicted RO/DP was also reduced in the simulated irrigation iteration. Runoff and DP predicted by the CIS-A was 85 mm for the season following the first observed soil water content measurement when the scheduler was corrected to reflect the observed soil water content and was reduced to zero with the simulated irrigation iteration.

CONCLUSION

Two ET-based irrigation scheduling tools were developed to track daily soil water deficits in the root zone of crops, one for use with annual crops (CIS-A) and one for use with perennial forage crops (CIS-F). Both schedulers were created using an Excel® spread sheet to track daily soil water deficits to help improve irrigation management decisions. The performance of the schedulers was tested by comparing scheduler predicted deficits to observed deficits obtained from soil moisture content measurements.

The CIS-A tended to predict a deficit greater than what was observed within the 105 cm control depth (MBE = -3.41 mm, RE = 13.58%). The greatest error observed between the CIS-A modeled deficit and the actual observed deficit occurred most at the start of each growing season when a deficit less than the observed was predicted and again at the end of each growing season when a deficit greater than what was observed was predicted. The end of season error between the CIS-A predicted deficit and observed deficit contributed significantly to the overall overestimation of the observed deficit for the entire study.

It is hypothesized that the source of the error in the end of season deficits is a result of plant water extraction from below the 105 cm control depth or the possible contribution of water to the modeled control depth from the unsaturated flow of water from a depth below the control depth. The most plausible solution to this problem would be to increase the control depth to at least 150 cm as Howell et al. (1995) indicate that corn can extract water from this depth. This could help to avoid the possibility of artificially introducing such error. Further tests of this tool should incorporate this suggestion and soil water content measurements should be taken to the same depth to validate the hypothesis. In general it is hypothesized that the CIS-A would perform even better if the model was not confined to the 105 cm control depth in this instance.

However, in soils that limit root growth to such depths, or shallower, the model would be satisfactory as is.

The CIS-A also tended to over predict RO/DP, especially in the initial part of the growing season. This problem can easily be resolved or the accuracy of the model can be enhanced by simply obtaining the actual deficit on the day that the scheduler is initiated, preferably at planting. Future tests of this model should initiate the scheduler with the correct observed deficit rather than the default deficit. Reducing as much of human induced error as possible would allow for better evaluation of the model and would also allow for a more in depth analysis of the proposed crop coefficient used to calculate ET_c.

The CIS-F also tended to overestimate the deficit for alfalfa over the 230 cm control depth. Evaluation of the CIS-F indicated overestimation of the deficit occurred most during the first cutting cycle of each year of the study. Much of the error encountered during this cycle could be explained by the difference between CIS-F estimated ET_c and actual ET measured by the lysimeters. The difference between observed and predicted ET is an indication of how important it is to obtain reliable ET information. The end of season deficits predicted by the CIS-F and the end of season observed deficits were very similar indicating that the CIS-F may in fact perform better than the statistics may indicate.

As a result of this study it is proposed that future testing of the irrigation scheduling tools should address the shortcomings detailed in this study. Future testing of the CIS-A should be carried out with a control depth of at least 1.5 m in corn to test the theory of end of season extraction of water below the control depth that was used in this study. An observed deficit should also be obtained on the day that the scheduler is initiated in order to further examine the possibility of over predicted RO/DP experienced early in the growing season. Along the same line, the performance of both irrigation scheduling tools would be greatly enhanced by simply correcting the predicted deficit on a periodic basis throughout the growing season with an observed deficit. It is also proposed that future testing of the schedulers implement on site rain gages, both in the field and on the exterior. Improvements in the accuracy of the schedulers could also be improved by accounting for spatial variation in precipitation between the field site and weather stations often experienced in eastern Colorado. Incorporation of these proposals should help to further validate the acceptability of the performance of the irrigation scheduling tools. On a final note, further testing of the CIS-F should also be carried out in a natural environment outside of a lysimeter to further test the performance of the tool. Although both schedulers tended to over predict the deficit throughout this study the tools do show promise of being used to improve irrigation management. This study demonstrates the potential of the tools to be used as a means to save water as well as energy costs associated with irrigation systems that require water to be pumped.

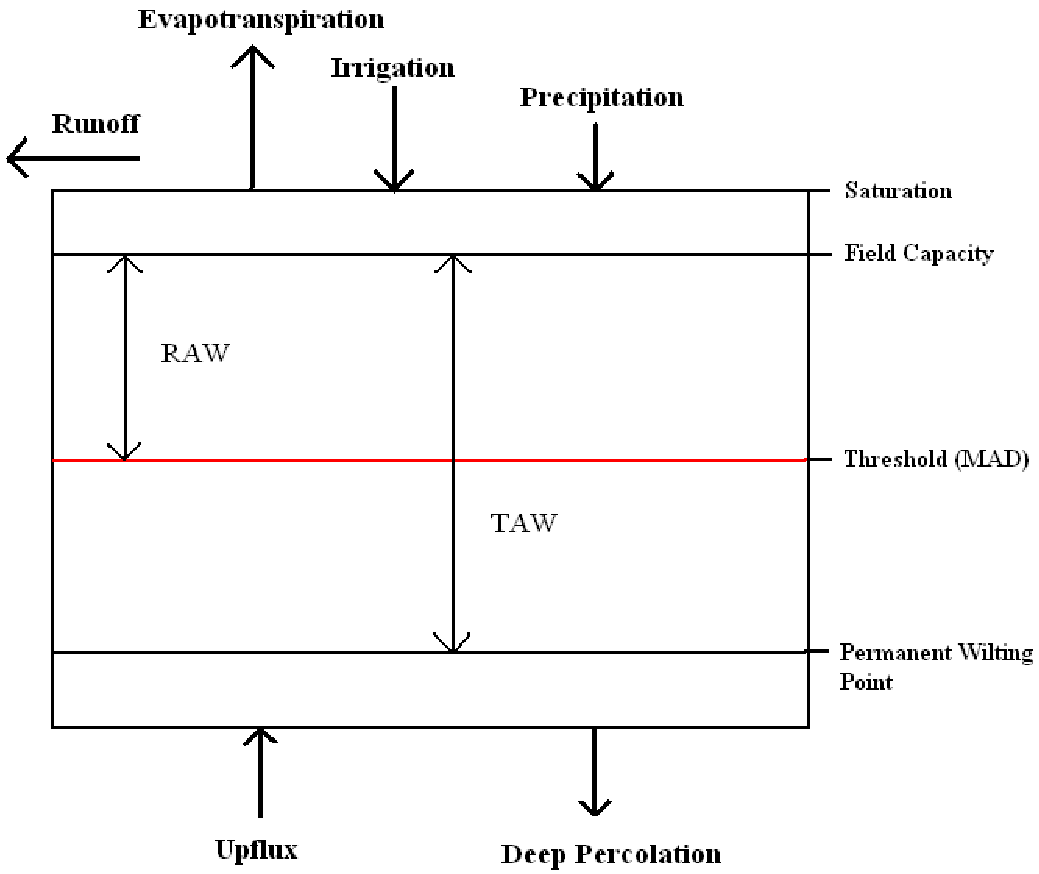

Fig. 1-1 – Graphical representation of soil water balance in a hypothetical root zone. Bold arrows indicate additions and subtractions of water from the root zone. Narrow arrows indicate plant available water: where RAW is readily available water, TAW is total plant available water, and MAD is management allowed depletion.

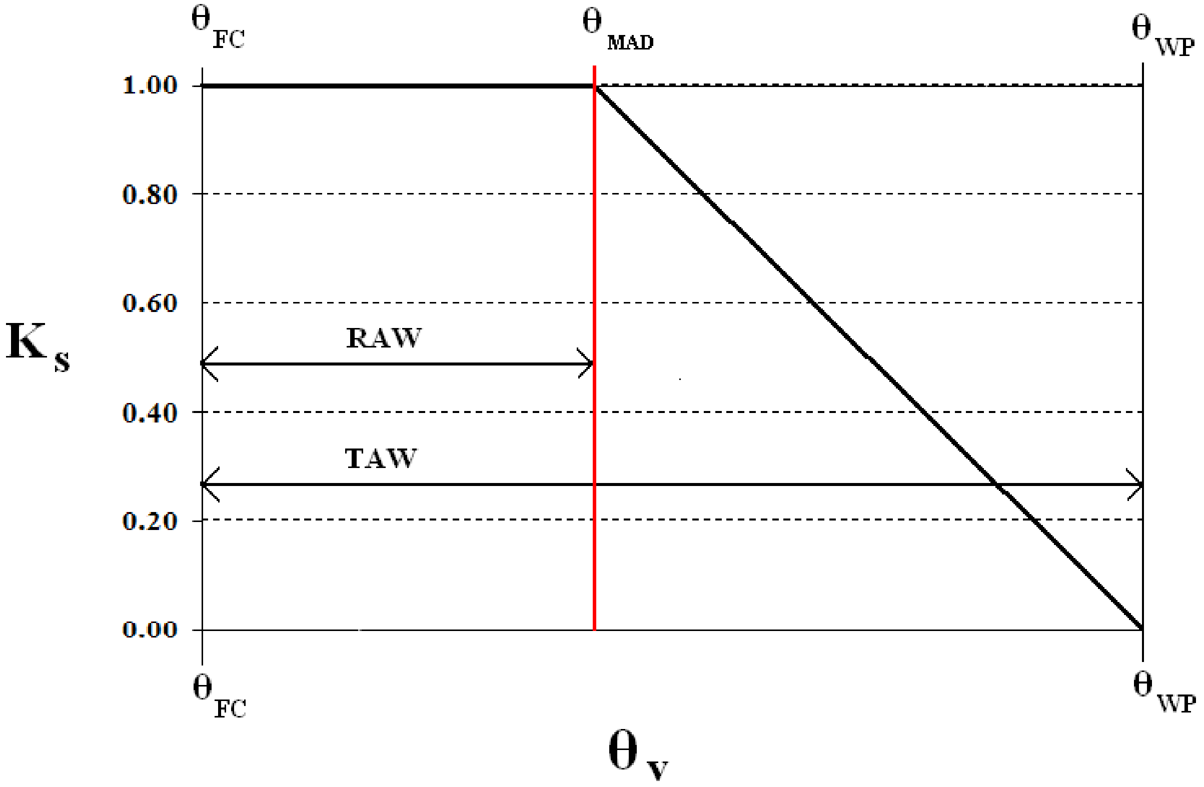

Fig. 1-2 – Graphical representation of soil water stress coefficient (K_s) and the impact on actual crop evapotranspiration. When volumetric water content in the root zone of a crop is between field capacity (θ_{FC}) and management allowed depletion (θ_{MAD}) no soil water stress occurs, therefore, $K_s = 1$. When volumetric water content (θ_v) drops below θ_{MAD} soil water stress begins to occur. As soil water is further depleted the value of K_s decreases proportional to θ_v until volumetric water content at permanent wilting point is reached.

Table 1-1 – Corn field soil properties used in the evaluation of the CIS-A. Soil properties from 2011 were used in the evaluation of the CIS-A for 2010 from the respective sites.

Year/Site	Depth (cm)	Bulk Density (g cm^{-3})	Field Capacity (cm^3 cm^{-3})	Wilting Point (cm^3 cm^{-3})	Total Available Water (cm^3 cm^{-3})
2011 North Site	0-15	1.16	0.331	0.171	0.160
	15-30	1.13	0.270	0.167	0.103
	30-45	1.33	0.277	0.141	0.136
	45-60	1.28	0.263	0.136	0.127
	60-90	1.30	0.256	0.108	0.148
	90-105	1.24	0.269	0.152	0.117
2011 South Site	0-15	1.06	0.331	0.147	0.184
	15-30	1.31	0.325	0.181	0.144
	30-45	1.25	0.271	0.137	0.134
	45-60	1.22	0.232	0.134	0.098
	60-90	1.40	0.248	0.121	0.127
	90-105	1.28	0.276	0.161	0.115
2012 North Site	0-15	1.11	0.316	0.163	0.153
	15-30	1.42	0.340	0.210	0.130
	30-45	1.44	0.300	0.153	0.147
	45-60	1.37	0.281	0.145	0.136
	60-90	1.35	0.267	0.112	0.155
	90-105	1.33	0.287	0.163	0.124
2012 South Site	0-15	1.16	0.332	0.161	0.171
	15-30	1.39	0.346	0.193	0.153
	30-45	1.39	0.301	0.153	0.148
	45-60	1.55	0.294	0.170	0.124
	60-90	1.39	0.246	0.120	0.126
	90-105	1.23	0.266	0.155	0.111

Table 1-2 – Soil properties of the alfalfa fields used in the evaluation of the CIS-F.

Depth (cm)	Bulk Density (g/cm^3)	Field Capacity (cm^3/cm^3)	Wilting Point (cm^3/cm^3)	Total Available Water (cm^3/cm^3)	Cumulative Available Water (cm)
0-23	1.36	0.291	0.154	0.137	3.151
23-36	1.36	0.290	0.162	0.128	4.815
36-100	1.45	0.242	0.099	0.143	13.967
100-170	1.43	0.252	0.107	0.145	24.117
170-230	1.35	0.296	0.142	0.154	33.357

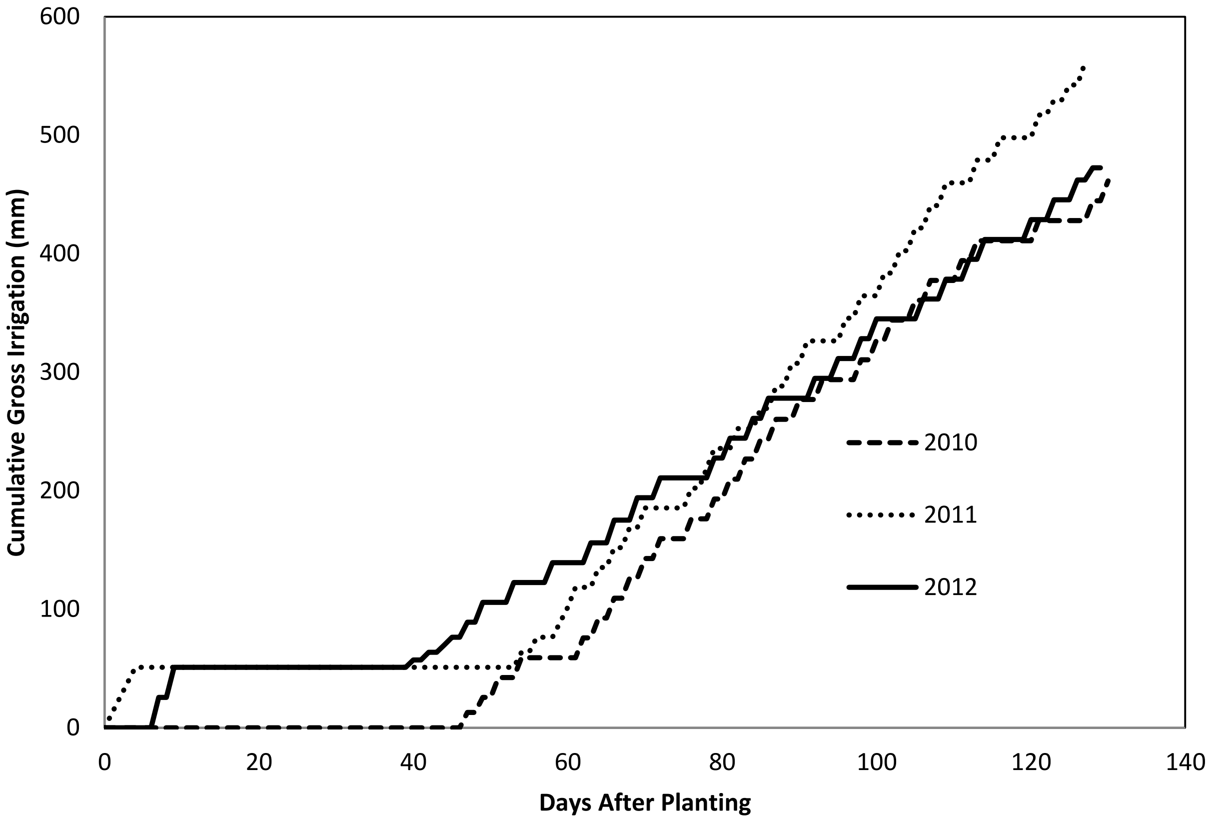

Fig. 1-3 – Comparison of cumulative gross irrigation water applied to the corn field during each season of the study from 2010-2012 from planting date till final irrigation.

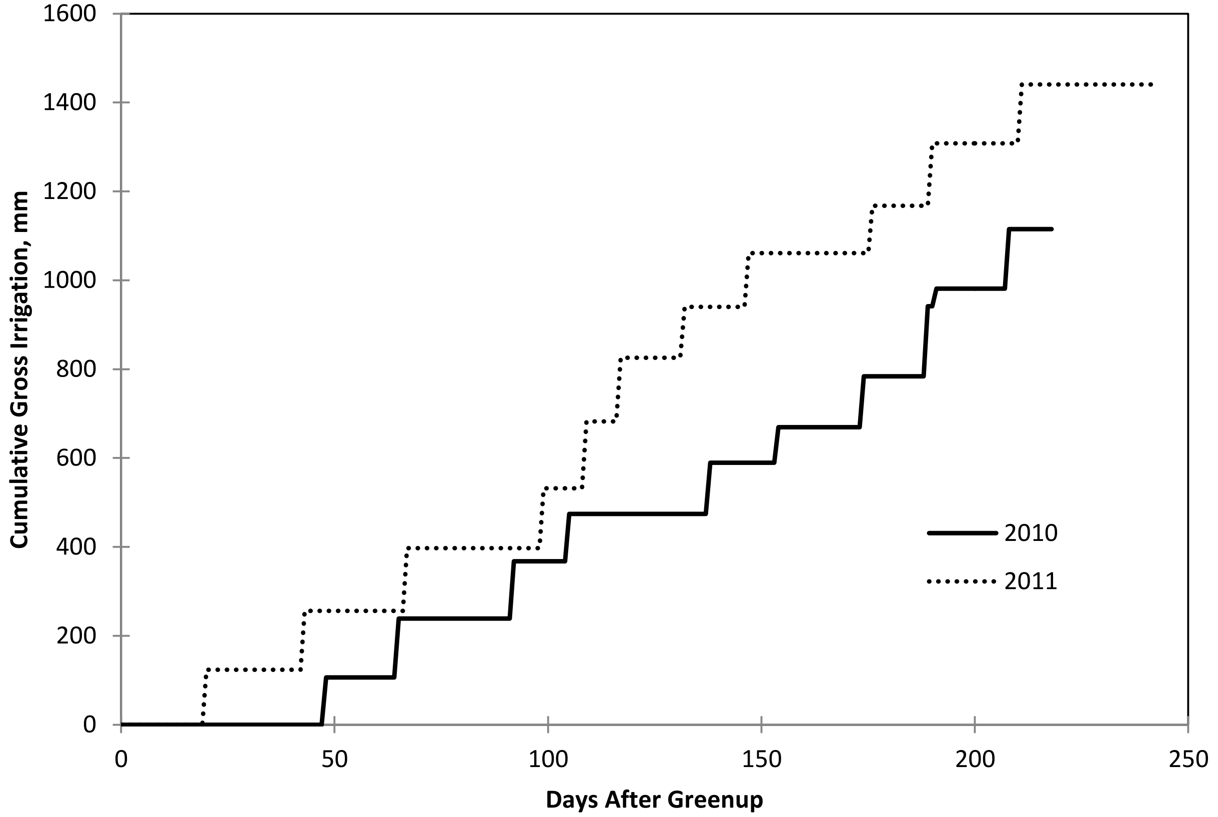

Fig. 1-4 – Comparison of cumulative gross irrigation applied to the lysimeters in the alfalfa fields during 2010 and 2011 from green up till final harvest.

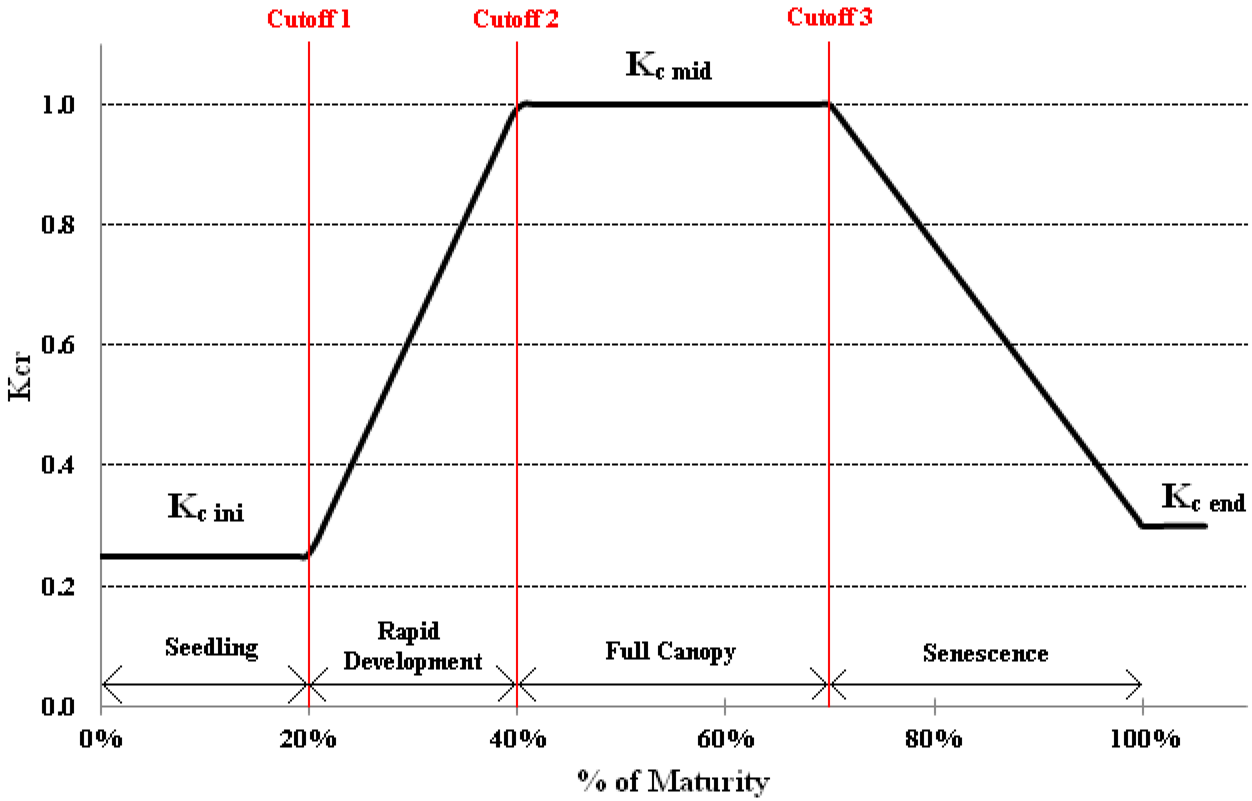

Fig. 1-5 – K_{cr} curve used to calculate corn ET_c in the CIS-A with crop development stages and $K_{c\ ini}$, $K_{c\ mid}$, and $K_{c\ end}$ portions of the K_{cr} curve indicated. Cutoffs are displayed in red and represent the percentage of crop maturity based on growing degree days.

Table 1-3 – Crop coefficient (K_{cr}) by development stage used in the CIS-A to calculate actual crop evapotranspiration for corn, where x = % of maturity (decimal fraction). Percent of maturity is calculated as percent of growing degree days (GDD) accumulated after emergence and where maturity is reached at 1389 GDD °C.

Development stage	**% of Maturity**	**K_c**	**K_{cr}**
Seedling	0-20	$K_{c\ ini}$	0.25
Rapid development	20-40	$K_{c\ ini}$ to $K_{c\ mid}$	$K_{cr} = 3.75x – 0.5$
Full canopy	40-70	$K_{c\ mid}$	1.0
Senescence	70-100	$K_{c\ mid}$ to $K_{c\ end}$	$K_{cr} = -2.33x – 2.63$
End	100	$K_{c\ end}$	0.30

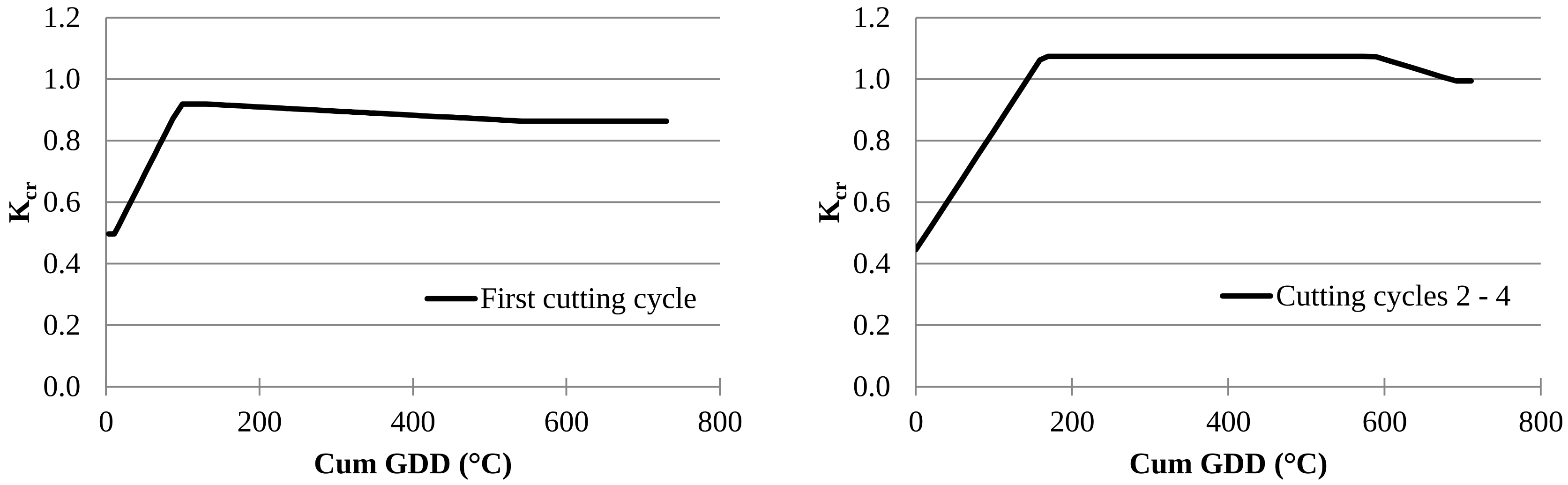

Fig. 1-6 – Diagram of general crop coefficient (K_{cr}) curves used to calculate alfalfa ET_c in the CIS-F for the 2010 and 2011 growing seasons. The first K_{cr} curve was developed for use during the first alfalfa cutting cycle and the second K_{cr} curve was developed for use during the remainder of the cutting cycles. Both curves were developed using lysimeter data.

Table 1-4 – Crop coefficient curves (K_{cr}) for each alfalfa cutting cycle used in the CIS-F to calculate ET_c, where x = growing degree days (GDD °C) accumulated after green up during the first cutting cycle and from the start of each subsequent cutting cycle thereafter.

Harvest/Cutting	K_c	K_{cr}	Cumulative GDD °C at Cutoff
1	$K_{c\ ini}$	0.497	10.90
	$K_{c\ ini}$ to $K_{c\ mid}$	$K_{cr} = 4.9 \times 10^{-4}x + 0.443$	96.77
	$K_{c\ mid}$	0.919	129.09
	$K_{c\ mid}$ to $K_{c\ end}$	$K_{cr} = -1.3 \times 10^{-4}x + 0.936$	543.84
	$K_{c\ end}$	0.864	
2-4	$K_{c\ ini}$	0.377	0.004
	$K_{c\ ini}$ to $K_{c\ mid}$	$K_{cr} = 3.9 \times 10^{-4}x + 0.377$	179.53
	$K_{c\ mid}$	1.074	605.05
	$K_{c\ mid}$ to $K_{c\ end}$	$K_{cr} = -8 \times 10^{-4}x +1.542$	708.49
	$K_{c\ end}$	0.994	

Table 1-5 – Comparison of CIS-A predicted deficits and observed deficits during the 2010-2012 corn growing seasons. Observed deficits were obtained manually through soil core sampling.

Site – Year	N[a]	RMSE[b] (mm)	MBE[c] (mm)	MAE[d] (mm)	RE[e] (%)
North 2010	16	12.97	-0.34	10.62	1.84
South 2010	16	16.38	-1.48	13.11	8.56
North 2011	16	12.10	-1.79	10.79	11.34
South 2011	16	15.72	-1.64	12.55	11.28
North 2012	15	22.89	-12.86	18.01	30.85
South 2012	15	13.42	-2.93	10.84	6.46
All	94	15.92	-3.41	12.61	13.58

[a] N = number of observations; [b] RMSE = root mean square error; [c] MBE = mean bias error; [d] MAE = mean absolute error; [e] RE = relative error.

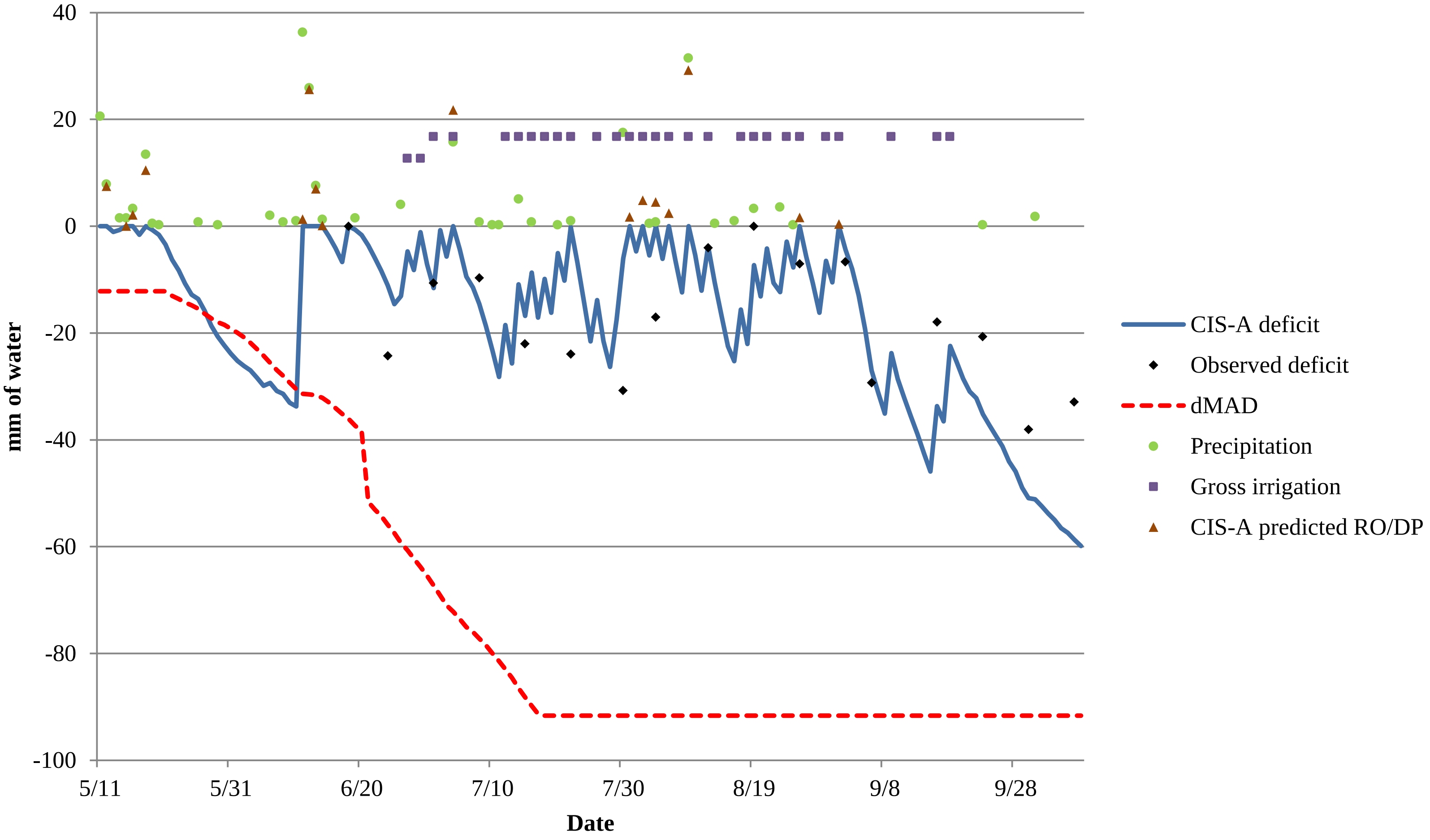

Fig. 1-7 – Comparison of CIS-A predicted deficit (blue line) and observed deficit (black diamonds) from the north site during the 2010 growing season. Also indicated is the depth of management allowed depletion (dMAD; dashed red line), precipitation, gross irrigation, and CIS-A estimated deep percolation and runoff (DP/RO). All parameters are represented as depth of water (mm).

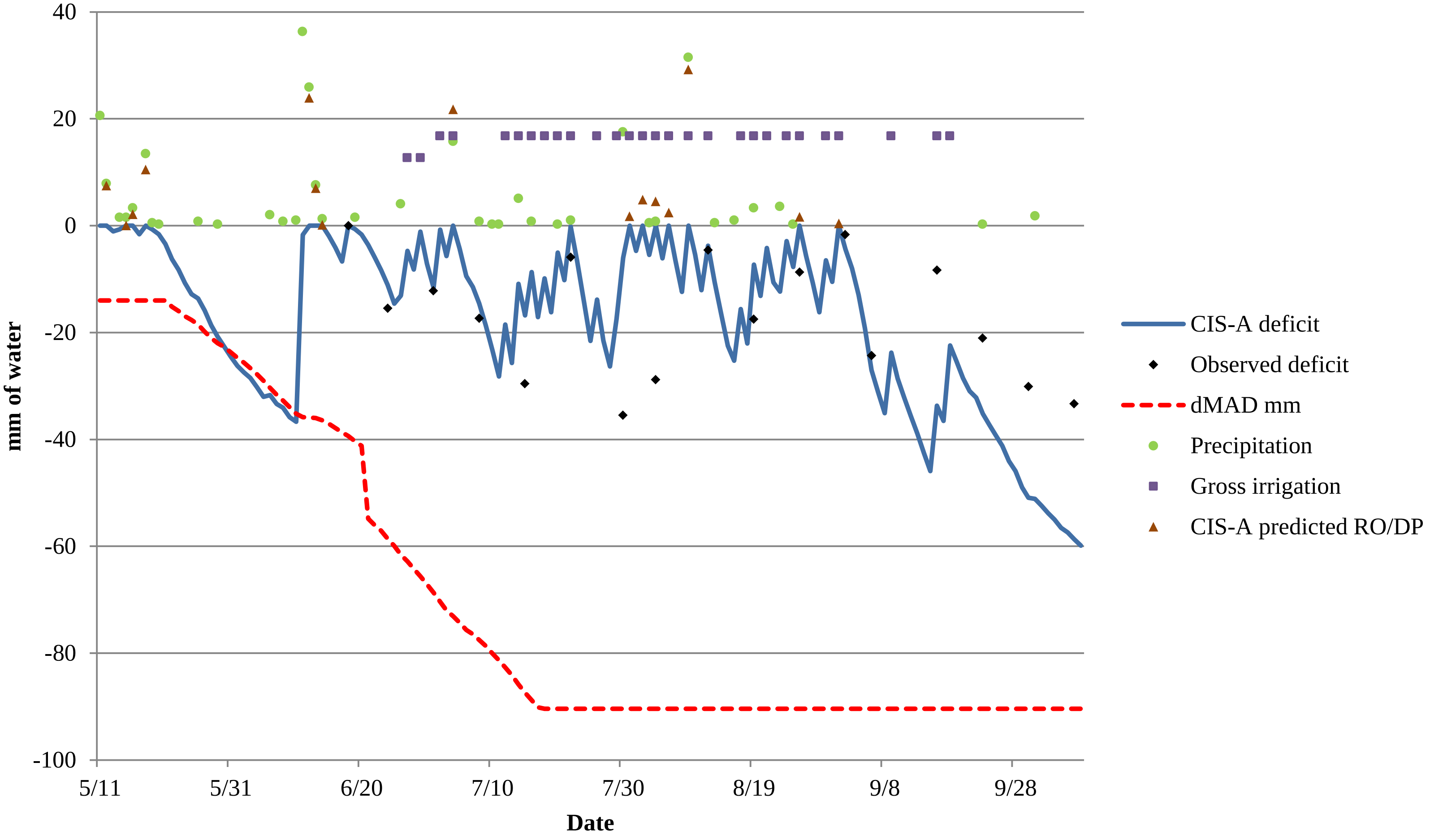

Fig. 1-8 – Comparison of CIS-A predicted deficit (blue line) and observed deficit (black diamonds) from the south site during the 2010 growing season. Also indicated is the depth of management allowed depletion (dMAD; dashed red line), precipitation, gross irrigation, and CIS-A estimated deep percolation and runoff (DP/RO). All parameters are represented as depth of water (mm).

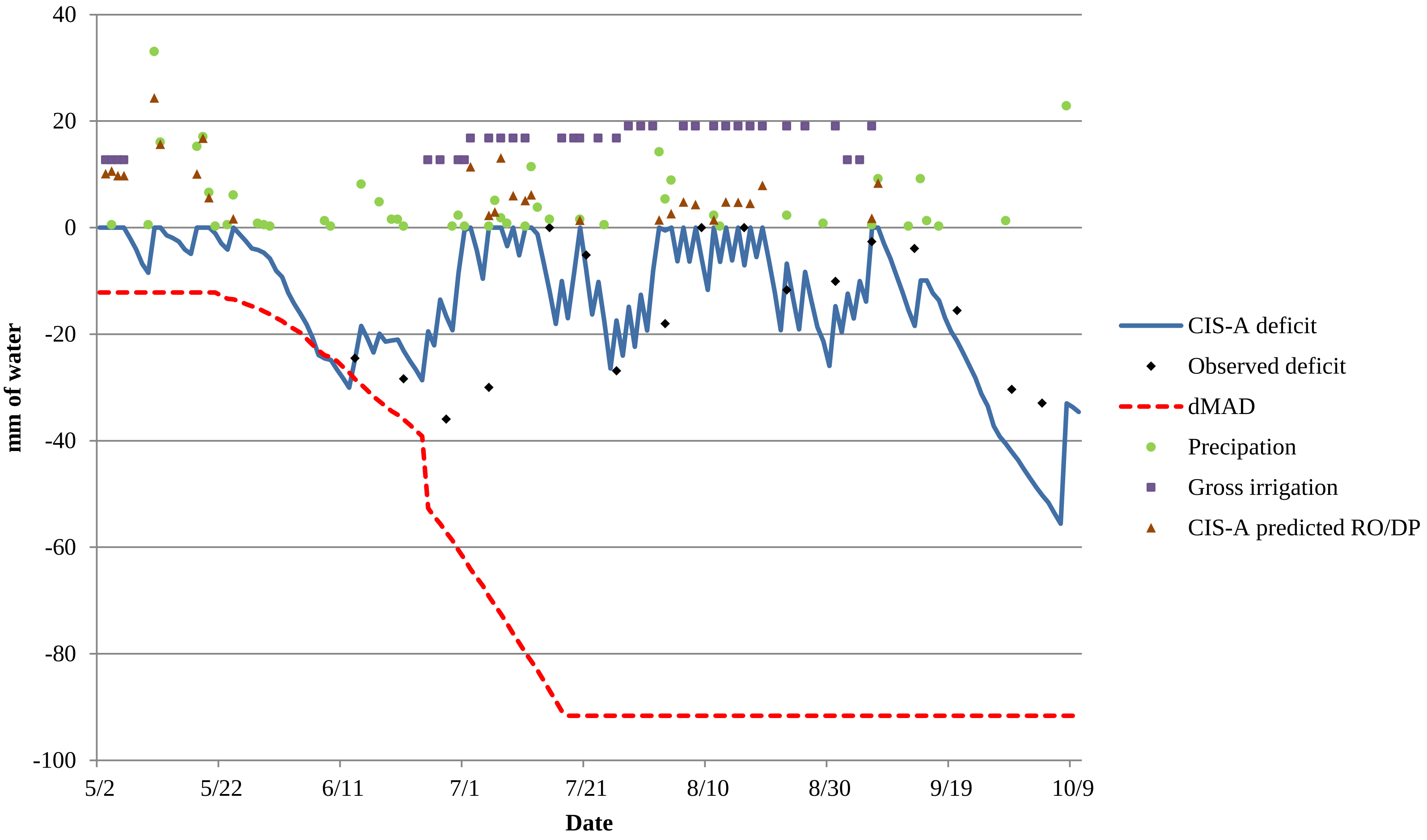

Fig. 1-9 – Comparison of CIS-A predicted deficit (blue line) and observed deficit (black diamonds) from the north site during the 2011 growing season. Also indicated is the depth of management allowed depletion (dMAD; dashed red line), precipitation, gross irrigation, and CIS-A estimated deep percolation and runoff (DP/RO). All parameters are represented as depth of water (mm).

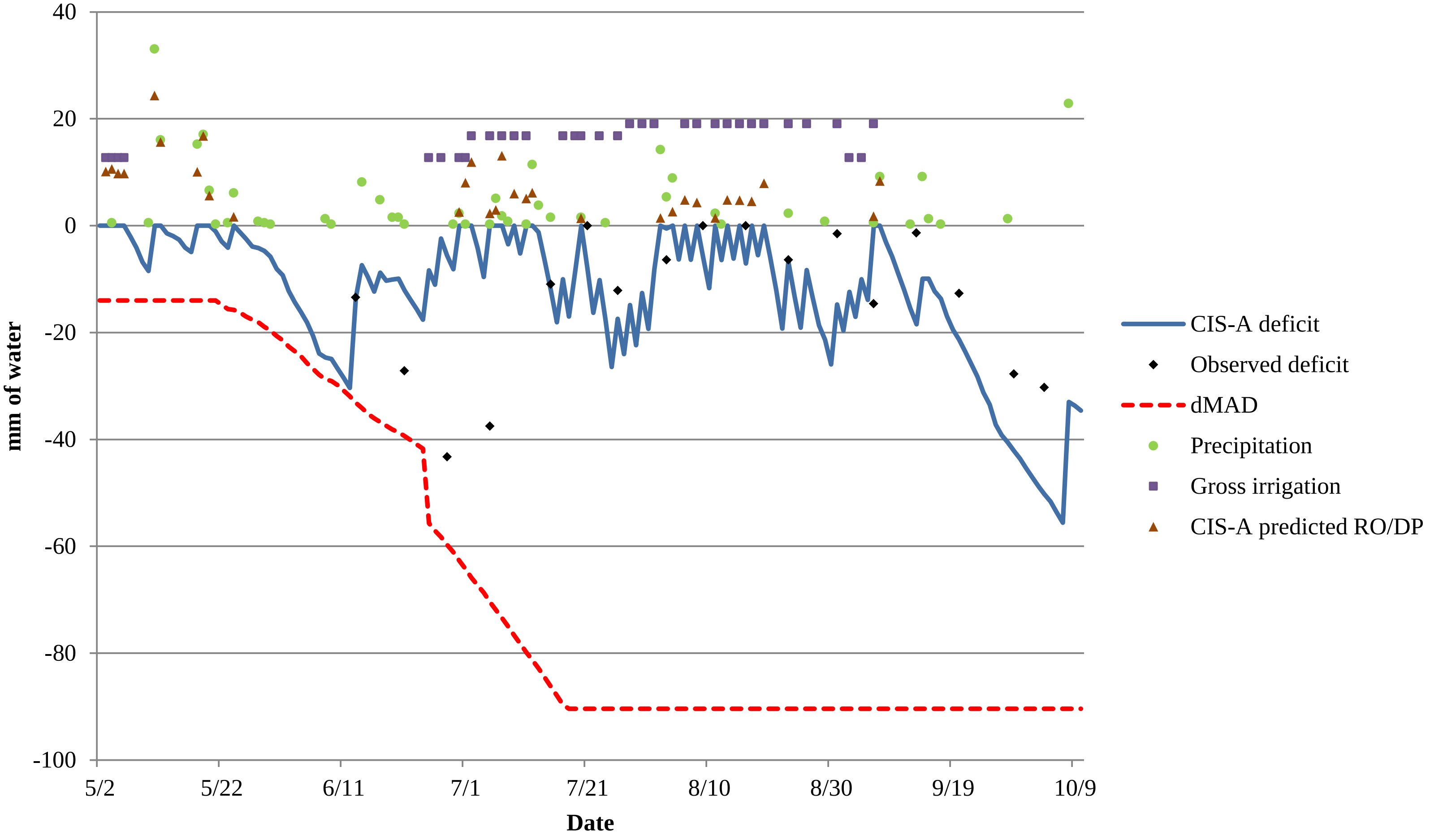

Fig. 1-10 – Comparison of CIS-A predicted deficit (blue line) and observed deficit (black diamonds) from the south site during the 2011 growing season. Also indicated is the depth of management allowed depletion (dMAD; dashed red line), precipitation, gross irrigation, and CIS-A estimated deep percolation and runoff (DP/RO). All parameters are represented as depth of water (mm).

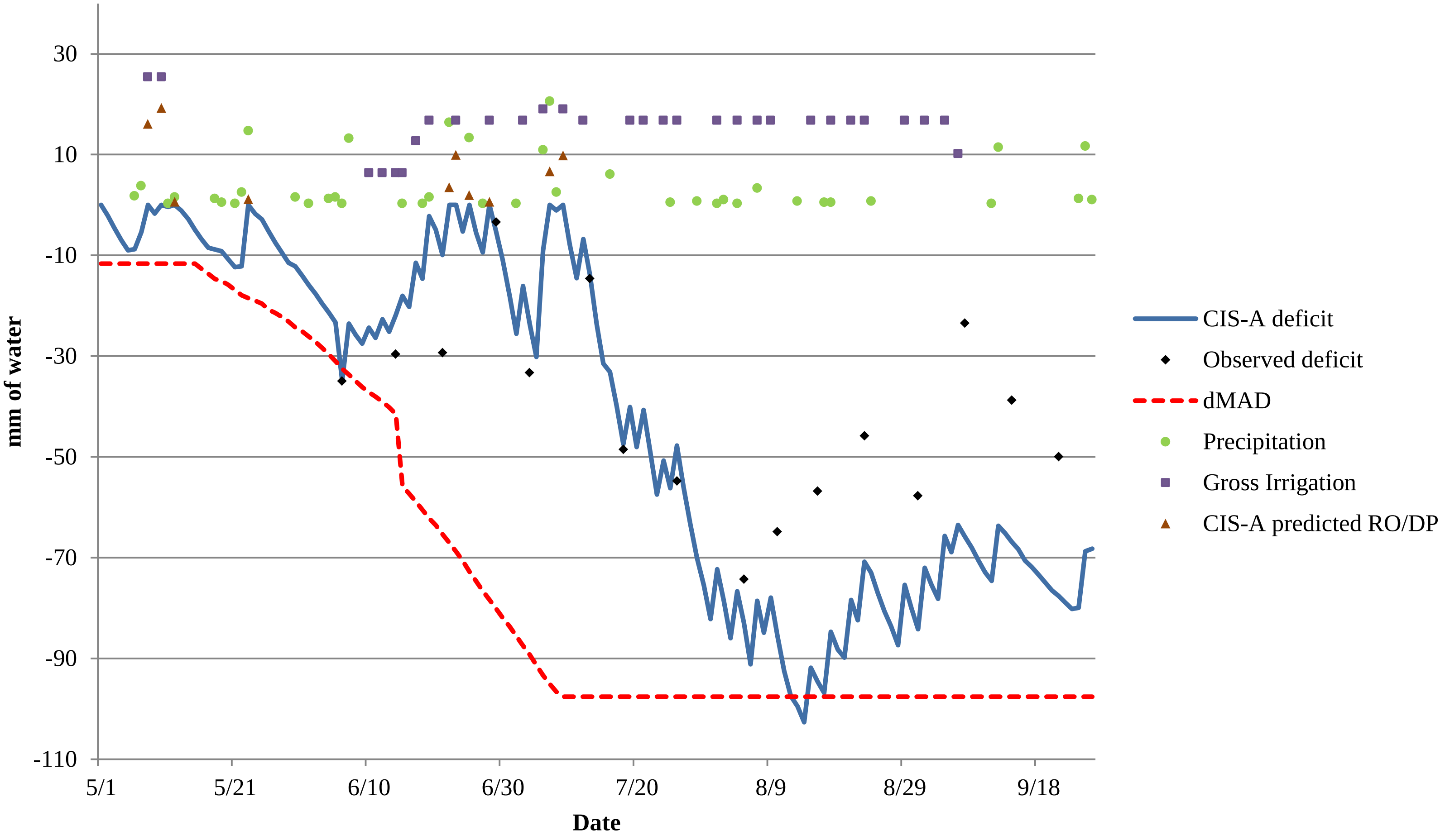

Fig. 1-11 – Comparison of CIS-A predicted deficit (blue line) and observed deficit (black diamonds) from the north site during the 2012 growing season. Also indicated is the depth of management allowed depletion (dMAD; dashed red line), precipitation, gross irrigation, and CIS-A estimated deep percolation and runoff (DP/RO). All parameters are represented as depth of water (mm).

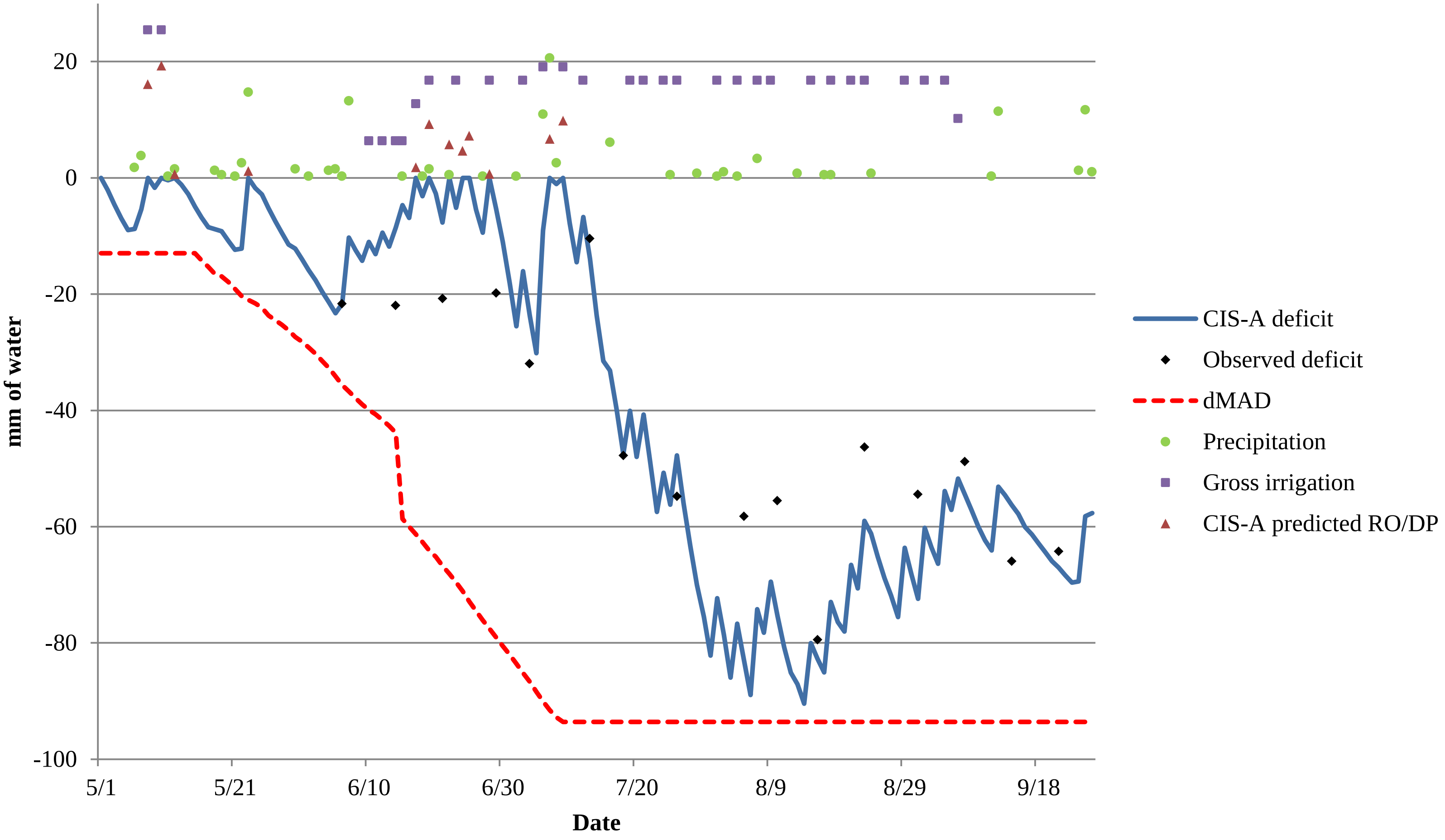

Fig. 1-12 – Comparison of CIS-A predicted deficit (blue line) and observed deficit (black diamonds) from the south site during the 2012 growing season. Also indicated is the depth of management allowed depletion (dMAD; dashed red line), precipitation, gross irrigation, and CIS-A estimated deep percolation and runoff (DP/RO). All parameters are represented as depth of water (mm).

Table 1-6 – Comparison of CIS-F predicted soil water deficits and observed soil water deficits for alfalfa during 2010 on the large lysimeter (LL) and 2011on the reference lysimeter (RL). Observed soil water deficits were obtained from Neutron Moisture Meter readings.

Site/Year	N[a]	RMSE[b] (mm)	MBE[c] (mm)	MAE[d] (mm)	RE[e] (%)
LL 2010	14	38.21	-32.84	32.94	34.11
RL 2011	16	22.02	-16.95	17.65	18.73

[a]N = number of observations; [b]RMSE = root mean square error; [c]MBE = mean bias error; MAE = mean absolute error; [e]RE = relative error.

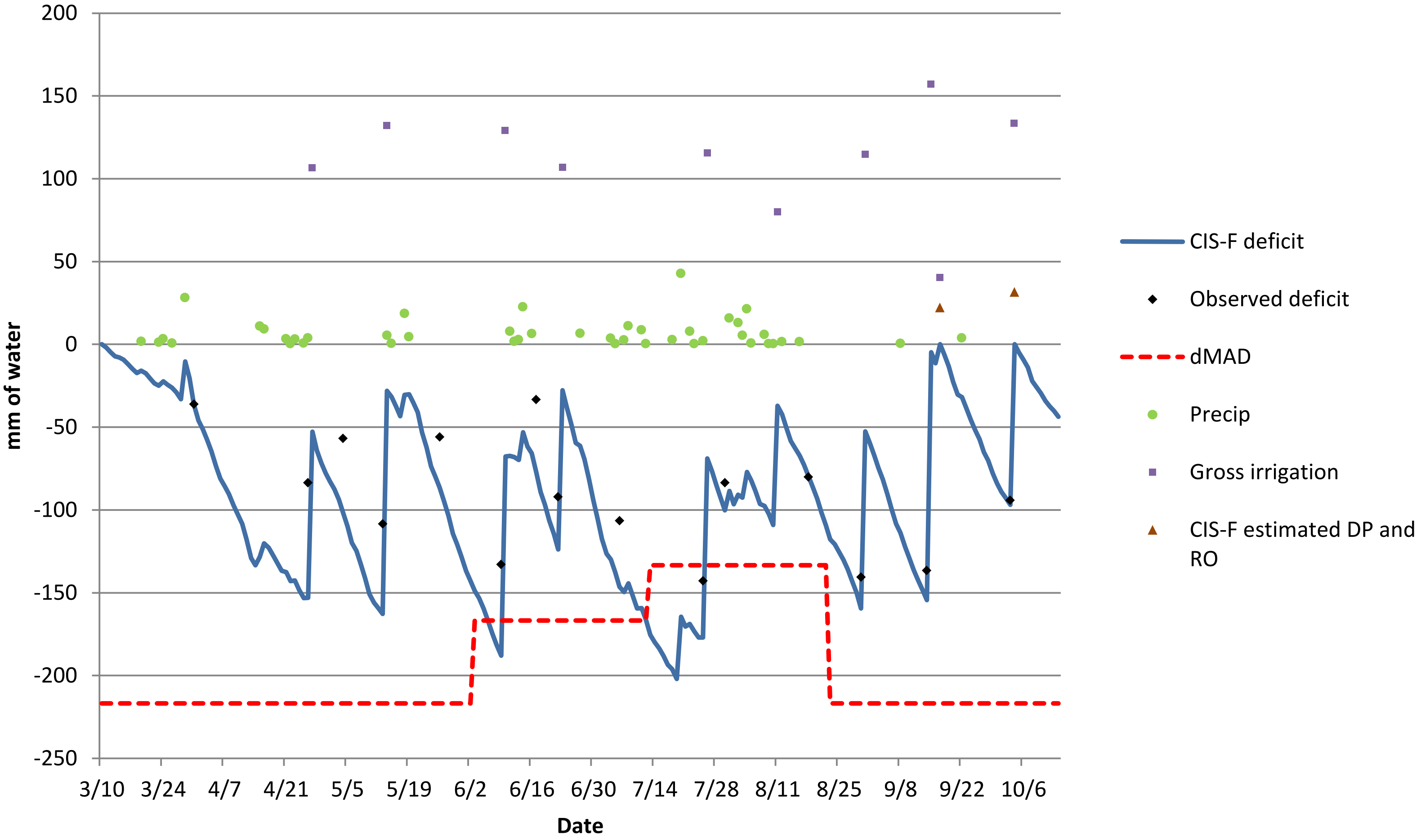

Fig. 1-13 – Comparison of CIS-F predicted deficit (blue line) and observed deficit (black diamonds) for alfalfa from the large lysimeter (LL) during the 2010 growing season. Also indicated is the depth of management allowed depletion (dMAD; dashed red line), precipitation, gross irrigation, and CIS-F estimated deep percolation and runoff (DP/RO). All parameters are represented as depth of water (mm). Each horizontal portion of dMAD is representative of a cutting period.

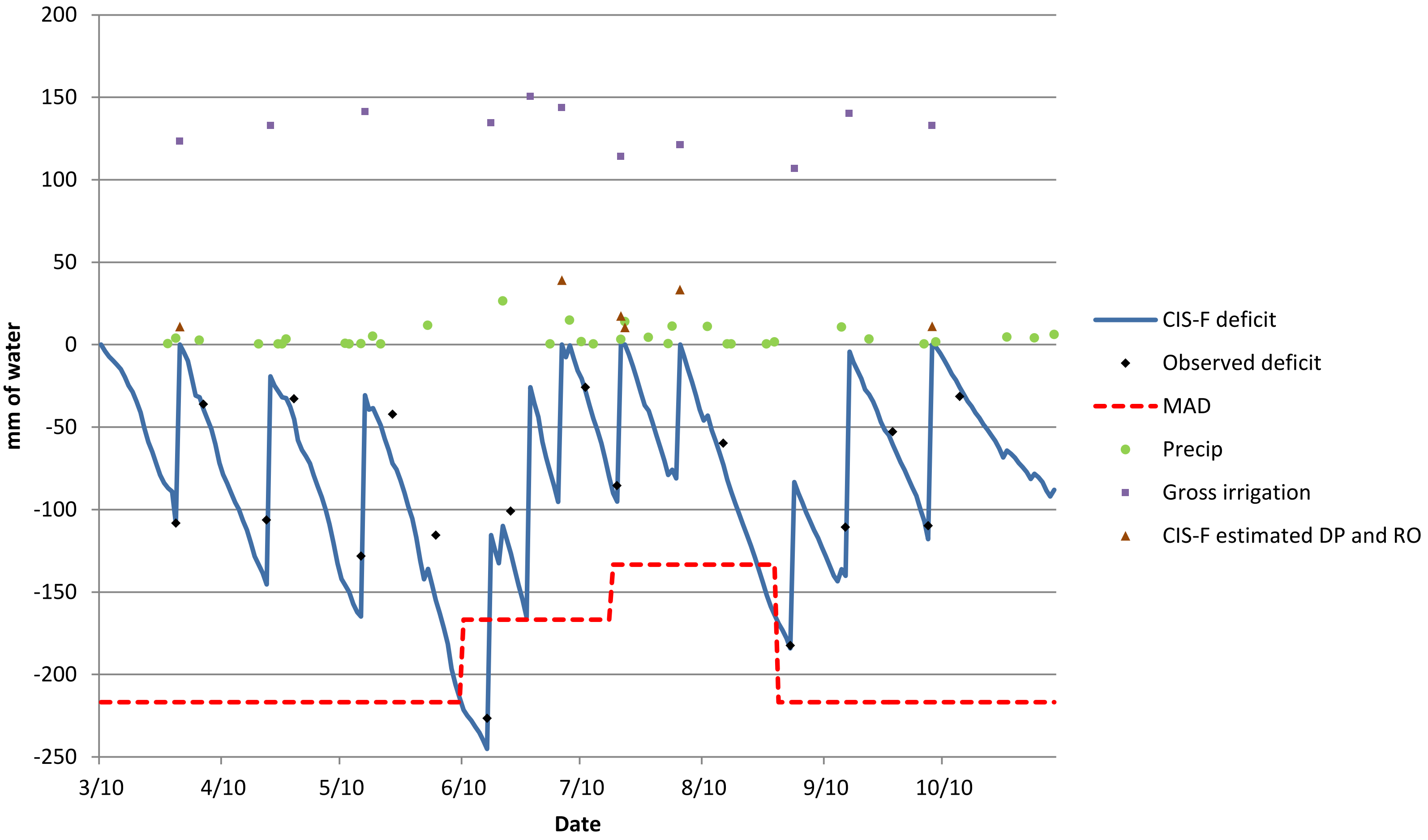

Fig. 1-14 – Comparison of CIS-F predicted deficit (blue line) and observed deficit (black diamonds) for alfalfa from the reference lysimeter (RL) during the 2011 growing season. Also indicated is the depth of management allowed depletion (dMAD; dashed red line), precipitation, gross irrigation and CIS-F estimated deep percolation and runoff (DP/RO). All parameters are represented as depth of water (mm). Each horizontal portion of dMAD is representative of a cutting period.

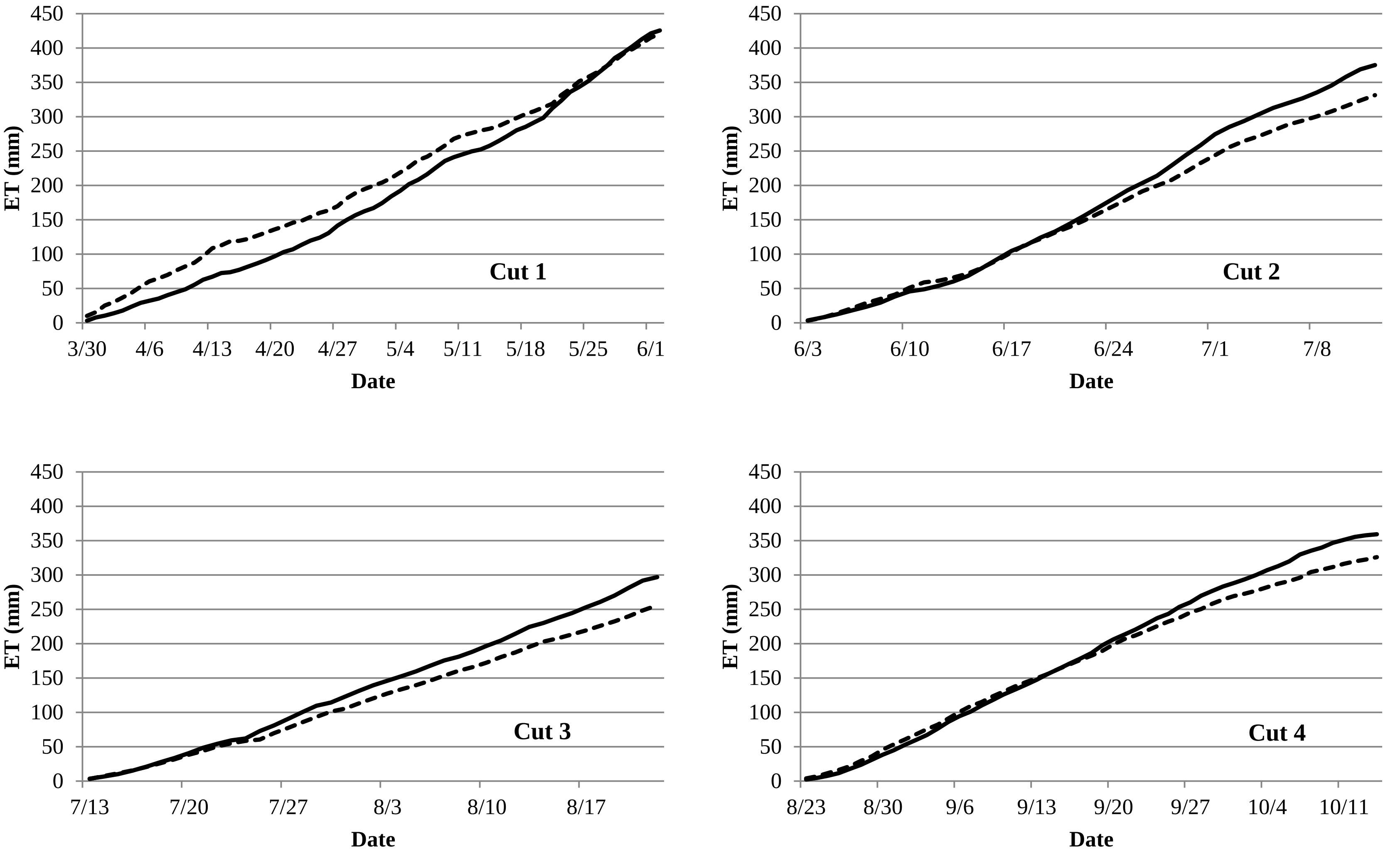

Fig. 1-15 – Comparison of alfalfa ET_c calculated using the ASCE Standardized Reference ET Equation for a tall crop and measured ET from the large lysimeter during 2010 for cuts 1 – 4. Dashed black line indicates cumulative calculated ET_c (CIS-F) during each cut and the solid black line represents cumulative measured ET from the large lysimeter for each cut.

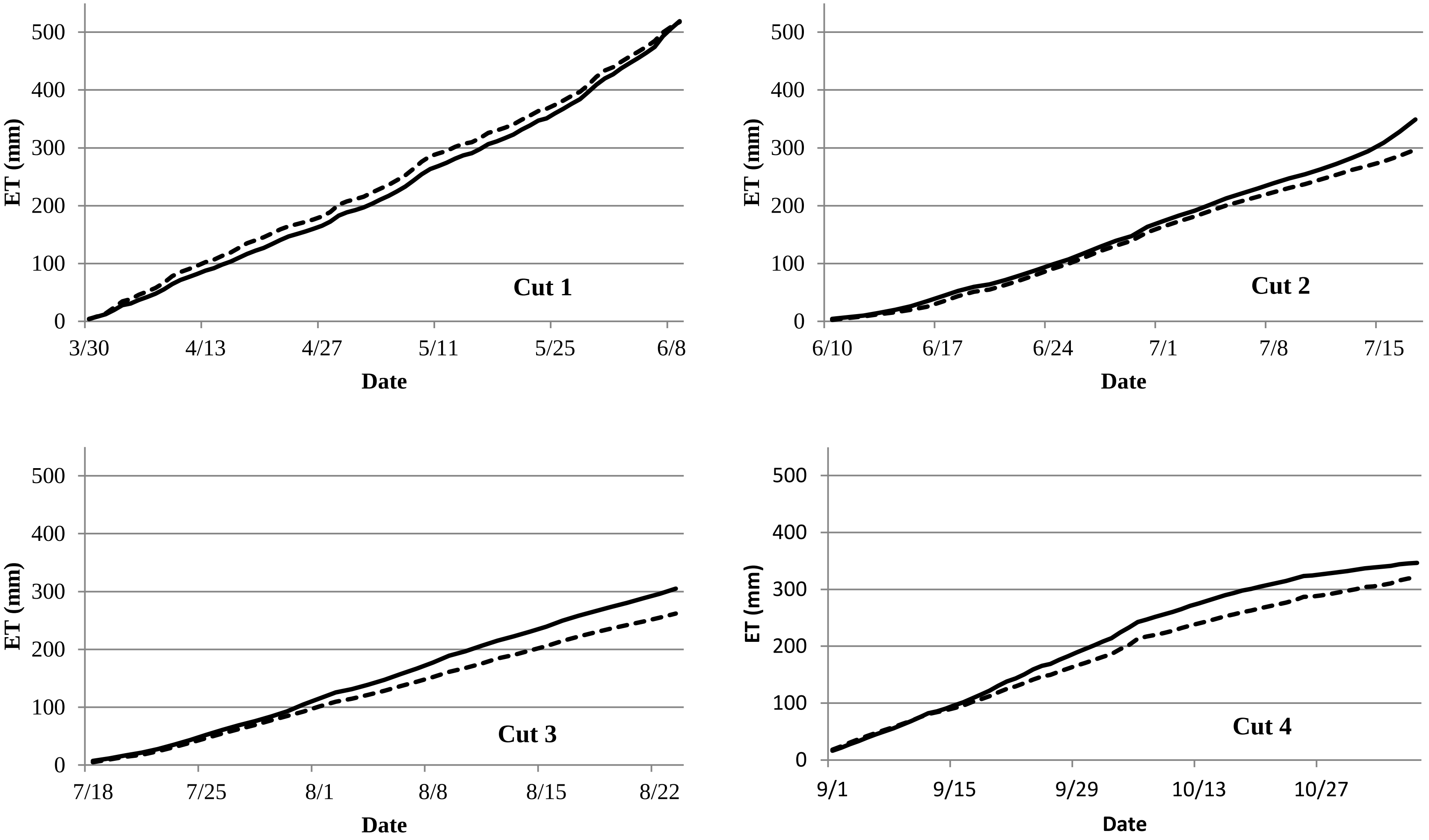

Fig. 1-16 – Comparison of alfalfa ET_c calculated using the ASCE Standardized Reference ET Equation for a tall crop and measured ET from the reference lysimeter during 2011 for cuts 1 – 4. Dashed black line indicates cumulative calculated ET_c (CIS-F) during each cut and the solid black line represents cumulative measured ET from the large lysimeter for each cut.

Table 1-7 – Comparison of CIS-F predicted soil water deficits and observed soil water deficits for alfalfa during 2010 on the large lysimeter (LL) and 2011on the reference lysimeter (RL) using proposed adjustments to crop coefficients. Observed soil water deficits were obtained from Neutron Moisture Meter readings.

Site/Year	N[a]	RMSE[b] (mm)	MBE[c] (mm)	MAE[d] (mm)	RE[e] (%)
LL 2010	14	20.92	-15.47	16.78	16.07
RL 2011	16	18.21	-5.97	14.89	6.60

[a]N = number of observations; [b]RMSE = root mean square error; [c]MBE = mean bias error; MAE = mean absolute error; [e]RE = relative error.

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CHAPTER 3: PERFORMANCE OF ATMOMETERS IN ESTIMATING REFERENCE EVAPOTRANSPIRATION IN A SEMI-ARID ENVIRONMENT

SUMMARY

Evapotranspiration (ET) based irrigation scheduling requires accurate measurements of reference evapotranspiration. Mathematical formulas with localized weather data can be used to accurately predict alfalfa reference ET rates (mm h^{-1} and mm d^{-1}). When local meteorological data are unavailable, a physical measurement of ET can be taken with an atmometer. The objective of this study was to determine if a Model E atmometer (ETgage Company, Loveland, CO), equipped with a canvas #54 cover, could be used to effectively estimate alfalfa reference ET. The ASCE Standardized Alfalfa Reference ET Equation (ASCE ET_{rs}) was used as the standard for comparison of atmometer ET values to determine atmometer performance. Four years of alfalfa ET, as determined by an atmometer (ET_{gage}), were compared to ASCE ET_{rs}. Daily as well as 2, 3, 5, and 7 day sums of daily ET_{gage} and ASCE ET_{rs} were compared using simple least-squares linear regression. Coefficients of determination (R^2) between daily ET_{gage} and ASCE ET_{rs} for all years were greater than or equal to 0.80. Throughout the study, the atmometer tended to underestimate ASCE ET_{rs}. Average seasonal underestimation of ASCE ET_{rs} measured by the atmometer ranged from 9.06% to 18.9%. Root Mean Square Error (RMSE) and Mean Bias Error (MBE) ranged from 1.14 to 1.82 mm d^{-1} and -0.66 to -1.51 mm d^{-1}, respectively. The atmometer underestimated daily ASCE ET_{rs} 88% of the time, with an average underestimation of 1.30 mm d^{-1}. Underestimation of ASCE ET_{rs} measured by the atmometer occurred most often on days when mean daily horizontal wind speeds were greater than 2 m s^{-1} and/or when mean daily air temperatures were below 20 °C. The atmometer performed best when the alfalfa was at reference condition. Localized calibration equations for reference and non-reference conditions with a temperature correction were developed to improve accuracy, with average magnitude of MBE reduced from -0.97 mm d^{-1} to 0.13 mm d^{-1}.

Keywords Evapotranspiration, Atmometer, Calibration

INTRODUCTION

Importance of irrigation and irrigation scheduling

Worldwide, irrigated lands constitute approximately 20% of the world’s total cultivated farmland but produce about 40% of the food and fiber (Hoffman et al., 2007). In the Western United States, irrigation is the largest consumer of fresh water resources and accounts for approximately 40% of all fresh water withdrawals in the United States (Hoffman et al., 2007). In 2007, there were 22.2 million hectares (54.9 million acres) of irrigated farmland in the United States, up 4.6% from 21.2 million hectares (52.5 million acres) in 2003. This irrigated land accounted for 112 billion m^3 (91.2 million acre-feet) of water applied for agricultural production (USDA, 2008). Irrigated crop production is the largest consumer of fresh water and thus has the greatest potential for water conservation. Tools have been developed to aid in on-farm irrigation scheduling and can help to more accurately determine the timing and amount of irrigation water to be applied.

More precise application of irrigation water has become an important topic of research in recent years due to economic, environmental, and political pressures on agriculture water supplies (Cooley et al., 2009). It is widely known that over-irrigation has unintended consequences. It can lead to surface and groundwater contamination from agrochemicals and nutrients, increases operation and management costs, and can cause reduction in crop yield and income (Pereira et al., 2002). Some areas could potentially become saline due to high water tables caused by over-irrigation. Conversely, it is also well documented that under-irrigation can have substantial negative impact on crop yields and bio mass production (Irmak et al. 2006; Payero et al. 2006; Traore et al. 2000). Stressing crops, especially during critical growth stages, is a major contributor to yield reduction. Appropriate irrigation scheduling is essential to attaining desired yields while also conserving water, soils, nutrients, and energy.

Accurate estimation of crop water use is an important aspect of making sound irrigation scheduling decisions. Over the past several decades numerous equations have been developed to estimate reference ET (ET_r) under a reference condition. In 2005 the Environmental and Water Resources Institute of the American Society of Civil Engineers (ASCE-EWRI) standardized the calculation of reference ET. The ASCE Penman-Monteith method from ASCE Manual 70 (Jensen et al., 1990) was used as a basis for standardization and development of the American Society of Civil Engineers Standardized Reference ET Equations for both grass, a short, smooth crop (ASCE ET_{os}), and alfalfa, a tall, rough agricultural crop (ASCE ET_{rs}). The purpose of the standardization of the ASCE Penman-Monteith was to encourage commonality, thus simplifying the development of crop coefficients and making it easier to transfer existing crop coefficients already being used in agriculture and landscape irrigation applications, and making it easier to make broad scope research comparisons (ASCE-EWRI, 2005). Hoffman et al. (2007) have indicated that the ASCE Standardized Reference ET Equation is considered to be one of the best methods to calculate reference ET. Furthermore, in 2003 the United States Supreme Court recommended the use of the ASCE Standardized Reference ET Equation to be used to determine reference crop ET and crop consumptive use for compliance with the Arkansas River Compact in the case of Kansas v. Colorado (Ley et al., 2010; Montgomery, 2003).

The use of the ASCE Standardized ET Equation to calculate reference ET requires the use of measured weather variables, including hourly or daily wind speed, solar radiation, air temperature, and humidity. In recent years there has been widespread placement of in situ weather stations and expansion of existing meteorological networks. For example, the Colorado Agricultural Meteorological Network (CoAgMet) now has in situ weather stations located in major agricultural regions of Colorado. However, as Alam and Elliot (2003) have indicated weather station data are still unavailable in many parts of the world because of prohibitive costs of weather stations and lack of local expertise. Even in developed countries like the U.S., there is still a need for an increase in the number and density of meteorological data collection systems because of the diversity of cropping systems, climate, soil characteristics, and management practices (Irmak et al., 2010). In order to obtain accurate weather data for use in the calculation of ET through the use of such equations as the ASCE Standardized Reference ET Equation, weather stations must be well maintained in accordance with guidelines set forth during the development of the equations, and located properly. Another drawback to the use of weather stations in collecting weather data are the costs involved in implementing extensive networks of such stations (Alam and Trooien, 2001). Weather stations are expensive and require long term commitments.

An alternative to the use of complex equations that require accurate measurements of meteorological data to calculate reference ET may be found through the use of atmometers. Atmometers are inexpensive, easy to read, and require little maintenance. For example, the cost of an automatic weather station in the U.S. may range from $3,000 to $6,000 while a logging atmometer costs around $700 to $800. An atmometer is a simple and inexpensive device that estimates evapotranspiration (ET) (Alam and Trooien, 2001). Atmometers have been designed to be a physically based model of a transpiring reference plant canopy (Altenhofen, 1985). The device consists of a cylinder, filled with distilled water, connected to a porous ceramic cup (which is covered with a cloth or fabric) via a small tube. The water evaporated from the ceramic cup mimics water evaporated from a reference crop canopy. Alam and Trooien (2001), Broner and Law (1991), and Irmak et al. (2005) provide more extensive descriptions of atmometer design and functionality. Different types of fabrics can be placed over the ceramic cup to imitate either grass or alfalfa based reference ET rates. For the atmometer instrument designed by the ETgage Company, Loveland, Colorado, a green canvas #54 cover is used to simulate alfalfa-based reference ET, whereas a denser canvas #30 cover is used to simulate ET from a grass reference canopy (ETgage Company). A Gore-Tex fabric is also available for use with tall crops, where the top of the atmometer is adjusted throughout the growing season to match the height of the crop canopy.

Atmometers can be used as an effective irrigation scheduling tool in place of more complicated mathematical formulas. One advantage of using an atmometer for irrigation scheduling is that localized weather data are not required to determine ET rates. Furthermore, the personalized placement of an atmometer can help reduce the effects of spatial weather variability experienced from field to weather station, especially if a field of interest is not located within a close proximity of an active and adequately maintained weather station.

The objectives of this study were: (1) to determine if an atmometer equipped with a canvas #54 cover could be used to effectively estimate alfalfa reference ET as calculated by the ASCE Standardized Reference ET Equation (ET_{rs}) in the semiarid environment of southeast Colorado; (2) to determine if the atmometer’s performance was negatively impacted by varied weather conditions experienced at the research site; and (3) to evaluate the performance of the atmometers under alfalfa reference and non-reference conditions. During four alfalfa growing seasons, ET was determined by both techniques under field conditions and these ET values were statistically compared in order to infer the atmometers performance. Calibration equations have also been proposed to improve the accuracy of the atmometer.

MATERIALS AND METHODS

Research site

This experiment was conducted at the Colorado State University Arkansas Valley Research Center (CSU-AVRC), Rocky Ford, Colorado, USA (38°2’17.30”N, 103°41’17.60”W, 1274 m above mean sea level). The climate of the studied area is semiarid, with mean annual precipitation measuring 306 mm, and mean annual maximum and minimum air temperatures of 20.9 °C and 2.2 °C, respectively. The research field is 4.06 ha (158 m x 256 m rectangle) and was planted to alfalfa in August 2007. Irrigation water was applied to the field via furrow irrigation. The research site is equipped with an automated weather station in the middle of the alfalfa field.

Equipment

Atmometer

The atmometer type used in this study was an ETgage Model E (ETgage Company, Loveland, CO, USA), and is an automated atmometer designed for use with a datalogger. The Model E measures evaporation rates in 0.254 mm increments and manual readings can also be taken via a glass sight tube and scale (1 mm increments) mounted on the side of the atmometer. A canvas #54 cover was used to simulate evaporation rates of reference alfalfa as described by the manufacturer. Three different Model E atmometers were used over the studied period: one in 2008, one in 2009 and 2010, and one in 2011. Prior to each growing season lab comparisons were performed and no significant differences were found between the performance of the devices used throughout the study. The atmometers were installed vertically on a post using the manufacturer provided metal mounting bracket. Placement of the device was approximately 2 m northwest of an automatic weather station. Installation height was set at 1.5 m above the soil surface so as to be approximately 1 m above the reference height of alfalfa which is 0.5 m. Distilled water was used to fill the atmometer column and water levels were maintained by refilling the instrument every two weeks. Data were recorded using a HOBO Pendant Event Data Logger UA-003-64 (Onset Computer Corporation, Bourne, MA, USA) that records an event (electrical pulse) every time 0.254 mm of water (ET) passes through a glass vial in the atmometer. Data were downloaded each season after system removal prior to first frost.

Weather station

Weather parameters used in the computation of ASCE Standardized Reference Equation for alfalfa (ET_{rs}) were collected from an onsite automated weather station. The weather station is located in the center of the study field. Incoming solar radiation ($W\ m^{-2}$) was measured using a Kipp & Zonen CM14 pyranometer (Kipp & Zonen, Delft, The Netherlands) installed 1.0 m above the ground. Wind speed ($m\ s^{-1}$) was measured at a height of 2 m above the soil surface using a R.M. Young 03101 Wind Sentry cup anemometer (R.M. Young Company, Traverse City, MI, USA). A Vaisala HMP45 sensor was used to measure air temperature (°C) and relative humidity (RH, %) at a height of 1.5 m above the soil surface (Vaisala, Helsinki, Finland). All meteorological parameters were recorded using a CR-7X data logger (Campbell Scientific, Inc. Logan, UT, USA) and measurements were taken on six second intervals. Data were averaged to 15-minute and hourly values, and hourly values were used in the hourly version of the ASCE Standardized Reference ET Equation.

ET_{rs} calculations

The hourly version of the ASCE Standardized Reference ET Equation (Eq. 1) was used to estimate ET_{rs}. Net radiation and ground heat flux were calculated from measured incoming solar radiation following the ASCE-EWRI (2005) guidelines. Net Radiation, wind speed, air temperature, and vapor pressure data obtained from the onsite weather station, were used to calculate hourly ET_{rs} (mm h^{-1}). Fifteen-minute averaged data were aggregated to hourly values for input into the hourly version of the ASCE Standardized Tall Reference Equation. Daily ET_{rs} (mm d^{-1}) was calculated as the sum of hourly ET_{rs} for each day. The hourly ASCE Standardized Tall Reference ET Equation is given below (ASCE-EWRI, 2005).

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

where ET_{rs} is standardized reference crop evapotranspiration for tall surfaces (mm h^{-1}), R_n is calculated net radiation at the crop surface (MJ m^{-2} h^{-1}), G is soil heat flux density at the soil surface (MJ m^{-2} h^{-1}), T is mean hourly air temperature at 1.5 to 2.5-m height (°C), u_2 is mean hourly wind speed at 2-m height (m s^{-1}), e_s is saturation vapor pressure at 1.5 to 2.5-m height (kPa) and is a function of air temperature, e_a is mean actual vapor pressure at 1.5 to 2.5-m height (kPa) and is used to represent the water content of the air (relative humidity), Δ is the slope of the saturation vapor pressure-temperature curve (kPa $°C^{-1}$), γ is the psychrometric constant (kPa $°C^{-1}$), C_n is the numerator constant for tall reference and hourly time step (66 K mm s^3 Mg^{-1} h^{-1}) and

C_d is the denominator constant for tall reference and hourly time step [0.25 s m^{-1} (daytime), 1.7 s m^{-1} (nighttime)]. Units for the 0.408 coefficient are m^2 mm MJ^{-1}.

The ASCE Standardized Reference Equation recommends using weather data measured above a fixed canopy height, preferably clipped grass with a height of 0.12 m (ASCE-EWRI, 2005). Since wind speeds were measured above alfalfa that varied in height as it grew, corrections were made to the 2 m wind speed measurements. A translation algorithm (Equation 13 from Allen and Wright, 1997) was used to adjust wind speeds measured over the alfalfa field to equivalent wind speeds above a grass reference with a height of 0.12 m. A more detailed interpretation of the use of the translation algorithm is presented by Ley et al. (2010). Crop height measurements were made on a weekly basis from the beginning of each growing season. Alfalfa crop height measurements obtained during each individual cutting cycle from each season were used to model crop height during individual cutting cycles. These models were used to estimate crop height between measurements in order to calculate zero plane displacement, aerodynamic roughness lengths, and internal boundary layers for use in the wind speed adjustment algorithms.

Reference condition determination

Alfalfa reference conditions, as described by ASCE-EWRI (2005), were determined during each cutting cycle while the atmometers were actively deployed by using weekly crop height measurements. In 2011 a multispectral radiometer was also used to further infer uniformity across the alfalfa canopy. An MSR5, a 5-band radiometer with similar bandwidths as LANDSAT Thematic Mapper (CROPSCAN Inc., Rochester, MN, USA), was used to determine Normalized Difference Vegetative Index (NDVI, Goward et al. 1991). Average and standard deviations of NDVI from measurements taken with the multispectral radiometer during one cutting period when the alfalfa was at reference height (40 to 60 cm) were calculated from readings taken along a transect running east to west through the middle of the research field. This was done to further validate the existence of reference conditions during 2011. MSR5 readings were not available for 2008-2010. However, NDVI was calculated using LANDSAT 5 reflectance images taken during two cutting cycles in 2010 when the alfalfa was at reference height. During the remainder of the study LANDSAT 5 overpasses were too far out of the date range of measured reference height to use the data to infer uniformity while the crop was at reference height. During these periods reference conditions were assumed to be satisfied based on crop height and irrigation management. In all years of the study the requirement of at least 100 m of fetch with the same vegetation was satisfied.

Development of calibration equations

Calibration equations were developed to help improve the accuracy of the atmometers in predicting ASCE ET_{rs}. Daily maximum air temperature (T_{max}, °C) was selected as a calibration parameter because it is widely available from local weather networks or easily obtained using personal air temperature sensors. Equations were developed using T_{max} (°C) and ET_{gage} (mm d^{-1}) readings as independent variables and $ET_{gage\ adj.}$ as the dependent variable for three conditions: reference, non-reference, and both conditions combined. The general equation takes the form $ET_{gage\ adj.} = A(ET_{gage}) - B(T_{max}) + C$, where A, B, and C are coefficients specific to each condition, ET_{gage} is daily measured ET from the atmometer in mm d^{-1}, and T_{max} is the maximum daily air temperature in °C. Daily T_{max} was obtained from the same weather station used to measure weather variables to calculate ET_r and was measured at a height of 1.5 m. Each model was developed using 70% of the data randomly selected from all years of the study and tested using the remaining 30%.

Preliminary comparisons showed that ET_{gage} values tended to under-estimate ASCE ET_{rs} values. Therefore, a simple offset of atmometer measured ET was also tested. All data were pooled and a single y-intercept was obtained by linear regression of ET_{gage} and ASCE ET_{rs} data. Because the slope of the regression line was near one the negative y-intercept was added to all the ET_{gage} values as a simple adjustment to atmometer ET under any condition.

Analysis

Four growing seasons (2008 – 2011) of atmometer measured ET (ET_{gage}) were compared to ASCE ET_{rs}. Daily atmometer-based alfalfa ET rates from automated recordings (not manual readings) were used for analysis. ASCE ET_{rs} was used as a standard for comparison of atmometer performance. Daily as well as 2, 3, 5, and 7 day sums of daily ET_{gage} and ASCE ET_{rs} were compared using simple linear regression to determine the effect of time period on ET_{gage} performance. The performance of the atmometers was further analyzed under reference (crop height between 40 cm and 60 cm) and non-reference conditions. Daily ET rates from both methods under reference and non-reference conditions were compared in order to more effectively evaluate the atmometer's ability to measure reference ET under both conditions. Other statistics calculated included root mean square error (RMSE, Eq. 2), mean bias error (MBE, Eq. 3), and relative error (RE, Eq. 4). An analysis of the atmometers' sensitivity to weather variables was also done to determine possible reasons for discrepancies seen between ET_{gage} and ASCE ET_{rs}. Sensitivity to weather was analyzed as follows. Daily ET rates determined using each method for all seasons were pooled and the performance of the atmometer versus ASCE ET_{rs} was analyzed under varied conditions of wind speed, solar radiation, air temperature, and RH. Daily error (ET_{gage} – ASCE ET_{rs}) was compared to mean daily weather parameters to determine if weather conditions adversely affected the atmometer's performance.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(P_i - O_i)^2}{N}} \qquad (2)$$

$$MBE = \frac{\sum_{i=1}^{N}(P_i - O_i)}{N} \qquad (3)$$

$$RE\ \% = \frac{(\bar{P}-\bar{O})}{\bar{O}} * 100 \tag{4}$$

where N is the number of observations, P and O are the predicted and observed values, respectively, and $\bar{P}$ and $\bar{O}$ are the mean of the predicted and observed values, respectively.

RESULTS AND DISCUSSION

Comparison of daily ET_{gage} and ASCE ET_{rs}

The Model E (ETgage Company Loveland, CO, USA) atmometers equipped with a canvas #54 cover used in this study performed well when compared to ASCE ET_{rs}, and similar results were observed during each year. Atmometer ET rates collected during the 2008-2011 growing seasons ranged from 0.25-12.45 mm d^{-1} over the entire study period. ASCE ET_{rs} for the same period ranged from 1.09-14.7 mm d^{-1} (Table 2-1). Good correlation between daily ET_{gage} and ASCE ET_{rs} values were seen in all years (Fig. 2-1), with R^2 values greater than or equal to 0.80 for all years. During each year of the studied period the atmometers tended to underestimate ET_r when compared to ASCE ET_{rs} (Table 2-2 and Fig. 2-2). Average yearly underestimation of ET_r by the atmometers ranged from 9.1% in 2008 to 18.9% in 2010. For the entire period of the study atmometers underestimated ASCE ET_{rs} on 88% of the days, with an average underestimation of 1.30 mm d^{-1}. On the other hand, the atmometers over predicted ET_{rs} by an average of 0.53 mm d^{-1} on the 49 days when overestimation did occur.

Closer observation of daily atmometer ET rates indicated that the device consistently underestimated ASCE ET_{rs} when ASCE ET_{rs} was either above 11 mm d^{-1} or below 5 mm d^{-1}. When daily ASCE ET_{rs} rates were above 11 mm d^{-1} the atmometers underestimated ET_r an average of 2.53 mm d^{-1}. The underestimation of ET_r measured by the atmometers at the higher daily rates of ASCE ET_{rs} were nearly 2 times greater than the underestimation observed over the entire studied period. When ASCE ET_{rs} rates were below 5 mm d^{-1} the atmometers underestimated ET_r by an average of 1.02 mm d^{-1}. Furthermore, when daily ASCE ET_{rs} rates were below 5 mm d^{-1} the atmometers underestimated ET_r 100% of the days that this occurred. In a similar study conducted by Chen and Robinson (2009) it was also found that atmometers underestimated ASCE ET_{rs} when low daily ET rates were recorded. This may be an indication that the resistance to diffusion of the atmometer may be different than that determined by the ASCE Reference ET Equation for a tall crop and thus is not a perfect physical model of a transpiring reference alfalfa canopy. In another study carried out by Gavilán and Castillo-Llanque (2008), the same results persisted when low daily ET values were observed. Although the comparison of atmometers by Gavilán and Castillo-Llanque (2008) was made to the FAO-56 PM equation (Allen et al., 1998) it may indicate that the error lies in the physics of the atmometer and not in the physically based ET equations.

Atmometer performance was also analyzed under alfalfa reference and non-reference conditions. Reference conditions were determined based on manual crop height measurements during each cutting cycle while the atmometers were actively deployed. Analysis of the atmometers performance during periods of reference and non-reference conditions indicated that the devices more accurately predicted ASCE ET_{rs} when reference conditions existed in the field. When daily ET rates from both methods were compared during reference conditions R^2 was 0.91 and RMSE was 1.37 mm d^{-1}. For the remainder of the study when reference conditions were not satisfied R^2 and RMSE were 0.80 and 1.47 mm d^{-1}, respectively. Although the atmometers more closely predicted ASCE ET_{rs} when reference conditions were satisfied, more evaluations of atmometer performance under reference conditions need to be carried out in order to more justly evaluate the instruments ability to accurately measure ET_r. This should be done because reference conditions only exist for a short duration during each alfalfa cutting cycle, thus the window of opportunity for evaluation is small. Therefore, a larger data set encompassing more years should prove valuable for such comparisons. Also, more research should be conducted to determine if conditions experienced during non-reference periods cause the atmometer to underperform more than during reference conditions, or if the ASCE ET_{rs} equation is overestimating ET_r because reference conditions are not satisfied.

Further analysis indicated that certain weather conditions can negatively affect atmometer performance when compared to ASCE ET_{rs}. Mean daily wind speed over the entire studied period was 2.12 m s^{-1}, thus a comparison was made between the atmometer measured ET and ASCE ET_{rs} when mean daily wind speeds were above 2 m s^{-1} and below 2 m s^{-1}. Findings revealed that the atmometer tended to underestimate ASCE ET_{rs} the most on days when mean daily wind speeds were greater than 2 m s^{-1}, and less on days when mean daily wind speeds were less than 2 m s^{-1}. When mean daily wind speeds were greater than 2 m s^{-1} RMSE, MBE, and RE values were larger in magnitude than those values when mean daily wind speeds were less than 2 m s^{-1}, in every year studied (Table 2-3). In 2008, the RE was nearly 2 times greater when mean daily wind speeds exceeded 2 m s^{-1}. When data from all years were combined the results suggested that the atmometers underestimated seasonal ASCE ET_{rs} by a little over 5% more when mean daily wind speed was greater than 2 m s^{-1}. In a study conducted by Chen and Robinson (2009) similar results were found where atmometer performance deteriorated with increasing wind speeds and it was determined that the insensitivity of the atmometer to higher wind speed is a major reason for increased discrepancies observed between ET_{gage} and ASCE ET_{rs}. Closer inspection revealed that when mean daily wind speeds, from all seasons, were compared with the daily "absolute" error (ET_{gage} – ASCE ET_{rs}) the atmometers mostly underestimated ASCE ET_{rs} when mean daily wind speeds exceeded 3 m s^{-1} (Fig. 3). During days when mean daily wind speeds were greater than 3 m s^{-1} the largest magnitude of daily error was also observed. Greater magnitudes of RMSE, MBE, and RE were also observed, 2.23 mm d^{-1}, -1.88 mm d^{-1}, and -21.90% respectively, when wind speeds were greater than 3 m s^{-1} for all years combined (data not shown).

When daily average temperature was less than 20 °C predominant underestimation of ASCE ET_{rs} also occurred, and MBE and RE were larger in all cases (Table 2-4). Closer inspection reveals that RE was nearly 2 times larger for all years during periods when mean daily air temperature was less than 20 °C versus periods when mean daily air temperature was greater than 20 °C. When data from all years were combined the atmometers underestimated seasonal ASCE ET_{rs} 11.52% more when mean daily air temperature was below 20 °C than when mean daily air temperature was greater than 20 °C. During this study 130 days (31% of total observations) had average daily air temperatures below 20 °C and contributed significantly to the overall seasonal underestimation of ET_r despite occurring at a time when low ET rates are likely to occur.

Analysis of atmometer performance under varied conditions of RH revealed that the instruments always underestimated ASCE ET_{rs} during days when mean daily RH was above 60% (Fig. 3). Relative error during periods when RH was >60% was more than two times higher than when RH was below 60%. However, the largest magnitude of error in daily ET_r estimation was observed when drier atmospheric conditions existed, i.e. below 60% RH. Over the entire studied period RE was more than two times greater during periods when RH was greater than 60% (Table 2-5). In fact, all model performance statistics used in the evaluation of the atmometer indicated that the device performed better when drier atmospheric condition existed.

Other studies (Chen and Robinson, 2009, and Gavilán and Castillo-Llanque, 2008) have also shown that the atmometer performs better under drier conditions. Further research needs to be conducted to determine the exact cause of the atmometers underestimation of ASCE ET_{rs}, but one likely source of the error is related to the resistance to vapor diffusion inherent in the device, either in the ceramic cup or the crop simulated fabric cover.

Similar results were seen when daily error was compared to solar radiation (R_s) as was seen with RH, but the trend in the magnitude of error was larger with increasing average daily solar radiation (Fig. 3). Average daily R_s over the entire studied period was approximately 25 MJ d^{-1} m^{-2}, and when average daily R_s was below 25 MJ d^{-1} m^{-2} predominant underestimation of ASCE ET_{rs} occurred. Although underestimation of ASCE ET_{rs} occurred throughout much of the study, the performance statistics RMSE and MBE indicate that the atmometer underperformed more when the higher rates (>25 MJ d^{-1} m^{-2}) of R_s were observed because of the greater error encountered under these conditions (Table 2-6). The exact cause of the increased error observed at the higher rates of daily average R_s are not immediately apparent, but one likely source could be related to the color of the fabric covering used to simulate the albedo of alfalfa. In a study conducted by Broner and Law (1991) it was determined that the crop albedo was satisfactorily simulated by the canvas covering. However, it was observed on several occasions that the canvas covering tends to accumulate dust, which could effectively increase the albedo of the canvas covering causing a greater reflectance of radiation than would be experienced from the crop canopy.

Comparisons of cumulative ET data

It is more common for irrigation managers to use multiple days of ET data in irrigation scheduling than individual days. As a result an evaluation of several possible scenarios was made. Two, 3, 5, and 7 day cumulative ET_{gage} and ASCE ET_{rs} comparisons were analyzed to determine the practicality of using such techniques for ET_r based irrigation scheduling purposes (Table 2-7). Improvement in R^2 and RMSE mm d^{-1} was seen in all summed scenarios when compared to that of daily ET comparisons from respective years. When summed statistics were compared to each other within each individual year there was an improvement in both R^2 and RMSE from 2 to 7 day sums. Exceptions occurred during 2010 and 2011 when the most improvement in R^2 and RMSE was obtained with 5 day sums over that of 7 day sums (Table 2-7). While R^2 and RMSE values improved with the summing of daily values the ratio of ET_{gage} and ASCE ET_{rs}, MBE and RE remained mostly consistent with that of the daily comparison statistics (Table 2-2 and Table 2-7). Similar results were observed by Gavilán and Castillo-Llanque (2008) when average weekly atmometer data was compared to FAO-56 PM equation. Irmak et al. (2005) also reported that considerable improvement in the comparison of atmometer measured ET_r and ET_r calculated using FAO-56 PM was seen when 3 and 7 day average values were used over that of daily values. Results from both studies indicate that the use of average values over periods longer than a day would improve the accuracy of the atmometer as R^2, MBE, and seasonal % error all improved. However, underestimation of ET was still observed. This study found nearly the same results with the use of cumulative data; however RE did not improve in all cases but did remain relatively constant. Alam and Trooien (2001) also found that 3 day sums of atmometer measured ET correlated well with the alfalfa-based modified Penman reference ET equation. Therefore, it can be concluded that the use of cumulative data should be utilized to help increase accuracy to further improve irrigation scheduling decisions based on the use of atmometer data.

Calibration

As a final result of this research calibration equations have been developed to help improve the accuracy of the ETgage Model E in predicting ET_r. Given that the atmometer will likely be used at locations where weather data are incomplete for calculation of ASCE ET_{rs}, the calibration equations were developed based on the most available weather parameter: daily maximum air temperature (T_{max}, °C). Calibration equations were developed using T_{max} (°C) and ET_{gage} (mm d^{-1}) as independent variables and $ET_{gage\ adj.}$ as the dependent variable for three conditions: reference, non-reference, and all conditions combined. The equation $ET_{gage\ adj.\ ref.} = 1.944 + 1.025 \times ET_{gage} - 0.029 \times T_{max}$ was used to adjust the atmometer measured ET during periods of reference conditions. During non-reference conditions the equation $ET_{gage\ adj.\ nref} = 3.608 + 1.063 \times ET_{gage} - 0.097 \times T_{max}$ was used to adjust atmometer measured ET. Finally, the equation $ET_{gage\ adj.\ gen.} = 2.868 + 1.006 \times ET_{gage} - 0.06 \times T_{max}$ was used to adjust atmometer measured ET regardless of condition. In all three cases improvement in atmometer performance was made using the respective calibration equations. RMSE, MBE, and RE all improved considerably over that of the original atmometer measured ET when compared to ASCE ET_{rs} (Table 2-8).

In the event that daily T_{max} data is unavailable a simple offset of atmometer measured ET rates can also be made to improve the accuracy the instrument. The shift is based on simple linear regression of all atmometer and ASCE ET_{rs} data in which a single y-intercept of -0.50 mm d^{-1} was obtained. The negative sign of the y-intercept indicated that ET_{gage} values were underestimating ASCE ET_{rs} values. Therefore, the 0.50 mm d^{-1} was added to all the ET_{gage} values as a simple offset. The R^2 value remained the same because the points and regression line were all shifted upward, but the error statistics did improve (errors were reduced) when adjusted atmometer ET values were compared to ASCE ET_{rs} values. With the simple offset, MBE, RMSE, and RE magnitudes were all reduced from that of the original comparisons (Table 2-8).

CONCLUSION

Atmometer measured ET data collected over 4 growing seasons showed good agreement with comparisons made to the American Society of Civil Engineers (ASCE) Environmental & Water Resources Institute (EWRI) Standardized Reference ET Equation for alfalfa (ASCE ET_{rs}). Underestimation of ASCE ET_{rs} occurred in all years during the study with an average seasonal underestimation near 14%. High wind speeds (> 3 m s^{-1}) and low temperatures (< 20 °C) were found to have the most significant impact on atmometer performance. During days with high wind speeds or low temperatures consistent underestimation of ASCE ET_{rs} was produced by the atmometers. Improvement was made in the accuracy of the atmometer when 2 to 7 day cumulative measured daily ET rates were compared to cumulative ASCE ET_{rs}. Thus, it is recommended that this procedure be utilized when using atmometer data for making irrigation scheduling decisions. With proper maintenance and care the atmometer could be considered an acceptable alternative to combination equations for estimating alfalfa based reference ET. It must also be noted that the accuracy of the atmometer could be further enhanced by performing site specific calibrations. A set of three calibration equations are provided to improve the atmometer alfalfa ET_r estimation in eastern Colorado. It is recommended that this be done when localized T_{max} data can be obtained within close proximity to the atmometer installation site. Also, a simple offset that can be added to all ET_{gage} values was also found to effectively reduce under-estimation of ASCE ET_{rs}. Nonetheless, if the atmometer is far removed from a weather station it still should provide valuable information to irrigators, and the incorporation of such devices can conceivably help improve irrigation management decisions.

Table 2-1 – Minimum and maximum daily reference ET (mm d^{-1}) measured with an atmometer (ET_{gage}) and calculated using the standardized equation of the American Society of Civil Engineers (ASCE ET_{rs}), during the 2008-2011 growing seasons.

Year	------ Min. (mm d^{-1}) ------		------ Max (mm d^{-1}) ------		------ Avg. (mm d^{-1}) ------	
	ET_{gage}	ASCE ET_{rs}	ET_{gage}	ASCE ET_{rs}	ET_{gage}	ASCE ET_{rs}
2008	0.25	1.38	12.45	12.35	6.58	7.24
2009	0.51	1.09	10.41	13.55	5.90	6.94
2010	1.02	2.13	11.18	13.86	6.49	8.01
2011	1.52	3.20	12.45	14.70	6.72	7.74

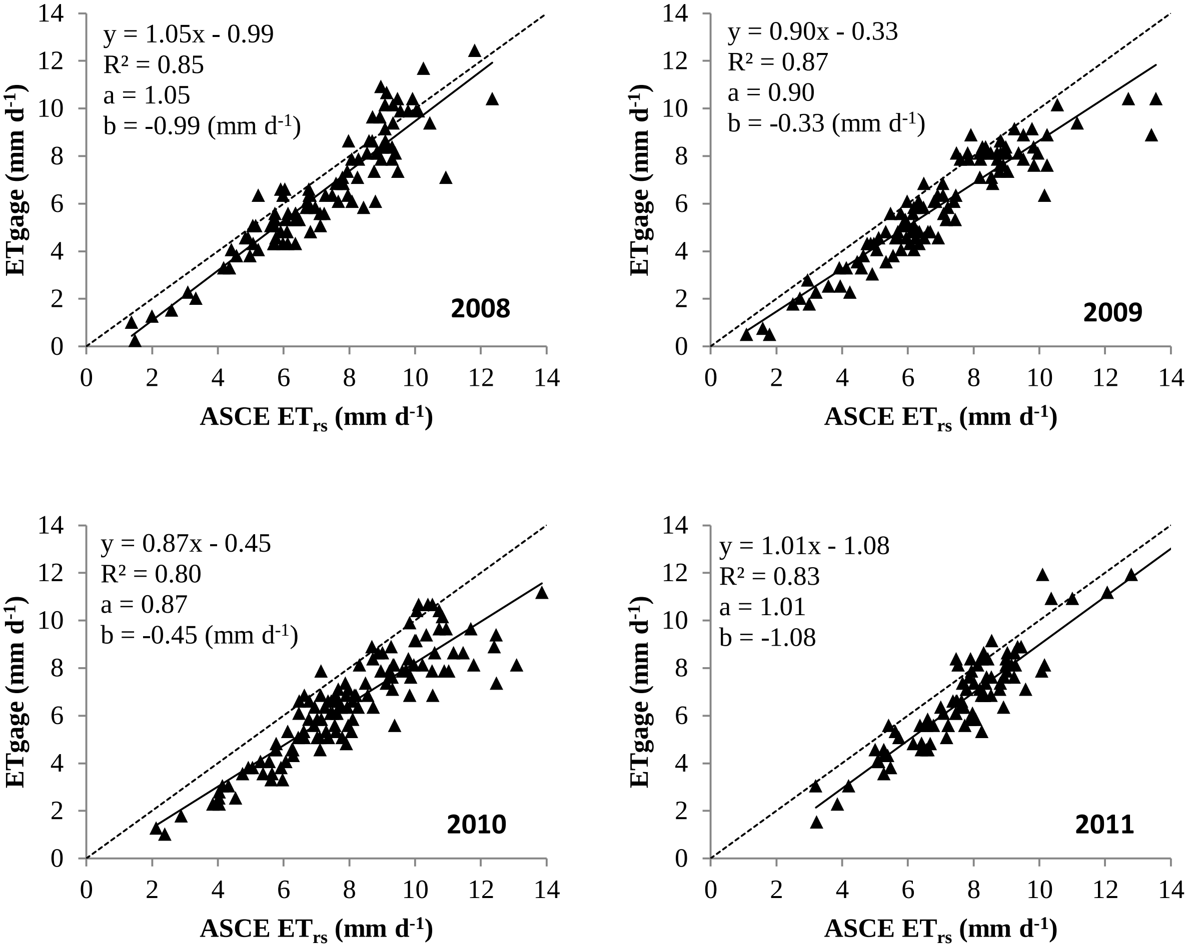

Fig. 2-1 – Comparison of daily ET (mm d^{-1}) from atmometer ET_{gage} and ASCE ET_{rs} for 2008, 2009, 2010, and 2011 growing seasons. The solid line represents the regression line (y = ax+b), where a = slope and b = intercept, the dashed line is a 1:1 line, and R^2: coefficient of determination. ASCE ET_{rs} is the independent variable.

Table 2-2 - Comparisons of daily atmometer ET_{gage} and ASCE ET_{rs} for 2008-2011 growing seasons. ASCE ET_{rs} is the independent variable.

Year	N[a]	ASCE ET_{rs} (mm d^{-1})	Ratio[b]	RMSE[c] (mm d^{-1})	MBE[d] (mm d^{-1})	RE[e] (%)
2008	103	7.24	0.91	1.14	-0.66	-9.06
2009	106	6.94	0.85	1.34	-1.04	-14.95
2010	127	8.01	0.81	1.82	-1.51	-18.90
2011	89	7.74	0.87	1.32	-1.02	-13.21
All	425	7.5	0.86	1.46	-1.08	-14.46

[a]N = number of observations; [b]Ratio = ET_{gage}/ASCE ET_{rs}; [c]RMSE = root mean square error; [d]MBE = mean bias error; [e]RE = relative error.

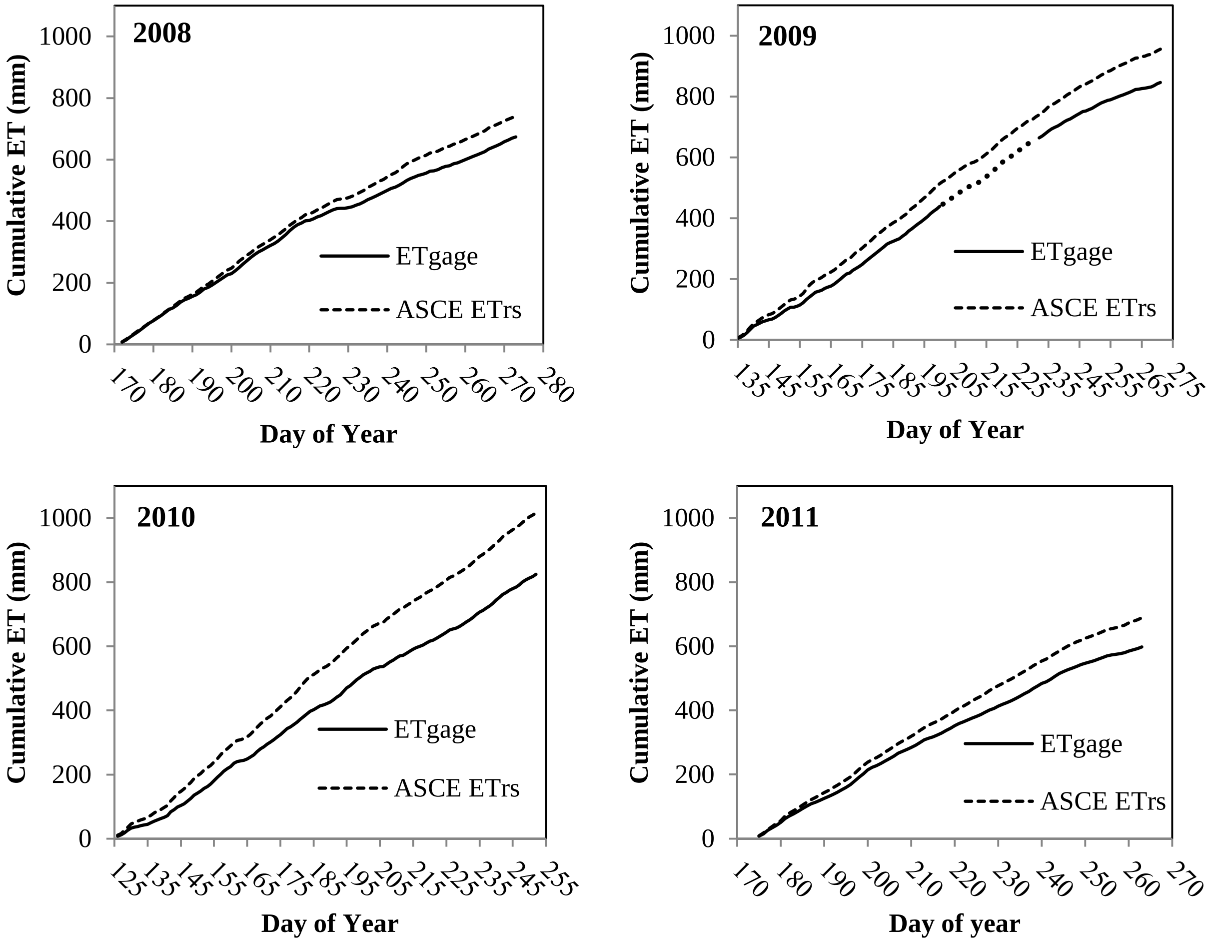

Fig. 2-2 – Comparisons of atmometer ET_{gage} and ASCE ET_{rs} seasonal cumulative ET for 2008, 2009, 2010, and 2011 growing seasons. The gap in the middle of the 2009 was due to missing atmometer data that was filled (dotted portion of curve) with ASCE ET_{rs} values.

Table 2-3 - Comparison of daily atmometer ET_{gage} and ASCE ET_{rs} for 2008-2011 growing seasons for daily average wind speeds below (<2) and above (>2) 2 m s^{-1}. ASCE ET_{rs} is the independent variable.

Year	N[a]		ET_{gage} (mm d^{-1})		ASCE ET_{rs} (mm d^{-1})		Ratio[b]		RMSE[c] (mm d^{-1})		MBE[d] (mm d^{-1})		RE[e] (%)	
	<2	>2	<2	>2	<2	>2	<2	>2	<2	>2	<2	>2	<2	>2
2008	50	52	6.63	6.53	7.05	7.42	0.94	0.88	0.93	1.32	-0.43	-0.89	-6.09	-11.93
2009	60	46	6.12	5.66	7.03	6.82	0.87	0.83	1.22	1.49	-0.94	-1.17	-13.35	-17.09
2010	53	74	5.89	6.98	7.01	8.72	0.84	0.80	1.32	2.11	-1.14	-1.78	-16.24	-20.44
2011	52	37	6.45	7.08	7.25	8.43	0.89	0.84	1.08	1.61	-0.81	-1.32	-11.18	-15.66
All	216	209	6.23	6.58	7.08	7.93	0.88	0.83	1.15	1.72	-0.83	-1.34	-11.79	-16.93

[a]N = number of observations; [b]Ratio = ET_{gage}/ASCE ET_{rs}; [c]RMSE = root mean square error; [d]MBE = mean bias error; [e]RE = relative error.

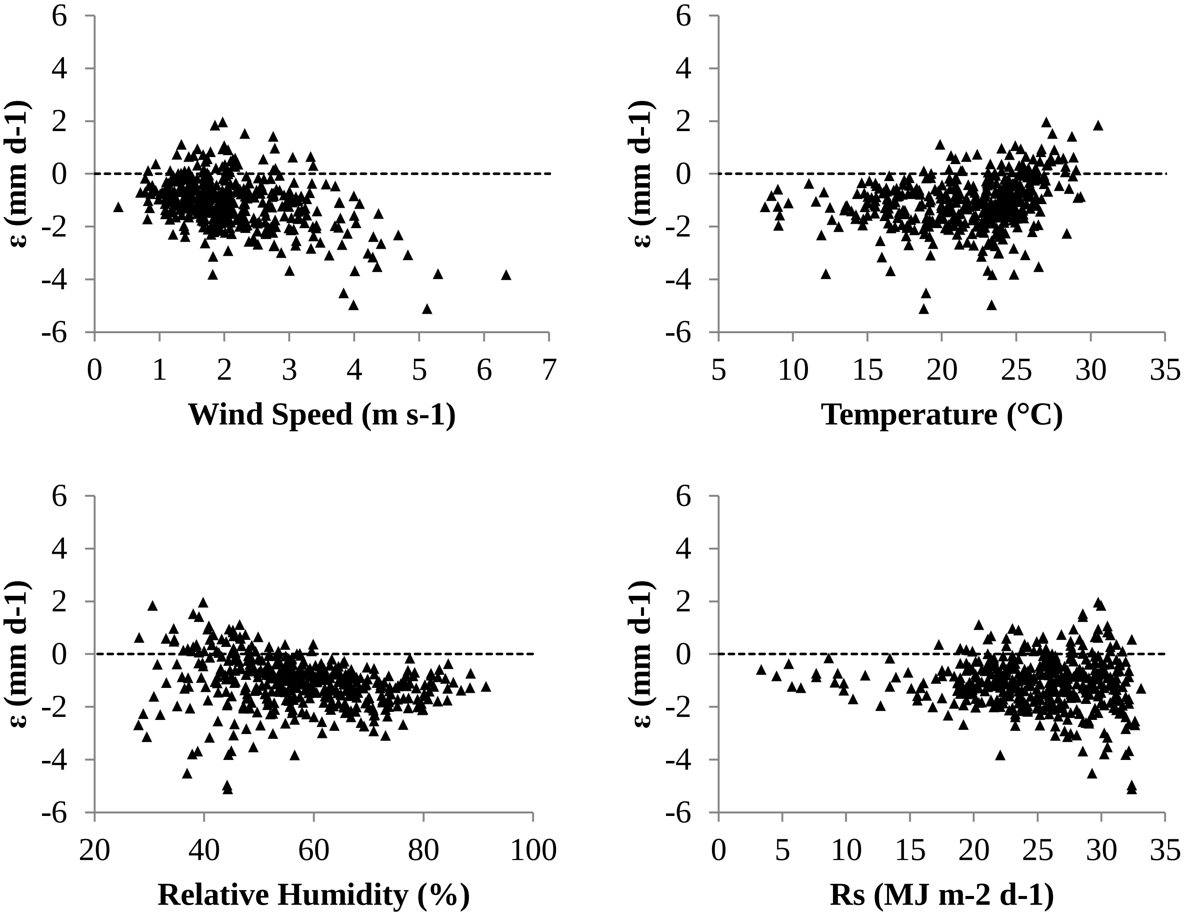

Fig. 3 – Comparison of daily error (ε) of atmometer (ET_{gage}) values: [ET_{gage} (mm d^{-1}) – ASCE ET_{rs} (mm d^{-1})] and mean daily weather parameters. Data from all years were combined for comparisons.

Table 2-4 - Comparison of daily atmometer ET_{gage} and ASCE ET_{rs} for 2008-2011 growing seasons for daily average temperatures below (<20) and above (>20) 20 °C. ASCE ET_{rs} is the independent variable.

Year	N[a]		ET_{gage} (mm d^{-1})		ASCE ET_{rs} (mm d^{-1})		Ratio[b]		RMSE[c] (mm d^{-1})		MBE[d] (mm d^{-1})		RE[e] (%)	
	<20	>20	<20	>20	<20	>20	<20	>20	<20	>20	<20	>20	<20	>20
2008	34	68	4.27	7.77	5.02	8.35	0.85	0.93	0.95	1.23	-0.76	-0.61	-15.07	-7.36
2009	51	55	4.17	7.52	5.42	8.35	0.77	0.90	1.44	1.25	-1.25	-0.84	-23.04	-10.08
2010	30	97	4.65	7.06	6.74	8.40	0.69	0.84	2.29	1.65	-2.09	-1.33	-31.06	-15.88
2011	15	74	4.08	7.27	5.16	8.26	0.79	0.88	1.63	1.96	-1.08	-0.99	-20.95	-11.94
All	130	295	4.30	7.34	5.59	8.34	0.77	0.88	1.57	1.41	-1.31	-0.99	-23.35	-11.83

[a]N = number of observations; [b]Ratio = ET_{gage}/ASCE ET_{rs}; [c]RMSE = root mean square error; [d]MBE = mean bias error; [e]RE = relative error.

Table 2-5 - Comparison of daily atmometer ET_{gage} and ASCE ET_{rs} for 2008-2011 growing seasons for daily average relative humidity below (<60) and above (>60) 60%. ASCE ET_{rs} is the independent variable.

Year	N[a]		ET_{gage} (mm d^{-1})		ASCE ET_{rs} (mm d^{-1})		Ratio[b]		RMSE[c] (mm d^{-1})		MBE[d] (mm d^{-1})		RE[e] (%)	
	<60	>60	<60	>60	<60	>60	<60	>60	<60	>60	<60	>60	<60	>60
2008	64	39	7.75	4.66	8.06	5.90	0.96	0.79	0.99	1.35	-0.30	-1.23	-3.78	-20.91
2009	54	52	7.68	4.05	8.62	5.20	0.89	0.78	1.48	1.19	-0.94	-1.14	-10.86	-21.97
2010	75	52	7.81	4.60	9.26	6.19	0.84	0.74	1.90	1.71	-1.46	-1.59	-15.73	-25.75
2011	60	29	7.42	5.26	8.18	6.83	0.91	0.77	1.17	1.65	-0.76	-1.56	-9.31	-22.88
All	253	172	7.67	4.56	8.56	5.93	0.90	0.77	1.43	1.50	-0.89	-1.37	-10.39	-23.10

[a] N = number of observations; [b] Ratio = ET_{gage}/ASCE ET_{rs}; [c] RMSE = root mean square error; [d] MBE = mean bias error; [e] RE = relative error.

Table 2-6 - Comparison of daily atmometer ET_{gage} and ASCE ET_{rs} for 2008-2011 growing seasons for daily average solar radiation below (<25) and above (>25) 25 MJ d^{-1} m^{-2}. ASCE ET_{rs} is the independent variable.

Year	N[a]		ET_{gage} (mm d^{-1})		ASCE ET_{rs} (mm d^{-1})		Ratio[b]		RMSE[c] (mm d^{-1})		MBE[d] (mm d^{-1})		RE[e] (%)	
	<25	>25	<25	>25	<25	>25	<25	>25	<25	>25	<25	>25	<25	>25
2008	54	49	4.98	8.35	5.82	8.80	0.86	0.95	1.15	1.12	-0.84	-0.45	-14.50	-5.10
2009	58	48	4.47	7.64	5.40	8.80	0.83	0.87	1.17	1.53	-0.93	-1.16	-17.27	-13.22
2010	37	90	4.52	7.30	5.96	8.85	0.76	0.83	1.55	1.92	-1.44	-1.54	-24.20	-17.44
2011	37	52	5.29	7.74	6.35	8.73	0.83	0.89	1.28	1.35	-1.06	-0.99	-16.74	-11.38
All	186	239	4.79	7.68	5.82	8.80	0.82	0.87	1.27	1.59	-1.03	-1.12	-17.76	-12.76

[a]N = number of observations; [b]Ratio = ET_{gage}/ASCE ET_{rs}; [c]RMSE = root mean square error; [d]MBE = mean bias error; [e]RE = relative error.

Table 2-7 – Comparison statistics of atmometer ET_{gage} and ASCE ET_{rs} for cumulative and averaged ET. ASCE ET_{rs} is the independent variable.

Year	Days summed or averaged	N[a]	ET_{gage} Summed (mm)	ASCE ET_{rs} Summed (mm)	ET_{gage} Mean (mm d^{-1})	ASCE ET_{rs} Mean (mm d^{-1})	Ratio[b]	R^2	RMSE[c] (mm)	MBE[d] (mm)	RE[e] (%)
2008	2	51	13.21	14.52	6.60	7.26	0.91	0.89	1.01	-0.66	-9.09
	3	34	19.82	21.78	6.60	7.26	0.91	0.91	0.92	-0.66	-9.09
	5	20	33.26	36.55	6.63	7.31	0.91	0.92	0.93	-0.68	-9.31
	7	14	46.76	51.38	6.65	7.34	0.91	0.95	0.82	-0.69	-9.46
2009	2	53	11.80	13.88	5.90	6.94	0.85	0.91	1.22	-1.04	-14.95
	3	35	17.72	20.85	5.91	6.95	0.85	0.91	1.19	-1.03	-14.83
	5	21	29.54	34.75	5.91	6.95	0.85	0.92	1.14	-1.03	-14.83
	7	15	41.35	48.65	5.91	6.95	0.85	0.96	1.08	-1.03	-14.83
2010	2	63	12.97	16.01	6.49	8.01	0.81	0.83	1.73	-1.52	-19.00
	3	42	19.46	24.02	6.49	8.01	0.81	0.85	1.68	-1.52	-19.00
	5	25	32.51	40.13	6.50	8.03	0.81	0.88	1.62	-1.52	-18.96
	7	18	45.39	56.04	6.49	8.01	0.81	0.86	1.61	-1.52	-19.00
2011	2	44	13.49	15.51	6.75	7.76	0.87	0.88	1.21	-1.02	-13.10
	3	29	20.32	23.36	6.78	7.79	0.87	0.90	1.17	-1.02	-13.13
	5	17	34.08	39.17	6.81	7.83	0.87	0.90	1.13	-1.01	-12.91
	7	12	47.97	55.14	6.86	7.88	0.87	0.89	1.13	-1.01	-12.82

[a]N = number of observations; [b]Ratio = ET_{gage}/ASCE ET_{rs}; [c]RMSE = root mean square error; [d]MBE = mean bias error; [e]RE = relative error.

Table 2-8 – Comparison of original and calibration equation adjusted daily atmometer ET_{gage} and ASCE ET_{rs} for 2008-2011 growing seasons during periods of reference and non-reference conditions. Calibration equations were developed using 70% of available data and verified using the remaining 30%. Also included are comparisons of original and y-intercept adjusted daily atmometer ET_{gage} and ASCE ET_{rs} for the 2008-2011 growing seasons. ASCE ET_{rs} is the independent variable.

Condition	N[a]	ASCE ET_{rs} (mm d^{-1})	Ratio[b]		R^2		RMSE[c] (mm d^{-1})		MBE[d] (mm d^{-1})		RE[e] (%)	
			orig.[f]	adj.[g]	orig.	adj.	orig.	adj.	orig.	adj.	orig.	adj.
Reference	18	7.44	0.88	1.05	0.92	0.91	1.15	0.84	-0.86	0.37	-11.56	5.0
Non-reference	109	7.38	0.85	1.01	0.83	0.83	1.39	0.86	-1.07	0.07	-14.51	1.0
All	127	7.50	0.87	1.02	0.86	0.87	1.28	0.78	-0.97	0.13	-12.87	1.7
y-intercept	425	7.50	0.86	0.92	0.82	0.82	1.46	1.14	-1.08	-0.59	-14.46	-7.81

[a]N = number of observations; [b]Ratio = ET_{gage}/ASCE ET_{rs}; [c]RMSE = root mean square error; [d]MBE = mean bias error; [e]RE = relative error; [f]orig. = ET_{gage} not adjusted; [g]adj. = ET_{gage} adjusted using calibration equations.

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CHAPTER 4: CONCLUSION AND RECOMMENDATIONS

Evapotranspiration (ET) information can be used to improve irrigation management practices. Knowing when and how much water to apply is helpful to assure crop water requirements are met and to prevent over irrigation. Economic, environmental, and political pressure will continue to drive the need for improved irrigation application efficiency, especially in Colorado where a growing population is placing an increasing pressure on limited fresh water resources. This thesis evaluated two ET-based tools that can be used for irrigation scheduling in Eastern Colorado: (1) an Excel® spreadsheet irrigation scheduler that estimates soil water deficits in the root zone using daily inputs of weather and irrigation data; and (2) an atmometer (ETgage Model E equipped with a canvas #54 cover) for estimating alfalfa reference ET.

The irrigation scheduling spreadsheet tools, one designed for use with annual crops (CIS-A) and one designed for use with forage crops (CIS-F), were developed to simplify the steps required to complete a water balance and provide estimates of irrigation water requirements and timing. The performances of the irrigation scheduling tools were found to be generally acceptable based on the relatively small magnitude of errors in the estimated deficits compared to total available water (TAW) in the soil profile. Root mean square error for the CIS-A was between 8.6 and 15.3% of TAW over the studied period, and RMSE was 6.6% of TAW in 2011 and 11.5% of TAW in 2010 for the CIS-F. The CIS-A did tend to overestimate the observed deficit during all years of the study and across all sites (relative error, RE = 13.58% and mean bias error MBE = -3.41 mm). Overall average error indicated that the CIS-A was within 15.92 mm (root mean square error, RMSE) and 12.61 mm (mean absolute error, MAE) of the observed deficit for the entire study. The CIS-F also predicted a deficit larger than the observed deficit throughout the study. The best performance of the CIS-F was obtained in 2011 (RMSE = 22.02

mm, MBE = -16.95 mm, MAE = 17.65 mm, and RE = 18.73%). The CIS-F did not perform as well in 2010 (RMSE = 38.21 mm, MBE = -32.84 mm, MAE = 32.94 mm, and RE = 34.11%), however much of the underperformance of the CIS-F in 2010 occurred in the initial part of the growing season and the performance for the remainder of the season was similar to 2011. As a result of this study the performance of the tools should prove to be useful for irrigation managers to improve irrigation management practices in Colorado.

Chapter two of this thesis also indicates the performance of the irrigation scheduling tools may be most limited by the accuracy of the ET information obtained. One of the most important components of the use of ET information in irrigation scheduling is to make certain that the ET information is accurate. The irrigation scheduling tools were primarily developed to use ET_{ref} information from CoAgMet, but at this time it is recommended that ET_{ref} be calculated using the ASCE-EWRI (2005) guidelines manually or obtained from another source because the values provided by CoAgMet were determined to be considerably higher than those calculated using other methods of calculating ET_{ref} using the ASCE-EWRI (2005) guidelines. Measures have been taken to diagnose and correct any issues associated with the calculation of ET_{ref} on the CoAgMet servers. However, at the close of this study the issue still persists. The problem is expected to be resolved in the near future.

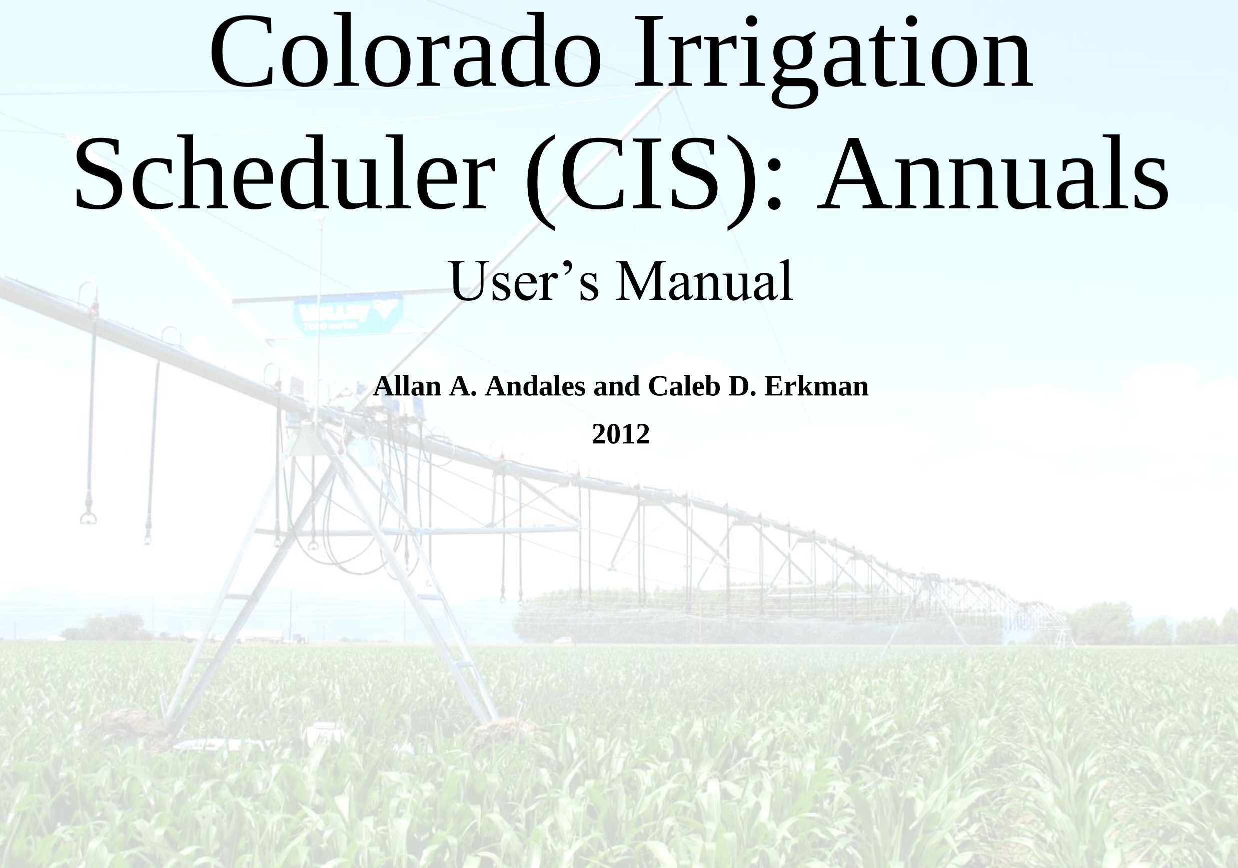
In the second study, atmometer performance was deemed to be acceptable (R^2 = >0.80, root mean square error RMSE = 1.46 mm), however improvements can be made. The Model E atmometer (ETgage Company, Loveland, CO, USA) underestimated ET_{rs} when compared to calculated ET_{rs} using the ASCE-EWRI (2005) guidelines in all years of the study (RE = -14.46% and MBE = -1.08 mm). The atmometer tended to underestimate ET_{rs} the most on days when cool air temperatures, high wind speeds, and high relative humidity was observed. Given the fact that the atmometer underestimated ET_{rs} it is recommended that when an atmometer of this type is used to obtain ET information in southeast Colorado that the calibration equations provided in chapter three of this thesis be used to improve accuracy. It is also recommended that if the device is used in areas other than southeast Colorado that the performance of the device should be tested before the ET information is deemed reliable.

If similar procedures are used to calibrate atmometers for other areas, like that outlined in chapter three of this study, the devices should prove to be a valuable tool for obtaining estimates of reference ET. Furthermore, the devices could also be used to obtain reference ET data for use in the CIS-A and CIS-F tools. Evapotranspiration data obtained through the use of a calibrated atmometer could help alleviate problems associated with acquisition of reliable ET information. Because the atmometer can be placed directly in or adjacent to a field of interest the effects of spatial variability experienced between field site and weather station can be minimized. This is especially true when weather stations used to obtain weather variables used to estimate ET using combination equations are distantly located from the field of interest, or are located over non-irrigated or poorly maintained sites. One of the greatest obstacles for an irrigation manager to overcome when using ET data to schedule irrigations is the reliability of the ET data.

In conclusion, ET information is a valuable tool that can be used by irrigation managers to make more informed irrigation scheduling decisions. Water lost from the soil through the processes of ET will need to be replaced in order to satisfy crop water requirements. This is especially true in arid and semi-arid regions where the amount of precipitation falls below what is needed to meet crop water requirements. When an irrigation manager understands the rate of crop ET they know the amount of water that has been extracted from the soil profile and thus the amount that needs to be replaced through irrigation. Knowing the amount of water that needs to be replaced also helps an irrigation manager reduce the potential for over-irrigation that may lead to environmental degradation from off-farm transport of agro-chemicals, increased operating costs, and wasting of limited fresh water resources.

APPENDICES

APPENDIX I: "COLORADO IRRIGATION SCHEDULER (CIS): ANNUALS" USER'S MANUAL



Colorado Irrigation Scheduler (CIS): Annuals

User's Manual

Allan A. Andales and Caleb D. Erkman

2012

The Colorado Irrigation Scheduler (CIS) uses soils data from the Natural Resources Conservation Service (NRCS) Web Soil Survey and weather data from the Colorado Agricultural Meteorological Network (CoAgMet) to estimate daily total soil water deficit for up to five different soil layers for an individual field. The soil water deficit can be compared to a management allowed depletion value for scheduling irrigations (amount and timing) for common irrigated crops grown in Colorado. The CIS has parallel spreadsheet and graphical interfaces to input gross irrigation, observed precipitation and soil moisture measurements that are used to calculate the soil water balance. It is recommended that the user first read 'Irrigation Scheduling: The Water Balance Approach' by Andales et al. (2011) to become familiar with concepts used in this manual. See http://www.ext.colostate.edu/pubs/crops/04707.pdf

Acknowledgement

This project was funded by the U.S. Department of Agriculture – Natural Resources Conservation Service – Colorado Conservation Innovation Grant no. 69-8B05-A-09-09 and by the Colorado Agricultural Experiment Station.

Table of Contents

I. Setting up Excel

Requirements for the CIS Tool

1) Microsoft Excel 2007 or newer
2) Macros need to be enabled
3) Data connections need to be enabled
4) An active internet connection

The procedures for initializing these settings in Microsoft Excel 2010 are described below. The interface for Microsoft Excel 2007 is slightly different, but the same settings are available.

1. Protected View

If you downloaded the CIS Tool from an internet source it will likely open in protected view, and a message will be displayed above the formula bar as shown in Figure 1a below. If this occurs click ‘Enable Editing’ to continue.

Protected View This file originated from an Internet location and might be unsafe. Click for more details.

Once you have imported your soil profile data you can input the data for your crop and begin irrigation scheduling. A pop-up window will collect the necessary crop specific

1 Welcome to the Annual Crop Irrigation Scheduler 2012

3 This tool uses specific soil profile and meterolgic data for your field to perform a daily water ballence to aid in irrigaton scheduling.

5 Inorder for this tool to work properly Macros and Data Connections need to be enabled. To do this click 'Allow Content' or 'Enable Content' when a 'Security Warning' about macros is displayed below the formula bar. If you want to stop these messages from appearing you can place the irrigation scheduler file in a 'Trusted Location' listed under File -> Options -> Trust Center -> Trust Center Setting -> Trusted Locations. It is also necessary to have an internet conection so that Excel can download weather data from CoAgMet.

7 The first step in setting up the irrigation scheduling tool is to import your soils data. Soils data is collected from the NRCS Web Soil Survey (WSS) via an interactive pop-up window. To import your soil data click the "Collect Soils Data" button bellow and follow the instructions. If you would perfer to manually enter soil profile data click "Enter Soil Data"

9 Once you have imported your soil profile data you can input the data for your crop and begin irrigation scheduling. A pop-up window will collect the necessary crop specific data and area specific meterological data from CoAgMet. To launch the CoAgMet pop-up window click the "Set Up Farm Using Data from CoAgMet" button below.

11 This workbook uses several additional sheets to perform analysis and store the data collected from the NRCS Web Soil Survey and CoAgMet websites, respectively. To show these sheets select the "Show Anaylsys" button below.

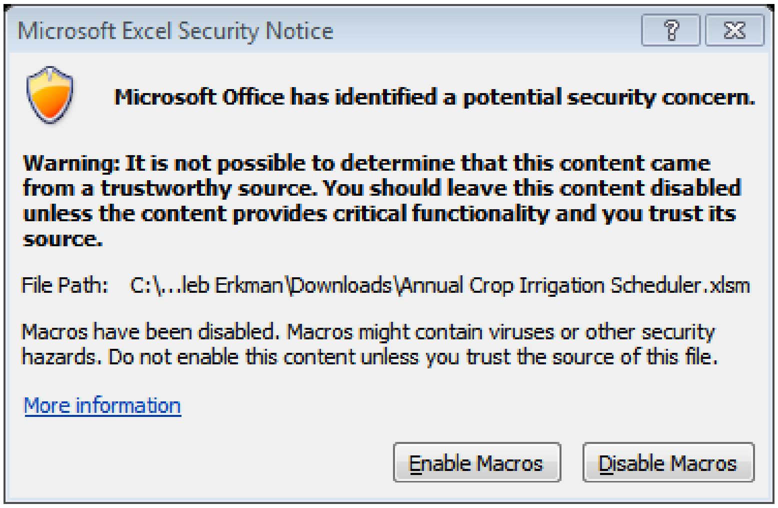
13 To delete all saved data on the irrigation scheduler and start over click the reset button.

15 To delete only the saved crop data and keep the imported soils data click the 'Reset Crop' button.

Figure 1a: Protected View Warning message in Excel 2010

2. Macros

Enabling macros allows the necessary background programs to run. However macros can be dangerous if from an untrusted source. Because of this, Excel may display a security warning when the CIS opens similar to Figure I.2.A or Figure I.2.B below.



Microsoft Office has identified a potential security concern.

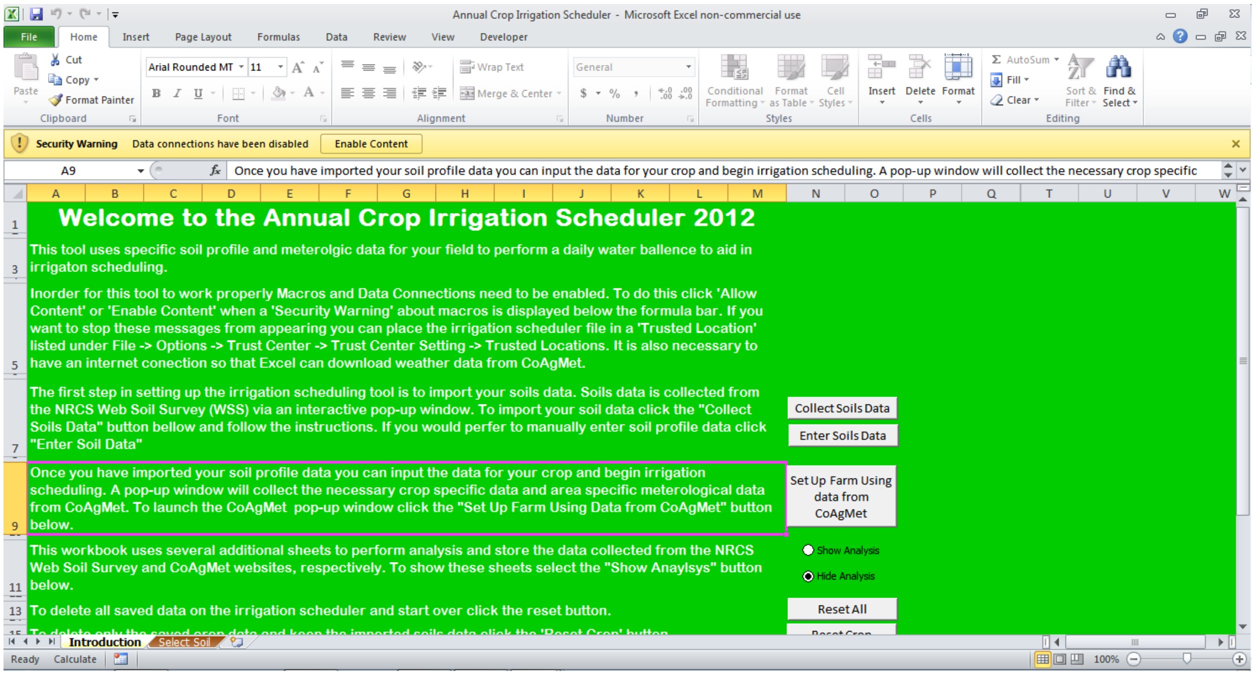
Warning: It is not possible to determine that this content came from a trustworthy source. You should leave this content disabled unless the content provides critical functionality and you trust its source.

File Path: C:\...leb Erkman\Downloads\Annual Crop Irrigation Scheduler.xlsm

Macros have been disabled. Macros might contain viruses or other security hazards. Do not enable this content unless you trust the source of this file.

Figure I.2.A: A possible macro security warning for Excel 2010

If this security warning is displayed click ‘Enable Macros’ before continuing.



Security Warning Data connections have been disabled

A9 Once you have imported your soil profile data you can input the data for your crop and begin irrigation scheduling. A pop-up window will collect the necessary crop specific

1 **Welcome to the Annual Crop Irrigation Scheduler 2012**

3 This tool uses specific soil profile and meterolgic data for your field to perform a daily water ballence to aid in irrigaton scheduling.

5 Inorder for this tool to work properly Macros and Data Connections need to be enabled. To do this click 'Allow Content' or 'Enable Content' when a 'Security Warning' about macros is displayed below the formula bar. If you want to stop these messages from appearing you can place the irrigation scheduler file in a 'Trusted Location' listed under File -> Options -> Trust Center -> Trust Center Setting -> Trusted Locations. It is also necessary to have an internet conection so that Excel can download weather data from CoAgMet.

7 The first step in setting up the irrigation scheduling tool is to import your soils data. Soils data is collected from the NRCS Web Soil Survey (WSS) via an interactive pop-up window. To import your soil data click the "Collect Soils Data" button bellow and follow the instructions. If you would perfer to manually enter soil profile data click "Enter Soil Data"

9 Once you have imported your soil profile data you can input the data for your crop and begin irrigation scheduling. A pop-up window will collect the necessary crop specific data and area specific meterological data from CoAgMet. To launch the CoAgMet pop-up window click the "Set Up Farm Using Data from CoAgMet" button below.

11 This workbook uses several additional sheets to perform analysis and store the data collected from the NRCS Web Soil Survey and CoAgMet websites, respectively. To show these sheets select the "Show Anaylsys" button below.

13 To delete all saved data on the irrigation scheduler and start over click the reset button.

15 To delete only the saved crop data and keep the imported soils data click the 'Reset Crop' button.

Figure I.2.B: Macro Security Warning for Excel 2010

When this security warning is displayed click ‘Enable Content’ to continue.

3. Data Connections

The CIS uses data connections to collect the appropriate weather data for the farm in question from the CoAgMet website. A security warning similar to the one shown in Figure I.2.B may also be displayed that warns the user that the file contains data connections. If this happens allow the content in a similar way as before.

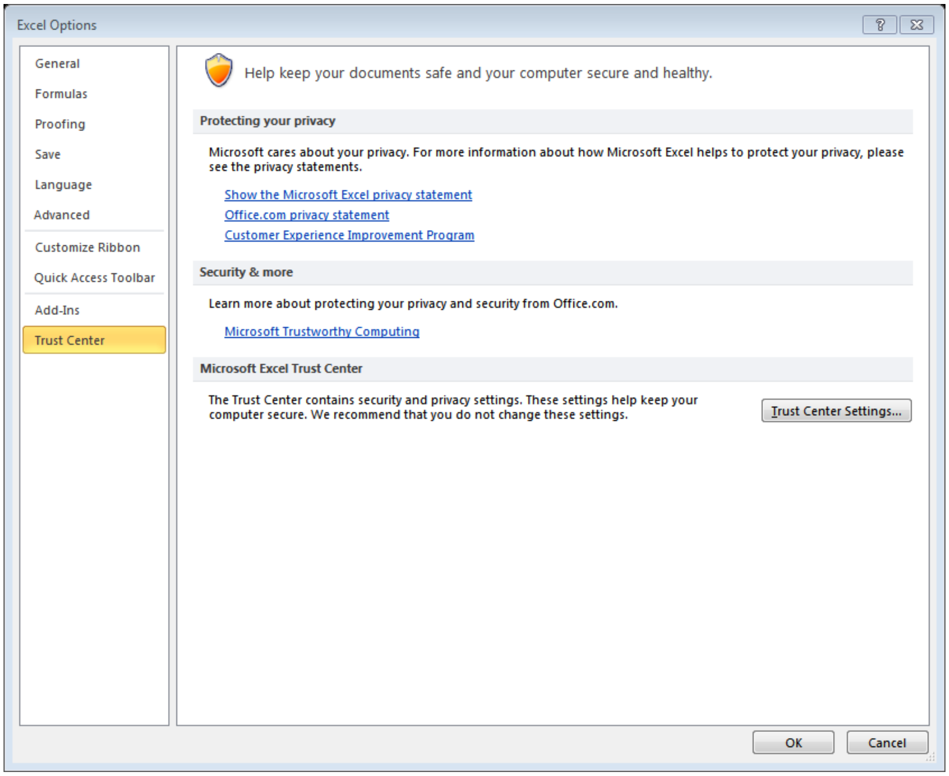
4. Secure Locations

The macro security warning and the data connections security warning will likely be displayed each time that the CIS Tool is opened. To keep this from occurring, the folder that contains the CIS file can be added to Excel's trusted locations. *Doing this is not necessary to run the CIS, but it will eliminate the need to allow content each time the CIS is opened.*

To do add a secure location, Open Excel and Select 'File' --> 'Excel Options' and select 'Trust Center' on the message box that is displayed (see Figure I.4.A).

Next click 'Trust Center Settings…' and select 'Trusted Locations' and click 'Add new location…' (see Figure I.4.B). Now click 'Add new location…' and use the browse button to select the folder where you will store the CIS file. Click Ok twice, to exit both input boxes.

Warning: It is not recommended that you put a folder that contains many files as Trusted Locations, because a file from an untrusted source could be inadvertently placed there and cause damage to your computer.



Help keep your documents safe and your computer secure and healthy.

Protecting your privacy

Microsoft cares about your privacy. For more information about how Microsoft Excel helps to protect your privacy, please see the privacy statements.

Show the Microsoft Excel privacy statement
Office.com privacy statement
Customer Experience Improvement Program

Security & more

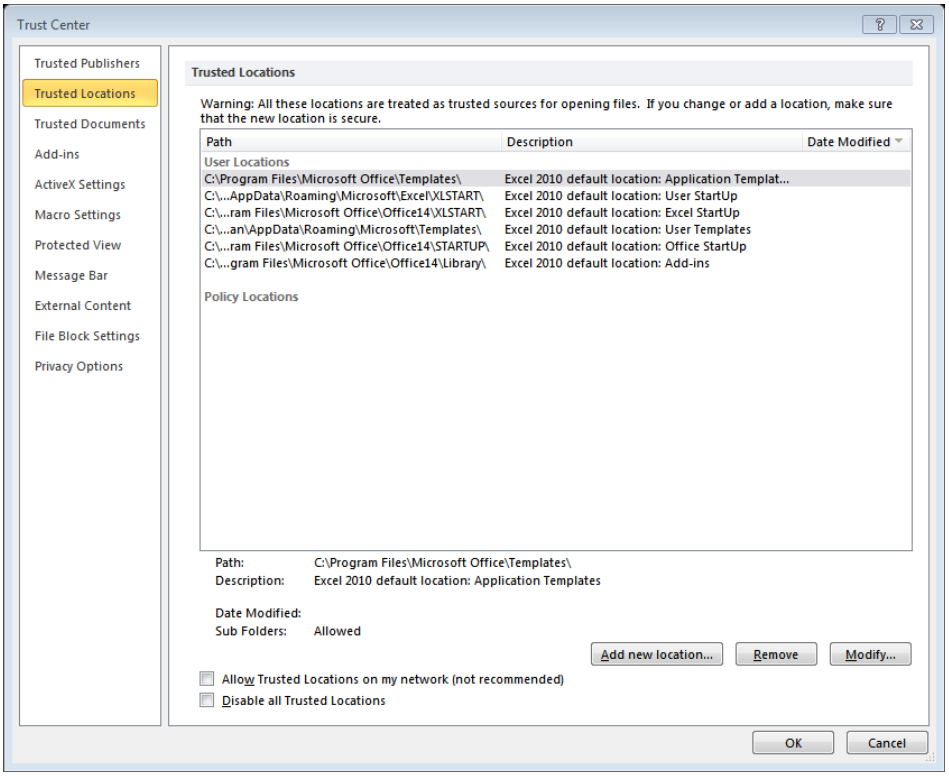
Learn more about protecting your privacy and security from Office.com.

Microsoft Trustworthy Computing

Microsoft Excel Trust Center

The Trust Center contains security and privacy settings. These settings help keep your computer secure. We recommend that you do not change these settings.

Figure I.4.A: Excel Options -> Trust Center



Trusted Locations

Warning: All these locations are treated as trusted sources for opening files. If you change or add a location, make sure that the new location is secure.

Path	Description	Date Modified
User Locations		
C:\Program Files\Microsoft Office\Templates\	Excel 2010 default location: Application Templat...	
C:\...AppData\Roaming\Microsoft\Excel\XLSTART\	Excel 2010 default location: User StartUp	
C:\...ram Files\Microsoft Office\Office14\XLSTART\	Excel 2010 default location: Excel StartUp	
C:\...an\AppData\Roaming\Microsoft\Templates\	Excel 2010 default location: User Templates	
C:\...ram Files\Microsoft Office\Office14\STARTUP\	Excel 2010 default location: Office StartUp	
C:\...gram Files\Microsoft Office\Office14\Library\	Excel 2010 default location: Add-ins	
Policy Locations		

Path: C:\Program Files\Microsoft Office\Templates\
Description: Excel 2010 default location: Application Templates

Date Modified:
Sub Folders: Allowed

☐ Allow Trusted Locations on my network (not recommended)
☐ Disable all Trusted Locations

Figure I.4.B: Trust Center ->Trusted Locations

II. Soils Data

Before beginning irrigation scheduling the soils data for the field of interest needs to be inputted. There are two options for entering soils data: the ‘Collect Soils Data’ and the ‘Enter Soils Data’ buttons.

The ‘Collect Soils Data’ button gives step-by-step instructions for querying the NRCS Web Soil Survey and copying the necessary tables into the CIS tool. The dominant soil type will be used for irrigation scheduling with the option of selecting a different soil type if desired.

The ‘Enter Soils Data’ button allows the user to directly enter the soil profile data that will be used for irrigation scheduling namely: depths, the available water content and field capacity for each soil layer.

Each of these methods has a button on the ‘Introduction’ sheet, more information and specific steps required for these options is provided below.

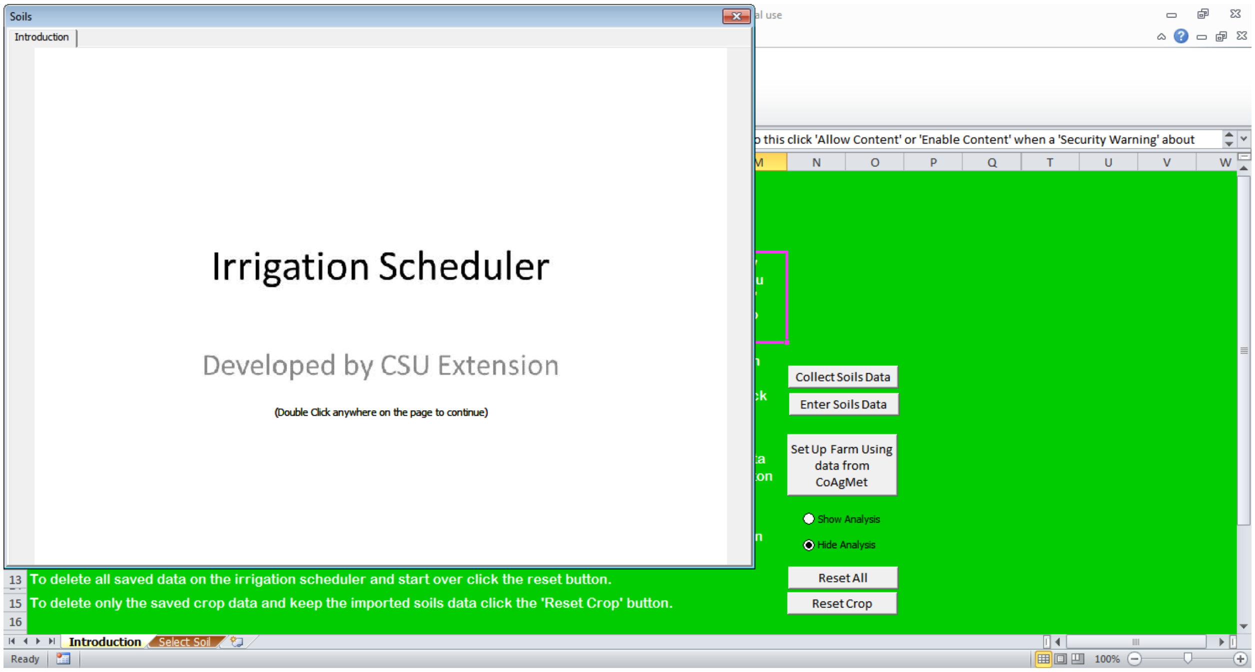
1. Collect Soils Data

The Web Soil Survey works best when used with Internet Explorer.

The ‘Collect Soils Data’ button on the Introduction Sheet will launch a form that gives step by step instructions for collecting the Soil Survey information from the NRCS Web Soil Survey. (See Appendix: B Web Soil Survey Slides for higher resolution versions of the instruction slides.) More detailed instructions for collecting soils data from the NRCS Web Soil Survey follow.

A. Starting the Soil Collection Form

When ‘Collect Soils Data’ is clicked the following introduction page will be displayed.



Irrigation Scheduler

Developed by CSU Extension

(Double Click anywhere on the page to continue)

this click 'Allow Content' or 'Enable Content' when a 'Security Warning' about

13 To delete all saved data on the irrigation scheduler and start over click the reset button.

15 To delete only the saved crop data and keep the imported soils data click the 'Reset Crop' button.

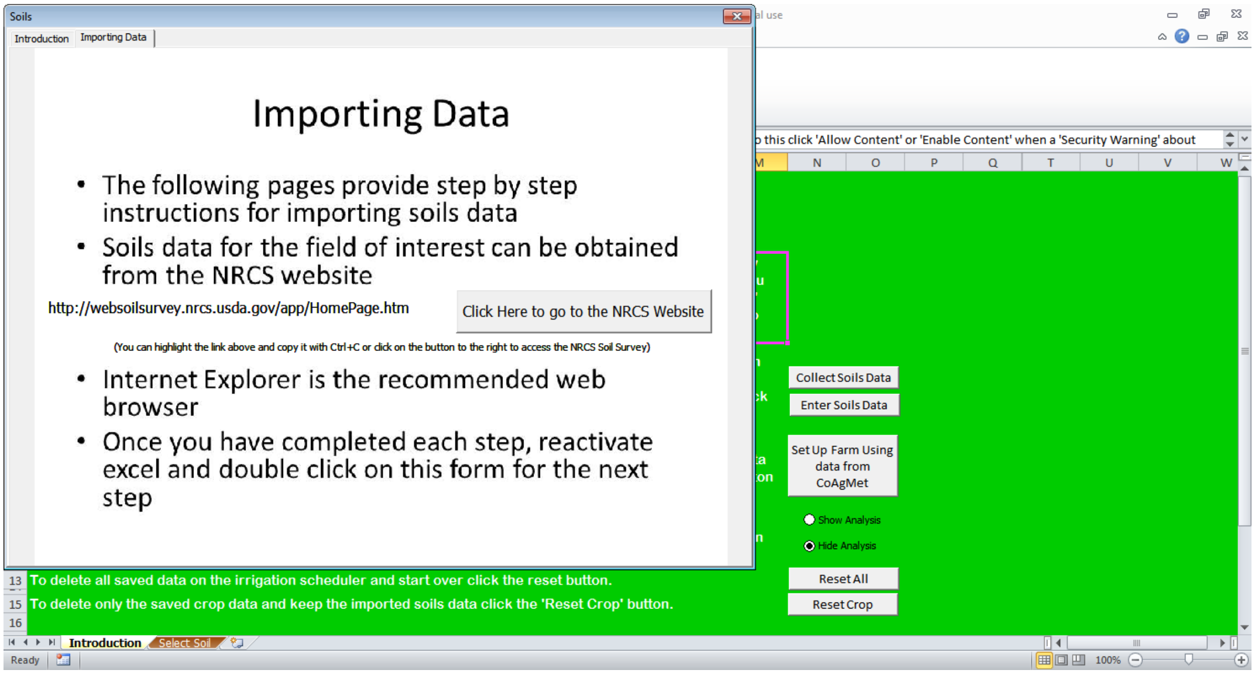
Figure II.1.A: Collecting Soils data Introduction.

Double-click anywhere on this form to advance to the first set of instructions.

B. Importing Data Instructions

The slide that is now displayed will explain how to go to the NRCS website. To ensure that the soils data copies correctly into Excel, it is recommended that Internet Explorer is used to access the Web Soil Survey. The use of another web browser such as Google Chrome or Firefox may cause formatting related errors when soils data is copied into Excel and may take several tries to get the soil data to copy correctly.

If Internet Explorer is your default web browser then click the button provided. If Internet explorer is not your default web browser then open Internet Explorer and copy-and-paste or type the web address shown in the form (http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm) into the Internet Explorer address bar. The usual drop-down menu will not be displayed if you right-click on the form in Excel, but Ctrl+C will still copy the highlighted text.



Importing Data

- The following pages provide step by step instructions for importing soils data
- Soils data for the field of interest can be obtained from the NRCS website

http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm

(You can highlight the link above and copy it with Ctrl+C or click on the button to the right to access the NRCS Soil Survey)

- Internet Explorer is the recommended web browser
- Once you have completed each step, reactivate excel and double click on this form for the next step

o this click 'Allow Content' or 'Enable Content' when a 'Security Warning' about

13 To delete all saved data on the irrigation scheduler and start over click the reset button.

15 To delete only the saved crop data and keep the imported soils data click the 'Reset Crop' button.

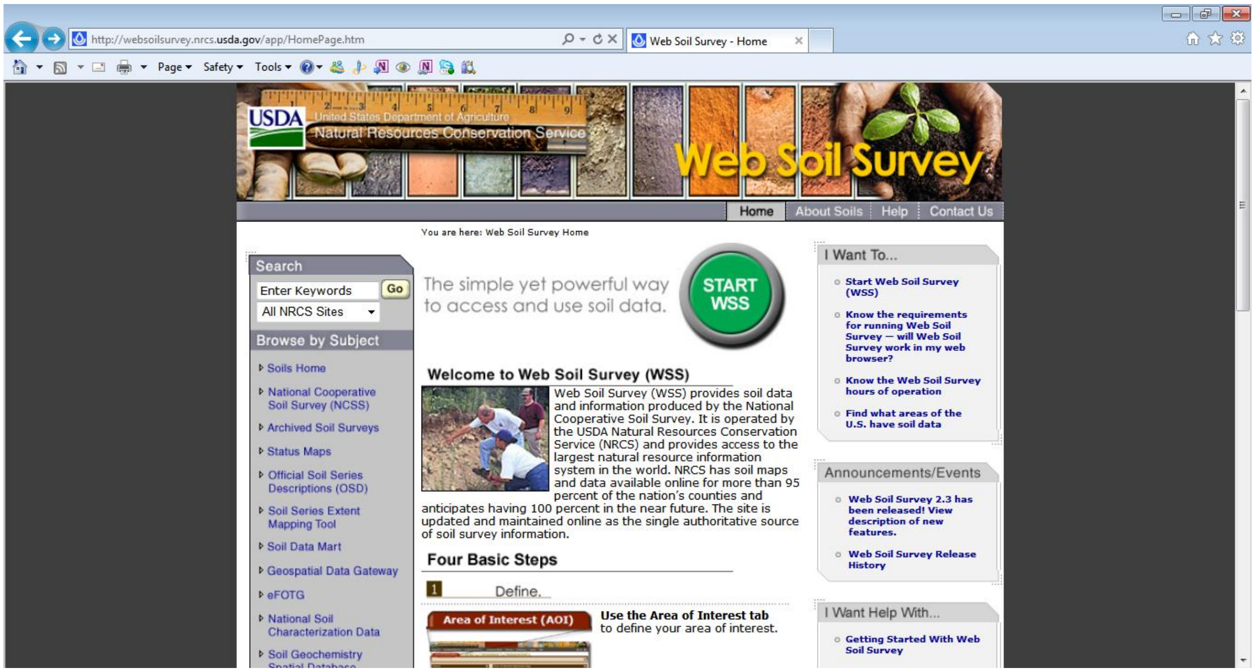
Figure II.3.B: Importing Data

Now, double-click anywhere on the slide to continue to the next instruction page.

At this point this manual will describe how to collect soils data from the NRCS Web Soil Survey in detail. Following this manual will avoid switching between Excel and Internet Explorer as each step is completed.

C. Starting the Web Soil Survey

The link provided above will open the introduction page of the NRCS Web Soil Survey. This page provides some information about the Web Soil Survey. To begin the Web Soil Survey click the green “Start WSS” button shown below in Figure II.1.C.



Welcome to Web Soil Survey (WSS)

Web Soil Survey (WSS) provides soil data and information produced by the National Cooperative Soil Survey. It is operated by the USDA Natural Resources Conservation Service (NRCS) and provides access to the largest natural resource information system in the world. NRCS has soil maps and data available online for more than 95 percent of the nation’s counties and anticipates having 100 percent in the near future. The site is updated and maintained online as the single authoritative source of soil survey information.

Four Basic Steps

Use the Area of Interest tab to define your area of interest.

Figure II.1.C: Starting the Web Soil Survey

D. Selecting an Area of Interest (AOI)

Once the Web Soil Survey loads, select an Area of Interest (AOI). For the AOI, select the field that you want to schedule irrigation for. The WSS provides several methods to select an AOI. Two of these are entering the street address of the field of interest or to successively zoom into the area where your farm is located until the field of interest fills most of the screen.

Once the field of interest fills most of the screen, select either the rectangle or the polygon AOI button in the Area of Interest Interactive Map tool bar. If the field of interest is non-rectangular then using the polygon tool will give more precise soil properties for your field.

To use the polygon tool, click on a starting point on the perimeter of the field. Now move around the field's perimeter clicking to add points as necessary to reflect the perimeter of the actual irrigated area. Once the field's perimeter is adequately selected, double-click to finalize the polygon. An example of selecting an area of interest with the polygon AOI tool is shown below in Figure II.1.D.

Once an AOI is selected a few message boxes will be displayed as WSS compiles the soil and spatial data for the selected field.

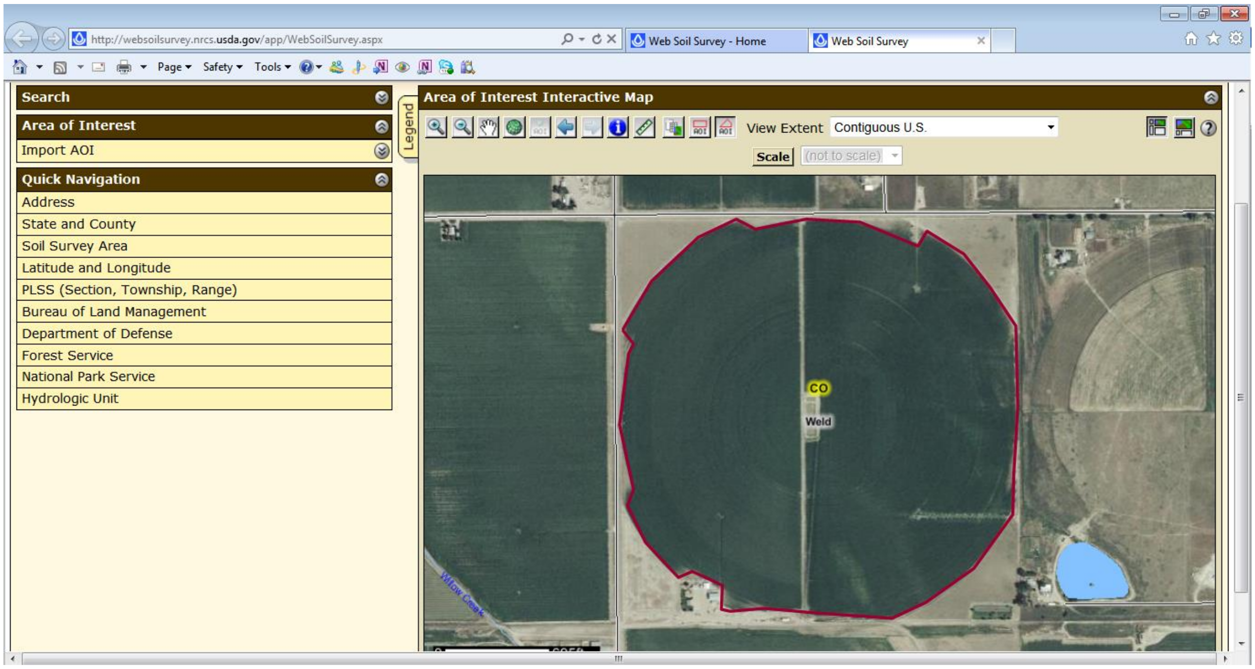
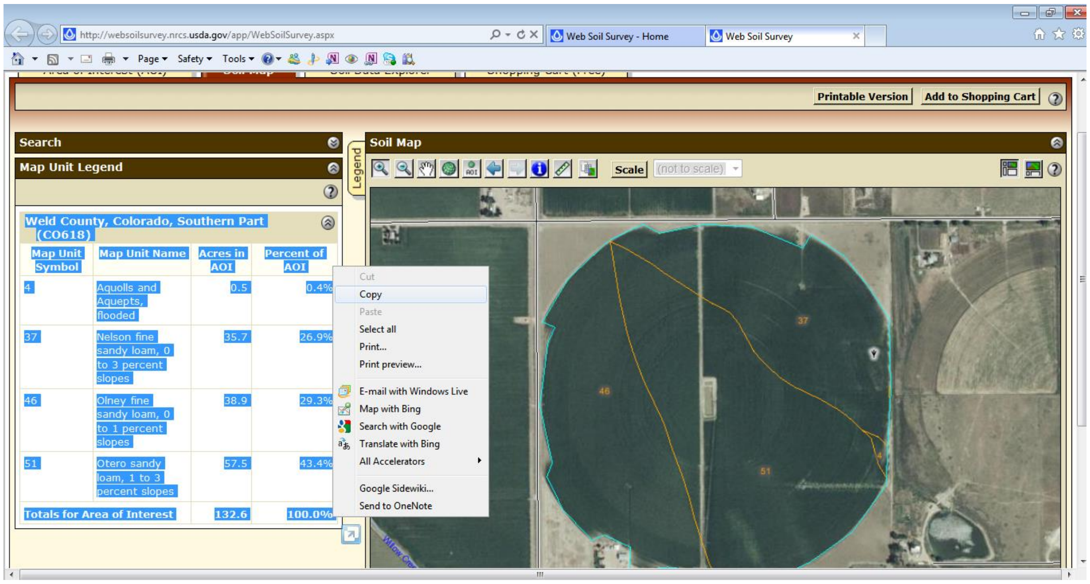


Figure II.1.D: Selecting an Area of Interest

E. Copying the Map Unit Legend

Now that an AOI is selected, click on the "Soil Map" tab near the top of the screen.

Next highlight the Map Unit Legend Table as shown below in Figure II.1.E.i , and copy it by right-clicking and selecting copy (as shown below) or pressing 'Ctrl' + 'C'.



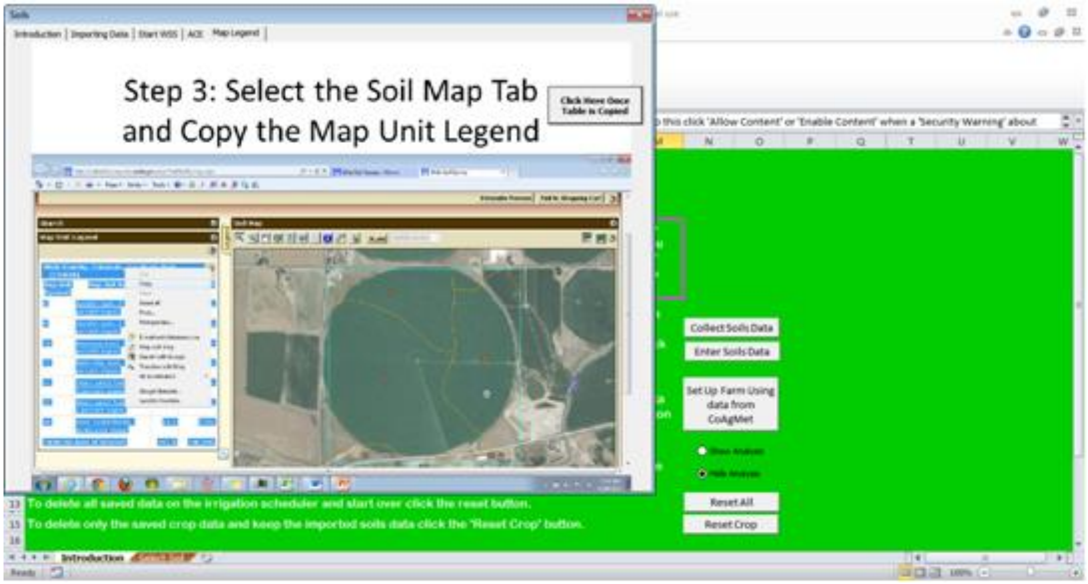
Weld County, Colorado, Southern Part (CO618)

Map Unit Symbol	Map Unit Name	Acres in AOI	Percent of AOI
4	Aquolls and Aquepts, flooded	0.5	0.4%
37	Nelson fine sandy loam, 0 to 3 percent slopes	35.7	26.9%
46	Olney fine sandy loam, 0 to 1 percent slopes	38.9	29.3%
51	Otero sandy loam, 1 to 3 percent slopes	57.5	43.4%
Totals for Area of Interest		132.6	100.0%

Figure II.1.E.i: Copying the Map Unit Legend Table

Now, activate Excel by clicking on the Excel Icon on the Windows Taskbar.

This will display Excel and the Soils form. Double click on the Soils form until the page shown in Figure II.1.E.ii is displayed. Now click the 'Click Here Once Table is Copied' button and wait until the next page is displayed. This may take a few minutes and may cause Excel or the Soil form to read (Not Responding). If this occurs continue to wait for the program to respond without taking any action.



Step 3: Select the Soil Map Tab and Copy the Map Unit Legend

To delete all saved data on the irrigation scheduler and start over click the reset button.

To delete only the saved crop data and keep the imported soils data click the 'Reset Crop' button.

Figure II.1.E.ii: Importing Map Unit Legend table into Excel

F. Collecting Soil Data

Now activate Internet Explorer using the Windows Taskbar.

On the WSS page select the “Soil Data Explorer” tab near the top of the page.

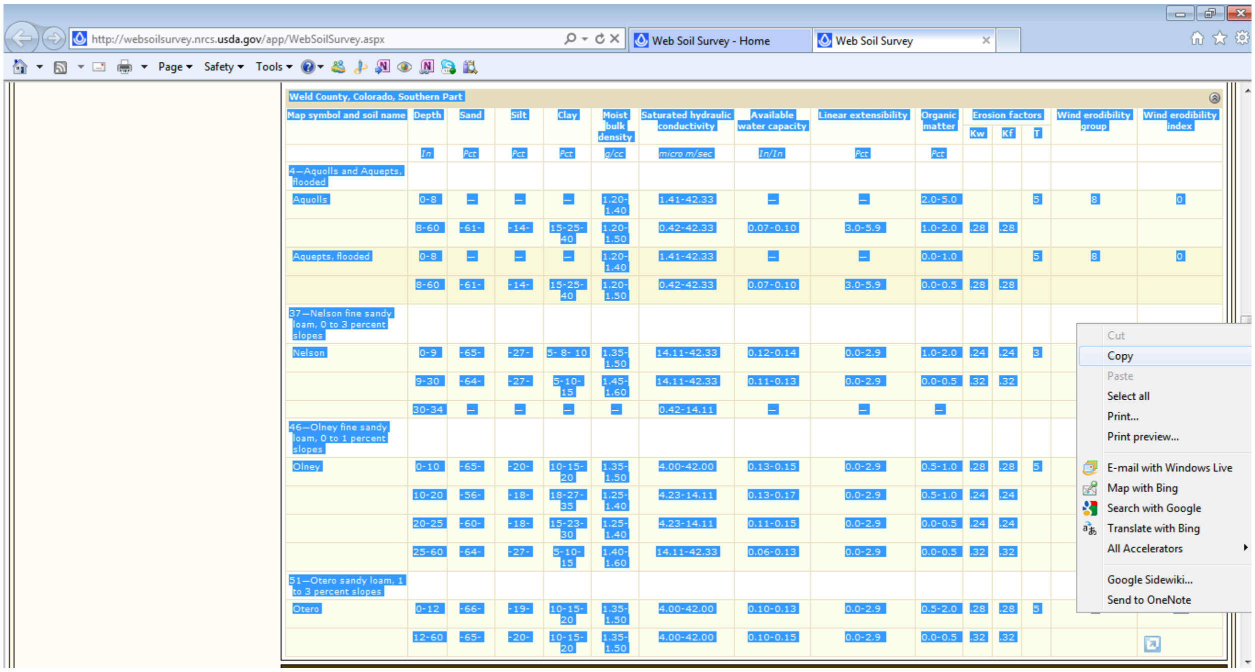
This will open a page with another tab strip below the tab strip at the top of the page. Select the “Soil Reports” tab on this secondary tab strip.

On the left hand side of the page there should now be a list of several soil reports that are available. Click on “Soil Physical Properties” located about two-thirds of the way down the list.

This will display a sub-list. On this list select “Physical Soil Properties”.

Now click the ‘View Soil Report’ button, and scroll down to “Report—Physical Soil Properties”

Next, highlight and the entire table as shown below in Figure II.1.A



Weld County, Colorado, Southern Part

Map symbol and soil name	Depth	Sand	Silt	Clay	Moist bulk density	Saturated hydraulic conductivity	Available water capacity	Linear extensibility	Organic matter	Erosion factors			Wind erodibility group	Wind erodibility index
										Kw	Kf	T		
	In	Pct	Pct	Pct	g/cc	micro m/sec	In/In	Pct	Pct					
4—Aquolls and Aquepts, flooded														
Aquolls	0-8	—	—	—	1.20-1.40	1.41-42.33	—	—	2.0-5.0			5	8	0
	8-60	-61-	-14-	15-25-40	1.20-1.50	0.42-42.33	0.07-0.10	3.0-5.9	1.0-2.0	.28	.28			
Aquepts, flooded	0-8	—	—	—	1.20-1.40	1.41-42.33	—	—	0.0-1.0			5	8	0
	8-60	-61-	-14-	15-25-40	1.20-1.50	0.42-42.33	0.07-0.10	3.0-5.9	0.0-0.5	.28	.28			
37—Nelson fine sandy loam, 0 to 3 percent slopes														
Nelson	0-9	-65-	-27-	5- 8- 10	1.35-1.50	14.11-42.33	0.12-0.14	0.0-2.9	1.0-2.0	.24	.24	3		
	9-30	-64-	-27-	5-10-15	1.45-1.60	14.11-42.33	0.11-0.13	0.0-2.9	0.0-0.5	.32	.32			
	30-34	—	—	—	—	0.42-14.11	—	—	—					
46—Olney fine sandy loam, 0 to 1 percent slopes														
Olney	0-10	-65-	-20-	10-15-20	1.35-1.50	4.00-42.00	0.13-0.15	0.0-2.9	0.5-1.0	.28	.28	5		
	10-20	-56-	-18-	18-27-35	1.25-1.40	4.23-14.11	0.13-0.17	0.0-2.9	0.5-1.0	.24	.24			
	20-25	-60-	-18-	15-23-30	1.25-1.40	4.23-14.11	0.11-0.15	0.0-2.9	0.0-0.5	.24	.24			
	25-60	-64-	-27-	5-10-15	1.40-1.60	14.11-42.33	0.06-0.13	0.0-2.9	0.0-0.5	.32	.32			
51—Otero sandy loam, 1 to 3 percent slopes														
Otero	0-12	-66-	-19-	10-15-20	1.35-1.50	4.00-42.00	0.10-0.13	0.0-2.9	0.5-2.0	.28	.28	5		
	12-60	-65-	-20-	10-15-20	1.35-1.50	4.00-42.00	0.10-0.15	0.0-2.9	0.0-0.5	.32	.32			

Figure II.1.A: Copying the Report –Physical Soil Properties Table. Note that the zoom on the WSS Page was adjusted so that the entire table fit in the screen. This is not necessary, but can be accomplished by holding the control key and scrolling on the mouse.

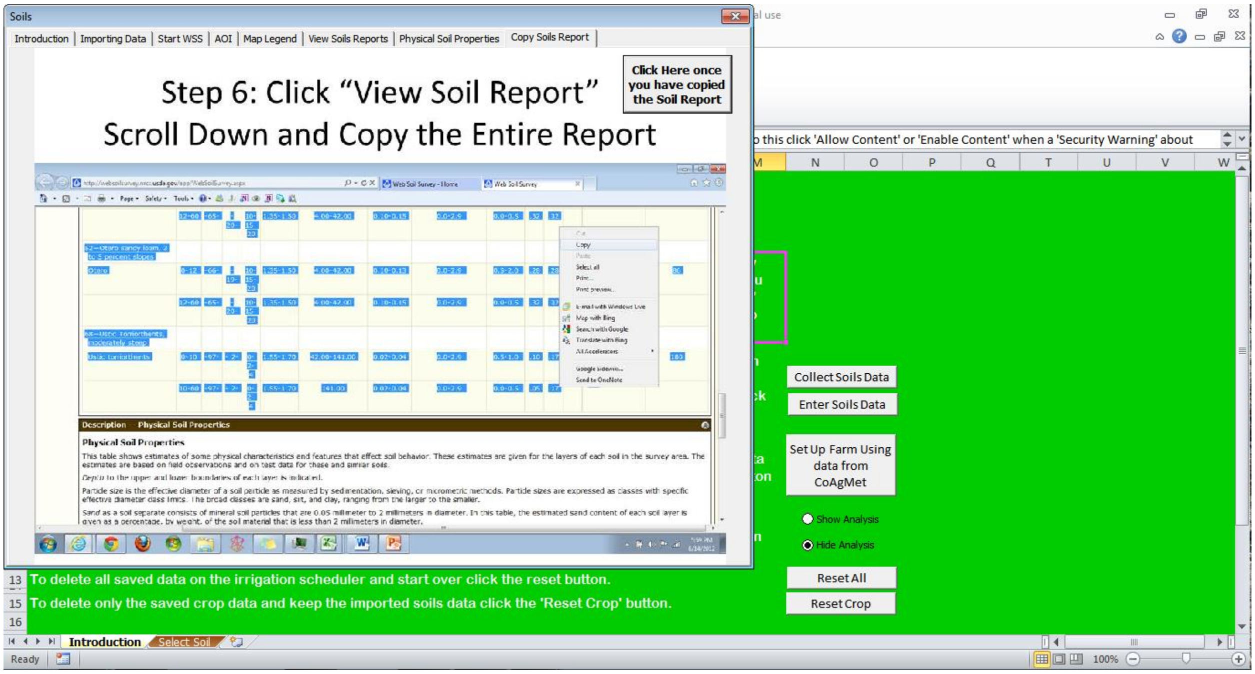
It is important that the highlighted area looks very similar to what is shown above, or else the table may not paste into Excel correctly.

Right-click and click ‘Copy’ or press Ctrl+C to copy the table at this point.

G. Importing the Soil Table

Activate Excel using the Windows Taskbar.

Double-Click on the Soils form until the ‘Step 6: Click “View Soil Report”’ is displayed as shown below in Figure II.1.G.



Step 6: Click “View Soil Report”
Scroll Down and Copy the Entire Report

o this click 'Allow Content' or 'Enable Content' when a 'Security Warning' about

Description Physical Soil Properties

Physical Soil Properties

This table shows estimates of some physical characteristics and features that effect soil behavior. These estimates are given for the layers of each soil in the survey area. The estimates are based on field observations and on test data for these and similar soils.

Depth to the upper and lower boundaries of each layer is indicated.

Particle size is the effective diameter of a soil particle as measured by sedimentation, sieving, or micrometric methods. Particle sizes are expressed as classes with specific effective diameter class limits. The broad classes are sand, silt, and clay, ranging from the larger to the smaller.

Sand as a soil separate consists of mineral soil particles that are 0.05 millimeter to 2 millimeters in diameter. In this table, the estimated sand content of each soil layer is given as a percentage, by weight, of the soil material that is less than 2 millimeters in diameter.

13 To delete all saved data on the irrigation scheduler and start over click the reset button.
15 To delete only the saved crop data and keep the imported soils data click the 'Reset Crop' button.

Figure II.1.G: Importing the Soil Report into Excel

Now click the ‘Click Here once you have copied the Soil Report’ button.

This will compile the soil report. Compiling the soil report may take several minutes and in this process Excel may read Not Responding. If this occurs, wait for Excel to respond without taking any action. If Excel takes more than two or three minutes to respond, use Windows Task Manager (Ctrl+Alt+Delete) to terminate Excel, and restart the program, coping the necessary tables as before.

If the soils report did not copy correctly, a message will prompt you to try again. If this happens repeat steps F and G.

When the soils data is finished compiling the ‘Soils’ form will disappear and the ‘Select Soil’ sheet will be selected (as shown in Figure II.1.H). At this point the WSS is no longer needed and Internet Explorer can be closed.

H. Verifying Soil Information

The soils data on this page should be checked to ensure that all values were available and appropriate. The most prominent soil type in the area of interest will be selected by default. This soil type will be used for irrigation scheduling purposes, and the soil layer depths shown will be used as the control volumes for each respective soil layer.

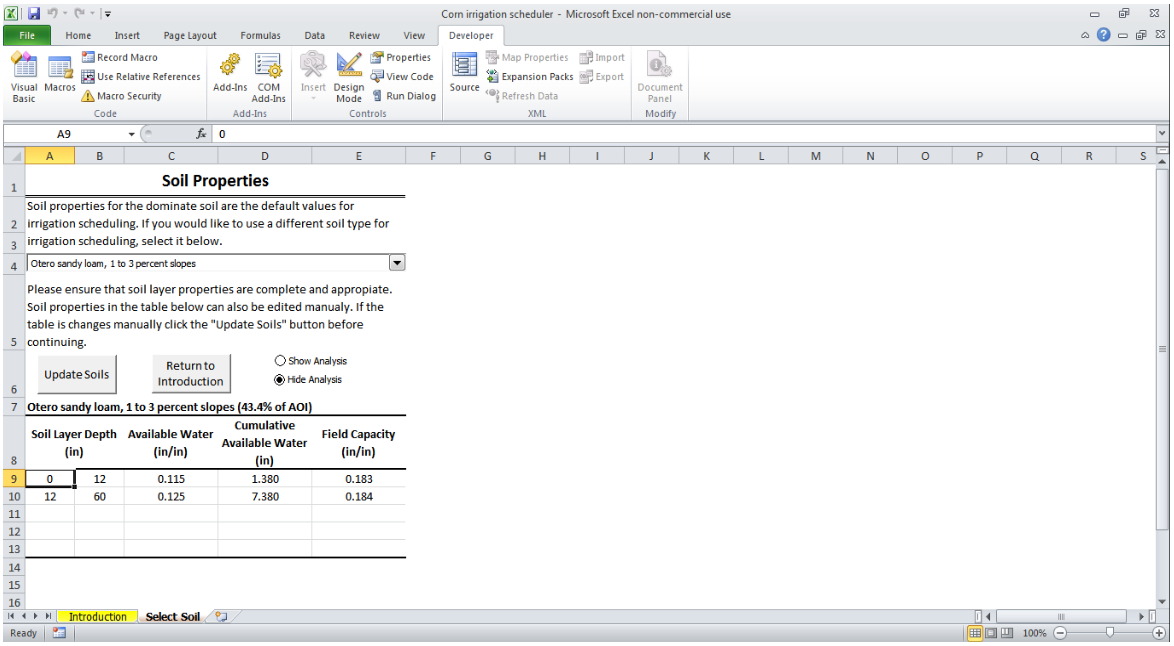
To use a different soil type for irrigation scheduling, select it using the drop down menu near the top of the page. (The percentage of the field that the selected soil type covers is shown in parentheses above the soil properties table.)

Once a soil type is selected, the user should verify that:

1. The deepest soil layer is at least as deep as the control depth (maximum rooting depth). If you believe that the deepest soil layer represents the deepest soil that the plant's roots can penetrate and this is less than the crop's control depth, then set the control depth equal to this deepest soil depth. Otherwise increase the maximum soil depth to be at least as deep as the control depth or add additional soil layers that cover the entire control depth.
2. There is an Available Water and a Field Capacity entered for each soil layer

The depths, available water capacity, and field capacity in the soil properties table can be changed manually if necessary. Click the 'Update Soils' button to save any manual changes to the Soil Properties table.

Once the soil properties table has been reviewed; click the 'Return to Introduction' button or select the 'Introduction' sheet to continue.



A9 0

Soil Properties

Soil properties for the dominate soil are the default values for irrigation scheduling. If you would like to use a different soil type for irrigation scheduling, select it below.

Otero sandy loam, 1 to 3 percent slopes

Please ensure that soil layer properties are complete and appropiate. Soil properties in the table below can also be edited manualy. If the table is changes manually click the "Update Soils" button before continuing.

Otero sandy loam, 1 to 3 percent slopes (43.4% of AOI)

Soil Layer Depth (in)		Available Water (in/in)	Cumulative Available Water (in)	Field Capacity (in/in)
0	12	0.115	1.380	0.183
12	60	0.125	7.380	0.184

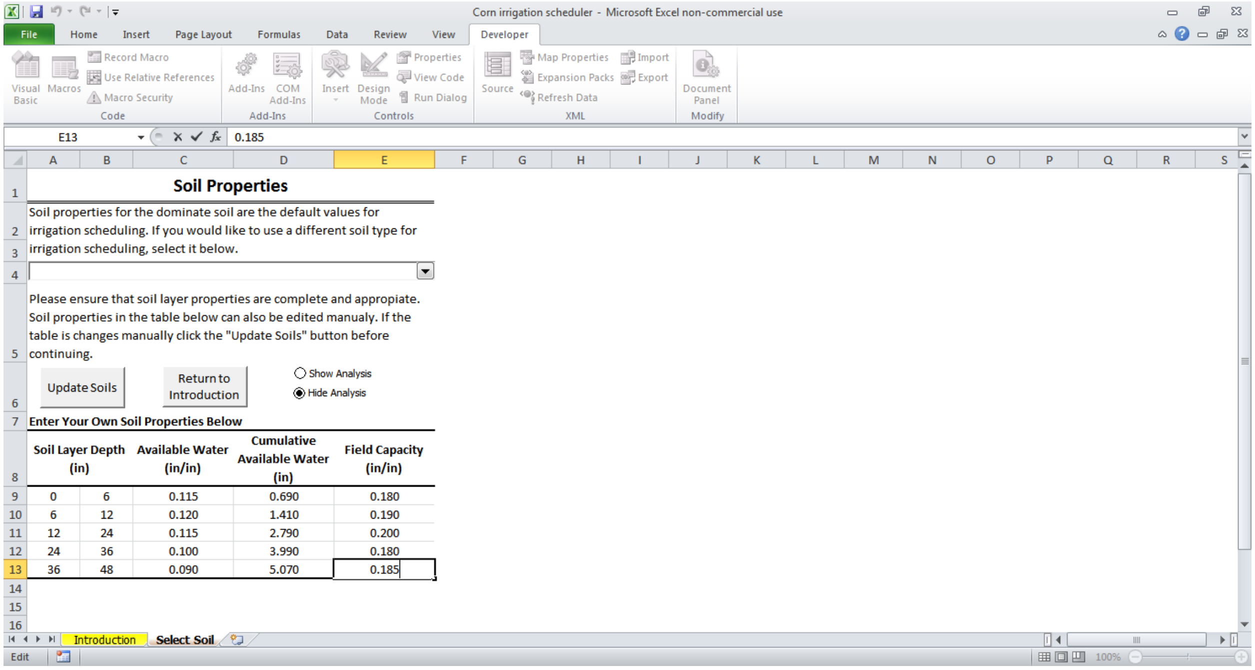
Figure II.1.H: Verifying Soil Properties

2. Enter Soils Data

The ‘Enter Soils Data’ button allows users to enter their own soil layer depths and properties without using the NRCS Web Soil Survey. The following steps explain how to enter your own soils data.

1. When the ‘Enter Soils Data’ button is selected default soil layer depths will be populated. These layer depths can be changed if desired.
2. Enter the available water content (in/in) for each layer.
3. Enter the field capacity (in/in) for each layer.
4. A spreadsheet model that estimates the field capacity and the available water content for a soil given the percent sand, percent clay and soil bulk density is included in the Analysis sheets. For more information about this model see “Soil hydraulic properties” in section V.7 Soil hydraulic properties.

Figure II.2 below shows a filled out Soil Properties table



Soil Properties

Soil properties for the dominate soil are the default values for irrigation scheduling. If you would like to use a different soil type for irrigation scheduling, select it below.

Please ensure that soil layer properties are complete and appropiate. Soil properties in the table below can also be edited manualy. If the table is changes manually click the "Update Soils" button before continuing.

Update Soils

Return to Introduction

○ Show Analysis

● Hide Analysis

Enter Your Own Soil Properties Below

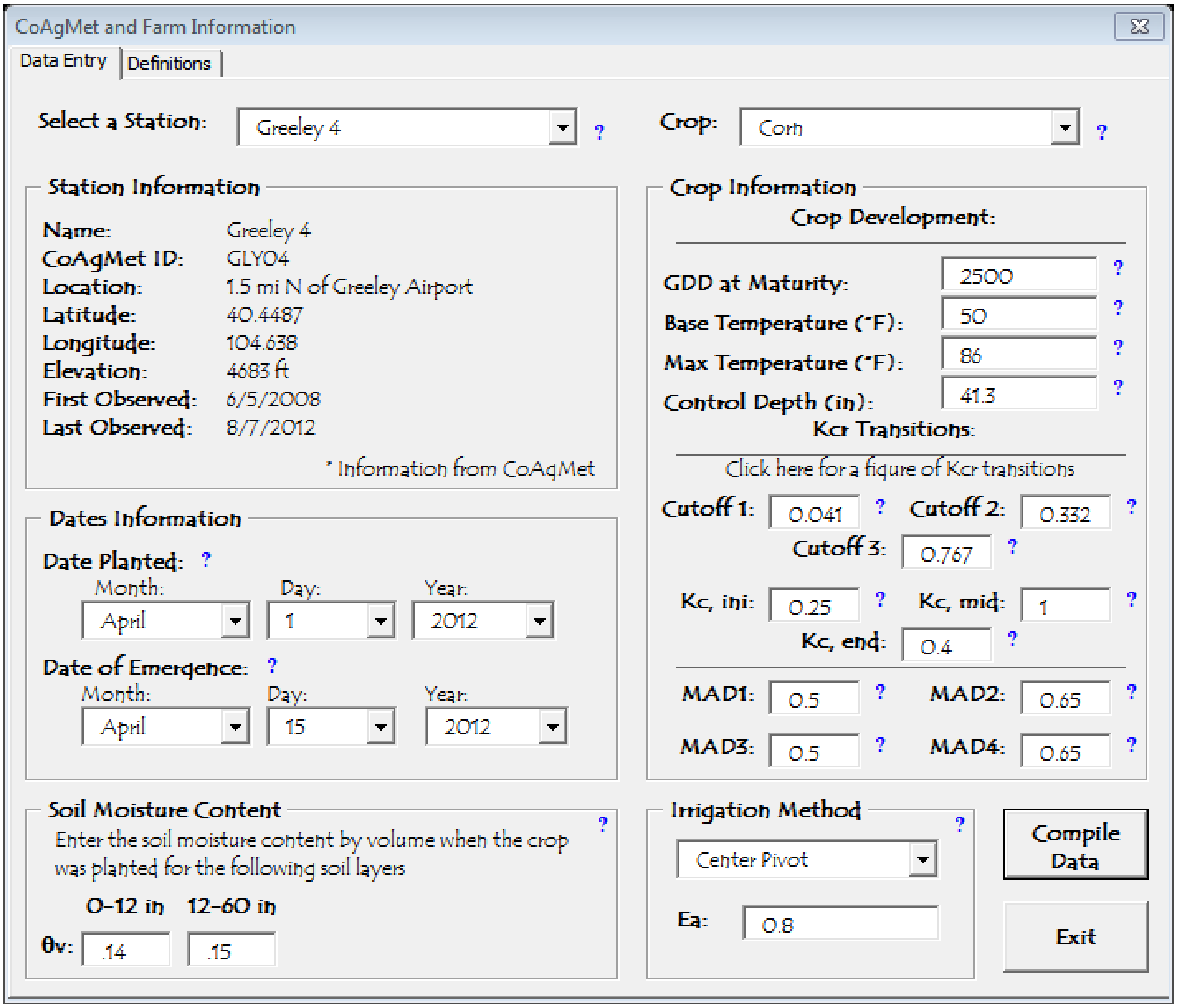
Soil Layer Depth (in)		Available Water (in/in)	Cumulative Available Water (in)	Field Capacity (in/in)
0	6	0.115	0.690	0.180
6	12	0.120	1.410	0.190
12	24	0.115	2.790	0.200
24	36	0.100	3.990	0.180
36	48	0.090	5.070	0.185

Figure II.2: Enter your own soil properties, filled out

III. Getting Weather Data

Once soils data are either collected or entered, the farm can be set up by selecting a weather station and entering crop and irrigation information. To do so click the ‘Set Up Farm Using data from CoAgMet’ on the ‘Introduction’ sheet. This will start the ‘CoAgMet and Farm Information’ form to get weather data from CoAgMet and to enter your crop properties. An example of the irrigation scheduler form filled out is shown in Figure III.1 below.

A description of the editable fields are listed below, each of these explanations can also be viewed by clicking on the question mark next to the respective field on the ‘CoAgMet and Farm Information’ form.



Select a Station: Greeley 4
Crop: Corn

Station Information
Name: Greeley 4
CoAgMet ID: GLY04
Location: 1.5 mi N of Greeley Airport
Latitude: 40.4487
Longitude: 104.638
Elevation: 4683 ft
First Observed: 6/5/2008
Last Observed: 8/7/2012
* Information from CoAgMet

Dates Information
Date Planted: Month: April Day: 1 Year: 2012
Date of Emergence: Month: April Day: 15 Year: 2012

Crop Information
Crop Development:
GDD at Maturity: 2500
Base Temperature (°F): 50
Max Temperature (°F): 86
Control Depth (in): 41.3
Kcr Transitions:
Click here for a figure of Kcr transitions
Cutoff 1: 0.041 Cutoff 2: 0.332
Cutoff 3: 0.767
Kc, ini: 0.25 Kc, mid: 1
Kc, end: 0.4
MAD1: 0.5 MAD2: 0.65
MAD3: 0.5 MAD4: 0.65

Soil Moisture Content
Enter the soil moisture content by volume when the crop was planted for the following soil layers
0-12 in 12-60 in
θv: .14 .15

Irrigation Method
Center Pivot
Ea: 0.8

Figure III.2: Example of Filled out CoAgMet and Farm Information Form

1. Select a Station

Select the weather station listed that is closest to your farm's location. Ensure that the dates that you want to collect data for fall within the first observed and last observed dates shown. If the last observed date for the station nearest your farm is older than acceptable, choose the next closest station.

2. Enter the plant date

Enter the date that the crop was planted or the green up date for winter wheat

3. Enter the emergence date

Enter the date that the crop emerged from the soil, for winter wheat the emergence date should be the same as the plant date.

4. Enter the Soil Moisture Content if available

Enter the volumetric soil moisture content (in/in) for each layer. The soil moisture content is used in conjunction with the soil layer data to determine the initial deficit for each soil layer.

If the soil moisture content is not entered the initial deficit is assumed to be zero, which corresponds to the soil being at field capacity.

5. Select a crop

Select the crop that you want to schedule irrigation for. If you have more than one type of crop you will need to run a separate CIS for each crop.

The following fields will be filled out with default values when a crop is selected and can be changed if the user prefers.

A. GDD at Maturity

Enter the number of growing degree days (GDD, in degrees Fahrenheit) from emergence until you expect your crop to reach maturity.

Default values are based on typical CoAgMet calculations at selected weather stations according to typical planting and harvest dates.

B. Base Temperature

The base temperature is the lowest temperature at which the selected crop can grow and is used to calculate the GDD accumulated each day. A default value taken from peer-reviewed articles or online GDD calculators (e.g., CoAgMet) for the selected crop is shown.

C. Max Temperature

The maximum temperature sets an upper limit beyond which the crop experiences heat stress that also limits growth.

The default values were taken from peer-reviewed articles or online GDD calculators (e.g., CoAgMet).

D. Control Depth

The control depth is used for calculated and observed total soil water deficits, also known as the maximum rooting depth. The root-zone for annual crops will increase as it accumulates GDD’s until it reaches this value.

E. Cutoff 1-3

Cutoff 1, 2 and 3 are the decimal fractions of GDDs at maturity that marks the end of the seedling phase, beginning of the full canopy phase, and the beginning of senescence, respectively. Default values are based on lengths of crop development phases from FAO-56 (Allen et al., 1998).

A diagram of the crop coefficient (Kcr) curve is provided in Figure III.5.

F. Kc ini, mid, and end

Kc, ini, Kc, mid, and Kc, end are the crop coefficients at emergence, full cover and maturity, respectively.

A diagram of the crop coefficient (Kcr) curve is provided in Figure III.5.

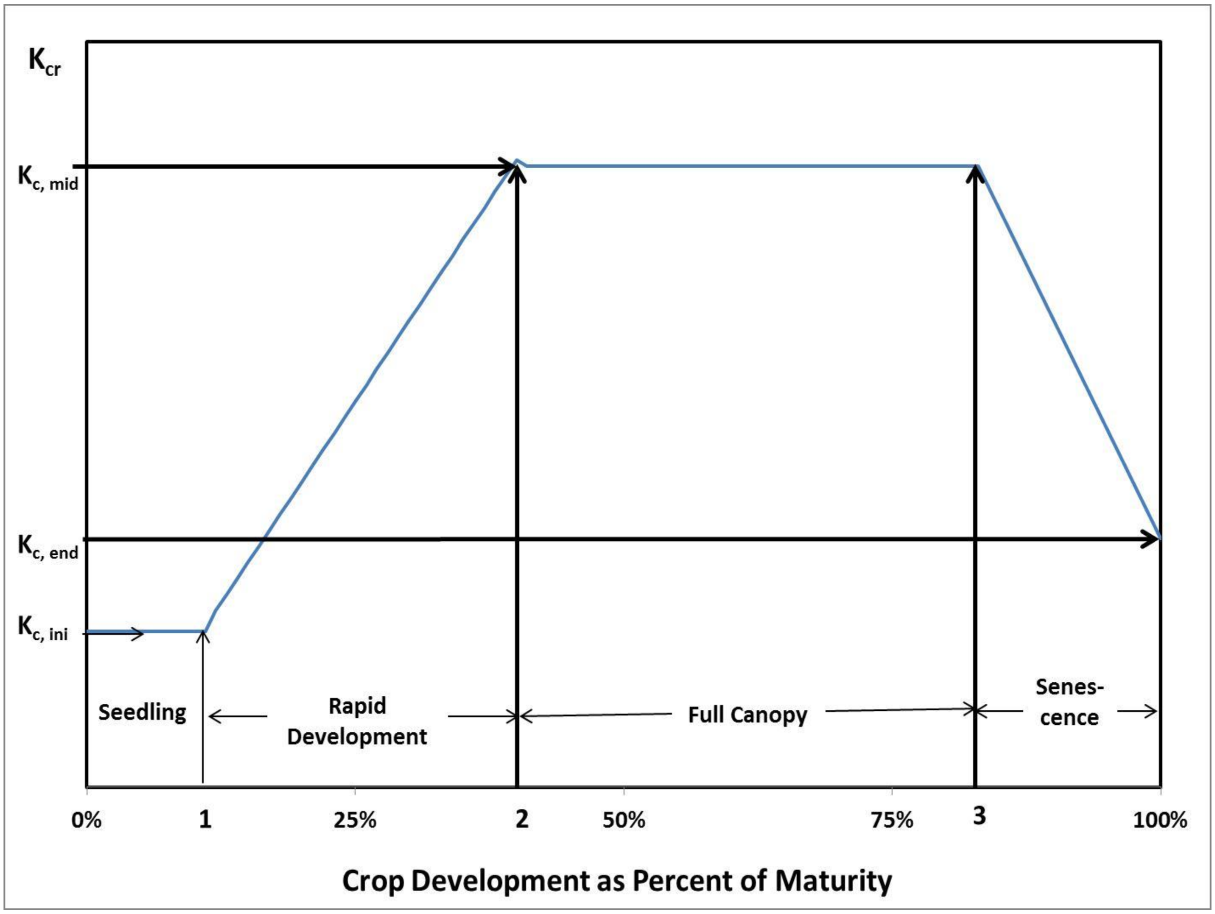


Figure III.5: Crop Coefficient Diagram with definitions of crop coefficient terms

G. MAD 1-4

Enter the managed allowable depletion (MAD) as a decimal fraction of total available water capacity for each of the crop developmental phases. MAD1 is the MAD for the seedling phase, MAD2 is the MAD for the rapid development phase, MAD3 is the MAD for the full canopy phase, and MAD4 is the MAD for the senescence phase.

Default values are taken from FAO-56 (Allen et al., 1998) and CSU Extension Fact Sheet No 4.715 (Al-Kaisi and Boner, 2009).

6. Irrigation Method

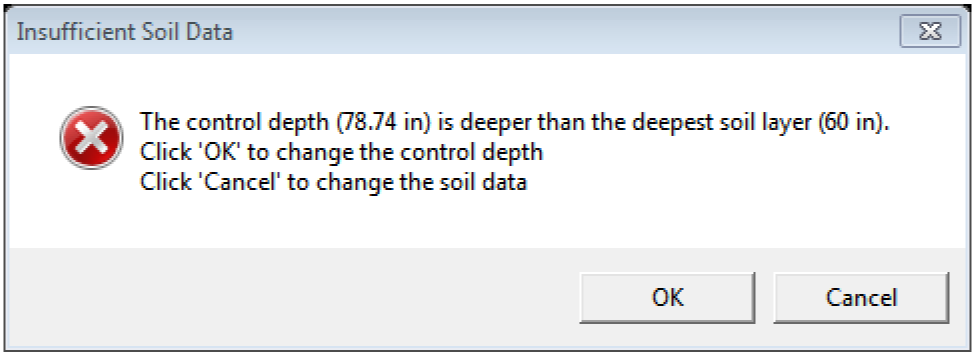
Irrigation application efficiencies for some common irrigation methods are provided.

Please select one from the list, or enter your own irrigation application efficiency (Ea) in the appropriate box. Typical values of Ea for different irrigation systems have been summarized by Barta et al. (2004).

7. Click Compile Data

When the compile button is clicked, Excel will query CoAgMet for the daily values of: alfalfa reference evapotranspiration (ETr) calculated from the ASCE standardized reference ET equation (Allen et al., 2005), precipitation, maximum temperature, and minimum temperature for dates up to two years after the plant date. Occasionally come CoAgMet stations are non-operational, and data is missing. If any data is missing you will be prompted to either enter a value for each missing field or neglect any contribution to the ET, precipitation or GDD (depending on which field is missing) for that day. Occasionally stations are non-operational for long periods of time. If this occurs, either enter all of your own data, or select the second closest station to your farm. Alternatively, you can enter missing data using the ‘EYO Data’ sheet. EYO stands for ‘enter your own’ data. All weather data that are manually entered are saved in this sheet. Instructions for using the ‘EYO Data’ sheet are given at the top of the sheet. See Appendix A: Common Errors: Missing Data for more information about dealing with missing information.

NCRS WSS data usually does not go deeper than 60 in. If your crop has a control depth greater than 60 in an ‘Insufficient Soil Data’ error similar to Figure III.7.B may appear. See Appendix A.4 Insufficient Soil Data for more information about this error. The ‘Water Chart’ sheet should now be selected, and irrigation scheduling can now begin.



The control depth (78.74 in) is deeper than the deepest soil layer (60 in).
Click 'OK' to change the control depth
Click 'Cancel' to change the soil data

Figure III.7.B: Insufficient Soil Data error message

In this example ‘Cancel’ was clicked and the lower bound of the deepest soil layer was changed from ‘60’ to ‘80’ then ‘Update Soils’ was clicked.

After the crop data is entered and the weather data is selected, the ‘Water Chart’ sheet will be selected and irrigation scheduling can begin.

IV. Irrigation Management

The CIS has two alternate methods for entering irrigation data: the graphical and the spreadsheet method.

1. The Graphical Method

The graphical method of irrigation scheduling operates off of the ‘Water Chart’ sheet. Any information that is entered using the graphical method will be available for the spreadsheet method and vice-versa.

The Water Chart Sheet shows a graph of the root-zone deficit, precipitation, depth of management allowable depletion of the root-zone, net irrigation, and runoff and percolation for dates since the crop was planted. An example of the water chart page (after crop data is entered) is shown below in Figure IV.1

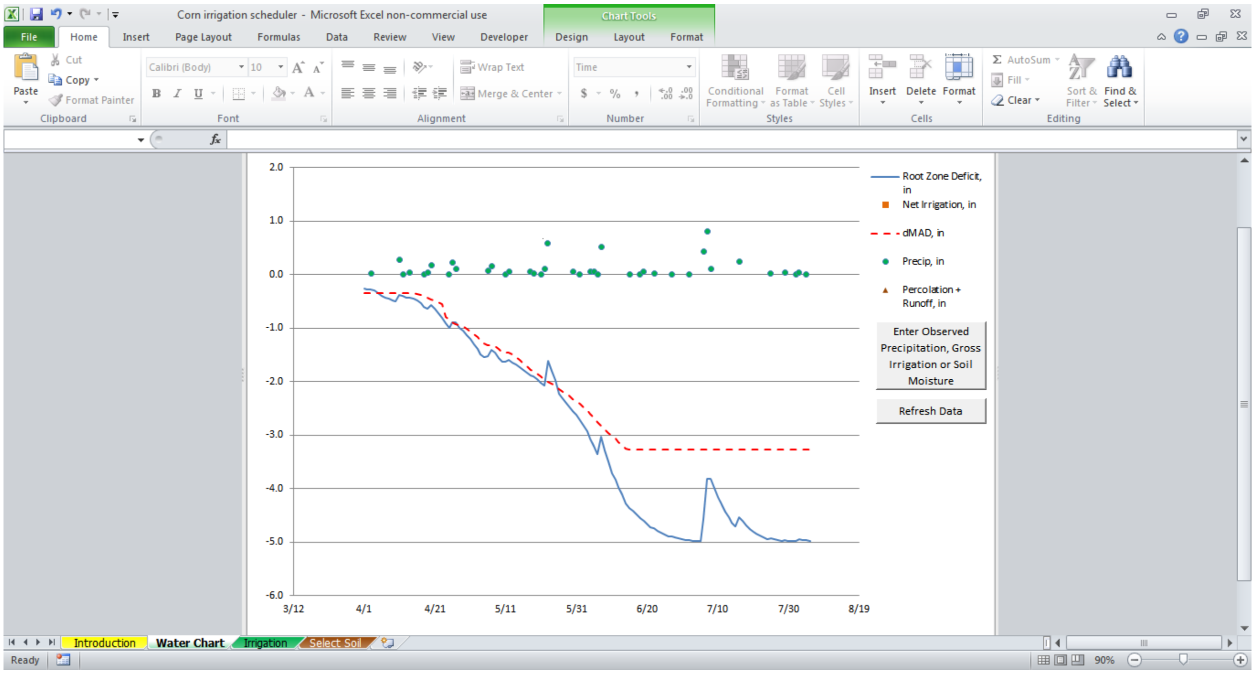


Figure IV.1: Default water chart before irrigation is entered

The Water Chart has two buttons: ‘Enter Observed Precipitation, Gross Irrigation or Soil Moisture’ and ‘Refresh Data’.

A. Enter Observed Precipitation, Gross Irrigation or Soil Moisture

This button will launch a form where observed precipitation, gross irrigation and observed soil moisture can be entered for any date. An empty version of the 'Irrigation Scheduler' form is shown below in Figure IV.1.A. This form has a list box containing the dates when irrigation could be applied, a multi-tab box where observed precipitation, gross irrigation and soil moisture can be entered and 'Input' and 'Quit' buttons. These features are described below.

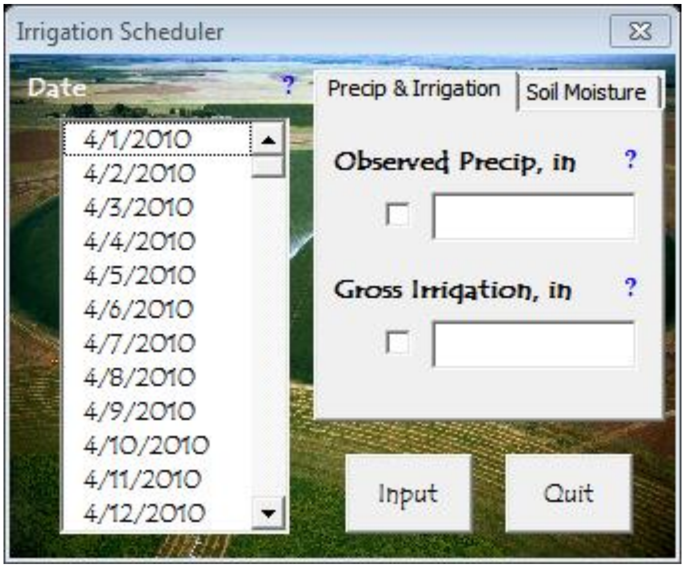


Figure IV.1.A: The 'Irrigation Scheduler' form

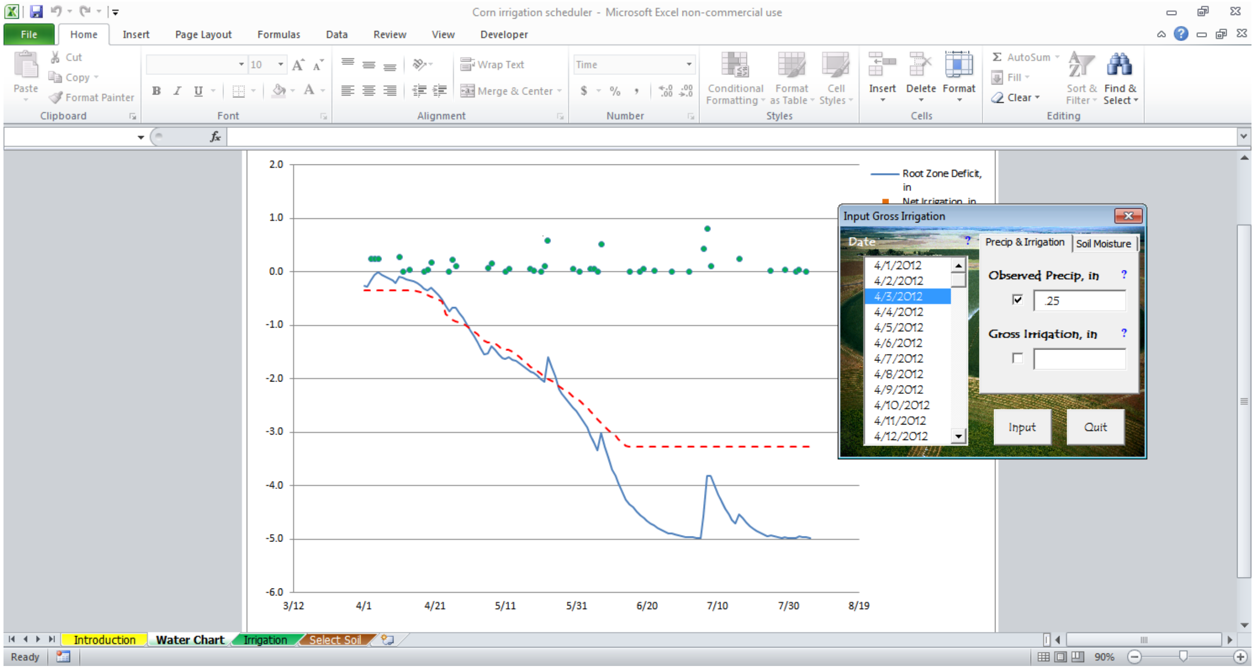
Dates

The form allows the user to enter data for any single date or for several dates at once where the same gross Irrigation, precipitation or soil moisture were observed. Click on the date to select it. Clicking on a selected date will unselect the date.

Observed Precipitation

If the precipitation at your field differs from the precipitation at the CoAgMet station where weather data was selected, the measured precipitation can be entered in the Observed Precipitation Box. To enter the observed precipitation click the check box, under the Observed Precipitation label and enter the observed value in the box. Then click ‘Input’ as shown below in Figure IV.1.Ai. Each time ‘Input’ is clicked all selected and entered fields will be cleared, so that the form is ready for more information to be entered.

There is no graphical difference between observed precipitation and downloaded precipitation from CoAgMet, but the observed precipitation will override the CoAgMet precipitation value.



Observed Precip, in ☑ 25

Gross Irrigation, in ☐

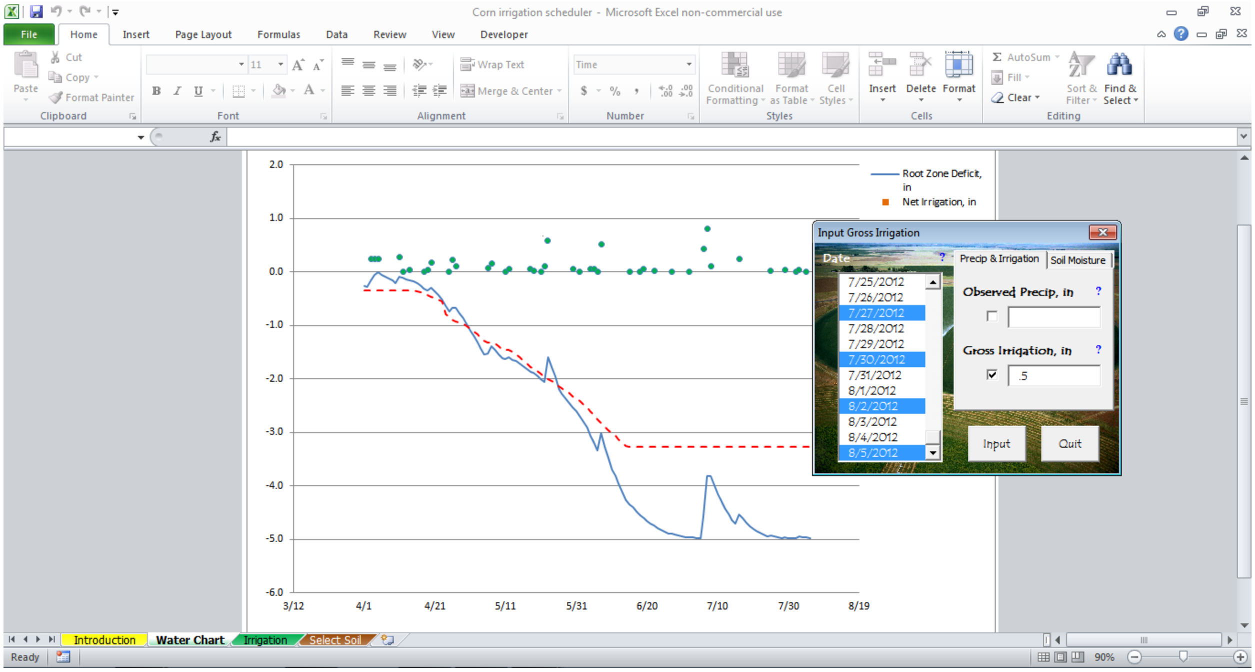
Figure IV.1.Ai: Entering Observed Precipitation

Gross Irrigation

Gross irrigation can be entered for each day separately or for several days at once if the same amount of gross irrigation is applied for each of the days. To enter gross irrigation values select the appropriate dates in the date list box, click the irrigation check box and enter the gross irrigation value (in inches) in the textbox under the Gross Irrigation label.

Click the Input button to enter the data.

Figure IV.1.Aii shows the irrigation form with 0.5 inch of gross irrigation applied every three days.



Input Gross Irrigation

Date: 7/25/2012, 7/26/2012, **7/27/2012**, 7/28/2012, 7/29/2012, **7/30/2012**, 7/31/2012, 8/1/2012, **8/2/2012**, 8/3/2012, 8/4/2012, **8/5/2012**

Precip & Irrigation | Soil Moisture

Observed Precip, in ☐

Gross Irrigation, in ☑ .5

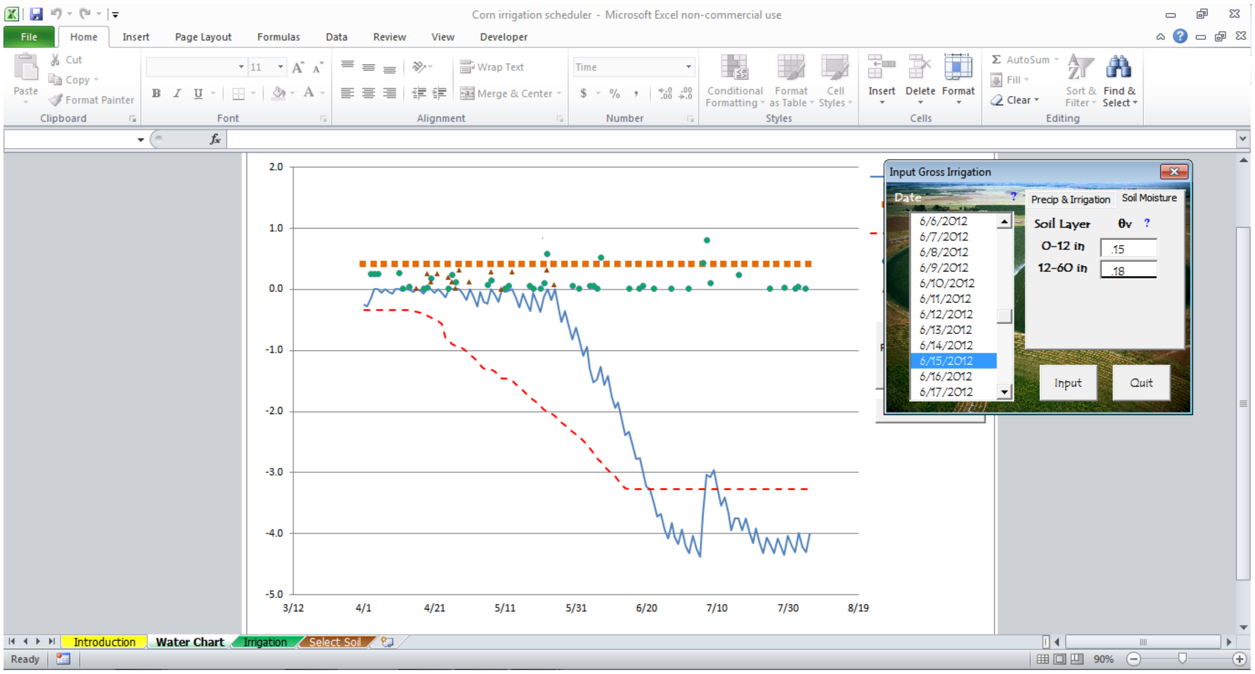
Input Quit

Figure IV.1.Aii: Entering Gross Irrigation with the form

Observed Soil Moisture

To enter observed soil moisture, select the soil moisture tab on the Input Gross Irrigation form. Select the date when the soil moisture measurements were made, enter the soil moisture content (θv) (inches of water per inch of soil), and click the ‘Input’ button.

Figure IV.1.Aiii shows the irrigation scheduler form filled out with some possible observed soil moisture contents.



Date: 6/6/2012, 6/7/2012, 6/8/2012, 6/9/2012, 6/10/2012, 6/11/2012, 6/12/2012, 6/13/2012, 6/14/2012, 6/15/2012, 6/16/2012, 6/17/2012

Soil Layer	θv
0-12 in	.15
12-60 in	.18

Figure IV.1.Aiii Entering Soil Moisture Content

Entering observed moisture content for a day will override the calculated deficit for that day.

Input Button

The Input button enters the observed precipitation and/or gross irrigation values that have been entered for the date(s) selected if the ‘Precip & Irrigation’ tab is selected. If the ‘Soil Moisture’ tab is selected then only the soil moisture data will be entered for the selected day(s).

Each time the Input button is clicked, the daily deficit is calculated for each soil layer, the graph is updated, and the irrigation form is reset.

Quit Button

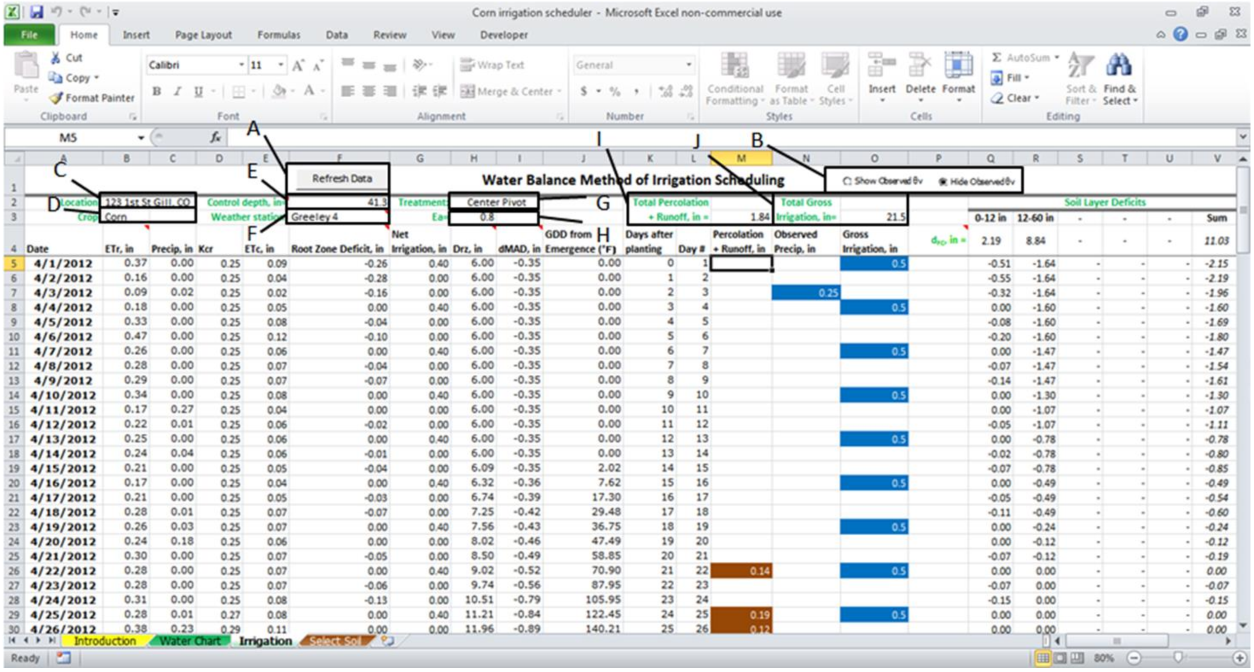
Use either the Quit button or the “x” on the Irrigation form to stop entering data using the irrigation form when finished.

B. Refresh Data

The refresh data button on the Water Chart Page will query CoAgMet for the most recent weather data, usually up to one day old. Any missing data that was entered before will need to be entered again. See Appendix B.2 Missing Data for more information about missing weather data.

2. The Spreadsheet Method

The spreadsheet method uses the 'Irrigation' Sheet. The Irrigation sheet shows numerical values for Date, ETr, Precip, Kcr, ETc, Root Zone Deficit, Net Irrigation, Drz, dMAD, GDD from Emergence (°F), Days after planting, Day #, Percolation + Runoff, Observed Precip, Gross Irrigation, and deficits for each layer for every day. All depths are in inches. Figure IV.2 shows the Irrigation sheet with the data that was entered above using the Graphical Method.



Water Balance Method of Irrigation Scheduling

○ Show Observed θv ● Hide Observed θv

Location: 123 1st St Gill, CO
Crop: Corn
Control depth, in= 41.3
Weather station: Greeley 4
Treatment: Center Pivot
Ea= 0.8
Total Percolation + Runoff, in = 1.84
Total Gross Irrigation, in= 21.5

	Date	ETr, in	Precip, in	Kcr	ETc, in	Root Zone Deficit, in	Net Irrigation, in	Drz, in	dMAD, in	GDD from Emergence (°F)	Days after planting	Day #	Percolation + Runoff, in	Observed Precip, in	Gross Irrigation, in		Soil Layer Deficits 0-12 in	12-60 in	-	-	-	Sum
4																d_{FC}, in =	2.19	8.84	-	-	-	11.03
5	4/1/2012	0.37	0.00	0.25	0.09	-0.26	0.40	6.00	-0.35	0.00	0	1			0.5		-0.51	-1.64	-	-	-	-2.15
6	4/2/2012	0.16	0.00	0.25	0.04	-0.28	0.00	6.00	-0.35	0.00	1	2					-0.55	-1.64	-	-	-	-2.19
7	4/3/2012	0.09	0.02	0.25	0.02	-0.16	0.00	6.00	-0.35	0.00	2	3		0.25			-0.32	-1.64	-	-	-	-1.96
8	4/4/2012	0.18	0.00	0.25	0.05	0.00	0.40	6.00	-0.35	0.00	3	4			0.5		0.00	-1.60	-	-	-	-1.60
9	4/5/2012	0.33	0.00	0.25	0.08	-0.04	0.00	6.00	-0.35	0.00	4	5					-0.08	-1.60	-	-	-	-1.69
10	4/6/2012	0.47	0.00	0.25	0.12	-0.10	0.00	6.00	-0.35	0.00	5	6					-0.20	-1.60	-	-	-	-1.80
11	4/7/2012	0.26	0.00	0.25	0.06	0.00	0.40	6.00	-0.35	0.00	6	7			0.5		0.00	-1.47	-	-	-	-1.47
12	4/8/2012	0.28	0.00	0.25	0.07	-0.04	0.00	6.00	-0.35	0.00	7	8					-0.07	-1.47	-	-	-	-1.54
13	4/9/2012	0.29	0.00	0.25	0.07	-0.07	0.00	6.00	-0.35	0.00	8	9					-0.14	-1.47	-	-	-	-1.61
14	4/10/2012	0.34	0.00	0.25	0.08	0.00	0.40	6.00	-0.35	0.00	9	10			0.5		0.00	-1.30	-	-	-	-1.30
15	4/11/2012	0.17	0.27	0.25	0.04	0.00	0.00	6.00	-0.35	0.00	10	11					0.00	-1.07	-	-	-	-1.07
16	4/12/2012	0.22	0.01	0.25	0.06	-0.02	0.00	6.00	-0.35	0.00	11	12					-0.05	-1.07	-	-	-	-1.11
17	4/13/2012	0.25	0.00	0.25	0.06	0.00	0.40	6.00	-0.35	0.00	12	13			0.5		0.00	-0.78	-	-	-	-0.78
18	4/14/2012	0.24	0.04	0.25	0.06	-0.01	0.00	6.00	-0.35	0.00	13	14					-0.02	-0.78	-	-	-	-0.80
19	4/15/2012	0.21	0.00	0.25	0.05	-0.04	0.00	6.09	-0.35	2.02	14	15					-0.07	-0.78	-	-	-	-0.85
20	4/16/2012	0.17	0.00	0.25	0.04	0.00	0.40	6.32	-0.36	7.62	15	16			0.5		0.00	-0.49	-	-	-	-0.49
21	4/17/2012	0.21	0.00	0.25	0.05	-0.03	0.00	6.74	-0.39	17.30	16	17					-0.05	-0.49	-	-	-	-0.54
22	4/18/2012	0.28	0.01	0.25	0.07	-0.07	0.00	7.25	-0.42	29.48	17	18					-0.11	-0.49	-	-	-	-0.60
23	4/19/2012	0.26	0.03	0.25	0.07	0.00	0.40	7.56	-0.43	36.75	18	19			0.5		0.00	-0.24	-	-	-	-0.24
24	4/20/2012	0.24	0.18	0.25	0.06	0.00	0.00	8.02	-0.46	47.49	19	20					0.00	-0.12	-	-	-	-0.12
25	4/21/2012	0.30	0.00	0.25	0.07	-0.05	0.00	8.50	-0.49	58.85	20	21					-0.07	-0.12	-	-	-	-0.19
26	4/22/2012	0.28	0.00	0.25	0.07	0.00	0.40	9.02	-0.52	70.90	21	22	0.14		0.5		0.00	0.00	-	-	-	0.00
27	4/23/2012	0.28	0.00	0.25	0.07	-0.06	0.00	9.74	-0.56	87.95	22	23					-0.07	0.00	-	-	-	-0.07
28	4/24/2012	0.31	0.00	0.25	0.08	-0.13	0.00	10.51	-0.79	105.95	23	24					-0.15	0.00	-	-	-	-0.15
29	4/25/2012	0.28	0.01	0.27	0.08	0.00	0.40	11.21	-0.84	122.45	24	25	0.19		0.5		0.00	0.00	-	-	-	0.00
30	4/26/2012	0.38	0.23	0.29	0.11	0.00	0.00	11.96	-0.89	140.21	25	26	0.12				0.00	0.00	-	-	-	0.00

Figure IV.2 Filled out Irrigation sheet, labeled fields are discussed below

The Irrigation sheet contains several editable fields and gives the ability to change values that were edited with either the 'CoAgMet and Farm Information' form or the 'Irrigation Scheduler' form.

All of the Crop and Farm information fields should be already filled out; however they can be changed on this page as necessary. A summary of each of these fields follows:

A. Refresh Data

The 'Refresh Data' button will get the most recent weather data from CoAgMet using the date shown in cell 'A5' as the plant date and the weather station in cell 'F3'. This will get up to one day old weather data. Any observed precipitation, gross irrigations, soil moistures or LAI values that have been entered will be saved, but if CoAgMet had missing data for your station, that missing data will need to be filled in or will be read from the 'EYO Data' sheet. See Appendix A.2 Missing Data for more information about missing data in CoAgMet.

B. Show/Hide Observed θv

The show / hide observed θv buttons show or hide columns that allow the user to enter soil moisture measurements for the soil layers specified on the 'Select Soil' sheet as shown in Figure IV.2.B. When a soil moisture value is entered the soil layer deficits will be automatically updated.

Column "W" contains the stress coefficient (Ks) that is calculated for the root-zone by the root-zone deficit algorithm. In general Ks is calculated as follows:

$$Ks = \frac{TAW - |D|}{(1 - MAD) * TAW}$$

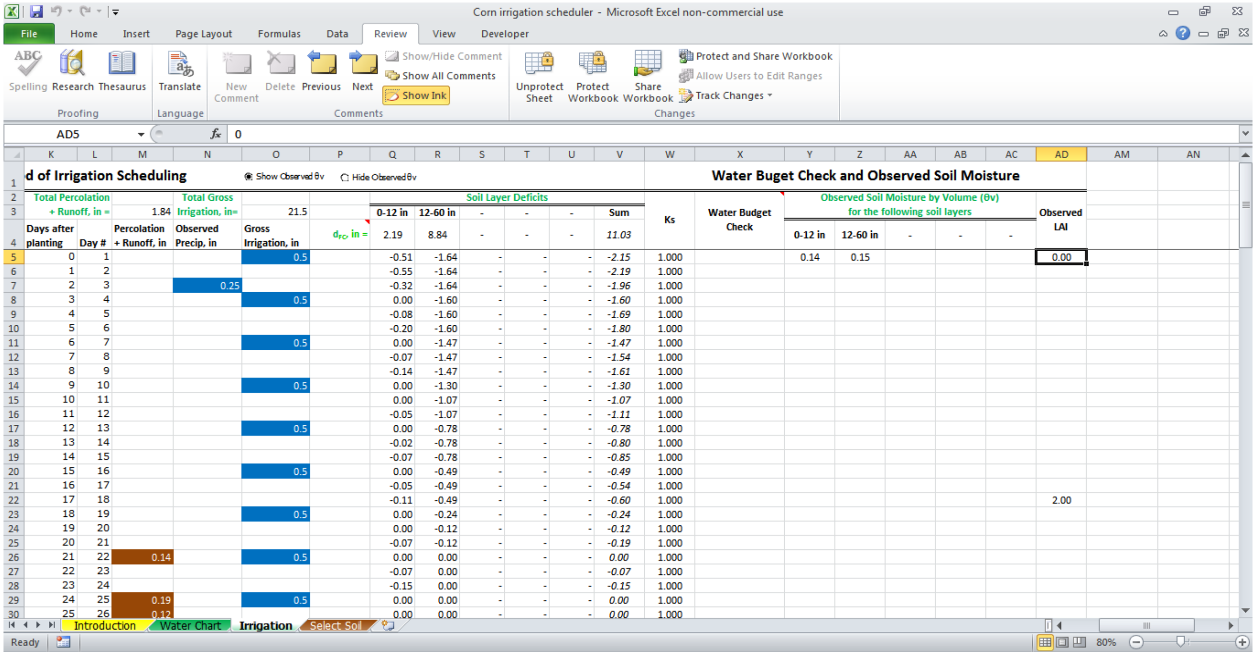
Where,

TAW is the total available water capacity in the root-zone (inches)
D is the root-zone deficit (inches)
MAD is the management allowable depletion, presented as a fraction of the available water content

Column "X" contains a daily water budget check. If the water did not balance then "False" will be displayed in the respective row of column "X", the water budget reading false when soil moisture values are entered indicates that the measured deficit differed from the calculated deficit by at least ±0.0001 in. The following water balance was used:

$$\Delta Total\ Deficit = Net\ Irrigation + Precip - ETc * Ks - (Percolation + Runoff)$$

Column “AD” contains the Observed LAI (leaf area index). The LAI is the ratio of total leaf area (one side only) and ground area. This is an advanced feature that allows the user to check the accuracy of the crop coefficient cutoffs and values used against the shape of the LAI curve. A graph of the LAI vs the Kcr is provided in the Analysis Pages. See section V.2 LAI for more information.



	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AM	AN
1	d of Irrigation Scheduling			◉ Show Observed θv		○ Hide Observed θv								Water Buget Check and Observed Soil Moisture								
2	Total Percolation			Total Gross					Soil Layer Deficits						Observed Soil Moisture by Volume (θv)							
3	+ Runoff, in =		1.84	Irrigation, in=	21.5		0-12 in	12-60 in	-	-	-	Sum	Ks	Water Budget Check	for the following soil layers					Observed LAI		
4	Days after planting	Day #	Percolation + Runoff, in	Observed Precip, in	Gross Irrigation, in	d_{FC}, in =	2.19	8.84	-	-	-	*11.03*			0-12 in	12-60 in	-	-	-			
5	0	1			0.5		-0.51	-1.64	-	-	-	*-2.15*	1.000		0.14	0.15				0.00		
6	1	2					-0.55	-1.64	-	-	-	*-2.19*	1.000									
7	2	3		0.25			-0.32	-1.64	-	-	-	*-1.96*	1.000									
8	3	4			0.5		0.00	-1.60	-	-	-	*-1.60*	1.000									
9	4	5					-0.08	-1.60	-	-	-	*-1.69*	1.000									
10	5	6					-0.20	-1.60	-	-	-	*-1.80*	1.000									
11	6	7			0.5		0.00	-1.47	-	-	-	*-1.47*	1.000									
12	7	8					-0.07	-1.47	-	-	-	*-1.54*	1.000									
13	8	9					-0.14	-1.47	-	-	-	*-1.61*	1.000									
14	9	10			0.5		0.00	-1.30	-	-	-	*-1.30*	1.000									
15	10	11					0.00	-1.07	-	-	-	*-1.07*	1.000									
16	11	12					-0.05	-1.07	-	-	-	*-1.11*	1.000									
17	12	13			0.5		0.00	-0.78	-	-	-	*-0.78*	1.000									
18	13	14					-0.02	-0.78	-	-	-	*-0.80*	1.000									
19	14	15					-0.07	-0.78	-	-	-	*-0.85*	1.000									
20	15	16			0.5		0.00	-0.49	-	-	-	*-0.49*	1.000									
21	16	17					-0.05	-0.49	-	-	-	*-0.54*	1.000									
22	17	18					-0.11	-0.49	-	-	-	*-0.60*	1.000							2.00		
23	18	19			0.5		0.00	-0.24	-	-	-	*-0.24*	1.000									
24	19	20					0.00	-0.12	-	-	-	*-0.12*	1.000									
25	20	21					-0.07	-0.12	-	-	-	*-0.19*	1.000									
26	21	22	0.14		0.5		0.00	0.00	-	-	-	*0.00*	1.000									
27	22	23					-0.07	0.00	-	-	-	*-0.07*	1.000									
28	23	24					-0.15	0.00	-	-	-	*-0.15*	1.000									
29	24	25	0.19		0.5		0.00	0.00	-	-	-	*0.00*	1.000									
30	25	26	0.12				0.00	0.00	-	-	-	*0.00*	1.000									

Figure IV.2.B Observed Soil Moisture, Ks, Water Budget Check, and Observed LAI columns

C. Location

The Location cell is for reference only, making it easier to differentiate between fields if irrigation scheduling is performed for several fields. The location will not be filled out by the ‘CoAgMet and Farm Information’ form, but can be entered on the ‘Irrigation’ sheet if desired.

D. Crop

The crop shown here is the crop that was selected on the ‘CoAgMet and Farm Information’ form. Changing the crop here will not change the crop parameters that are used by the CIS. The control depth can be changed on the ‘Irrigation sheet’. For information on how to change GDD cutoffs, Kcr levels, MAD levels, temperature cutoffs, or emergence date see Section V.4 Kcr.

E. Control Depth, in

The control depth is used for calculated and observed total soil water deficits, also known as the maximum rooting depth. The root-zone for annual crops will increase as it accumulates GDD’s until it reaches this value. When the control depth is changed on the Irrigation sheet, the soil layer deficits will automatically be recalculated.

F. Weather Station

The CoAgMet station that was selected on the ‘CoAgMet and Farm Information’ form is shown here. The comment in cell “F3” shows the information for the selected station.

Cell “F3” contains a drop down menu with all of the available CoAgMet weather stations allowing the user to change weather stations as necessary. If a station is selected that has a last observed date before the plant date an error messaged will be displayed. The weather data will be updated to a newly selected station when the ‘Refresh Data’ button is clicked.

G. Treatment

The treatment is the irrigation method used. A few standard irrigation treatments are listed in a drop down menu when cell “H2” is clicked. Selecting one of these default irrigation treatments will automatically update the Ea for the selected Irrigation treatment and recalculate the Soil Layer Deficits.

H. Ea

The irrigation application efficiency (Ea) is the ratio of the Net Irrigation to the Gross Irrigation. In other words, Ea is the fraction of the gross applied irrigation that gets stored in the root zone. Applied irrigation that is not stored in the root zone is assumed to be lost via surface runoff and/or deep percolation. When the Ea is changed on the Irrigation sheet, the Soil Layer Deficits will automatically be recalculated.

I. Total Percolation + Runoff

The CIS assumes that any net irrigation or precipitation that exceeds the current total soil deficit will either runoff or percolate. The total percolation + runoff is the sum of these daily runoff or percolation values over the course of the growing season to date. Percolation and runoff are usually caused by over irrigation, but can also be caused by a large precipitation event.

J. Total Gross Irrigation

The total gross irrigation applied over the growing season to date is recorded in cell “O3” for reference.

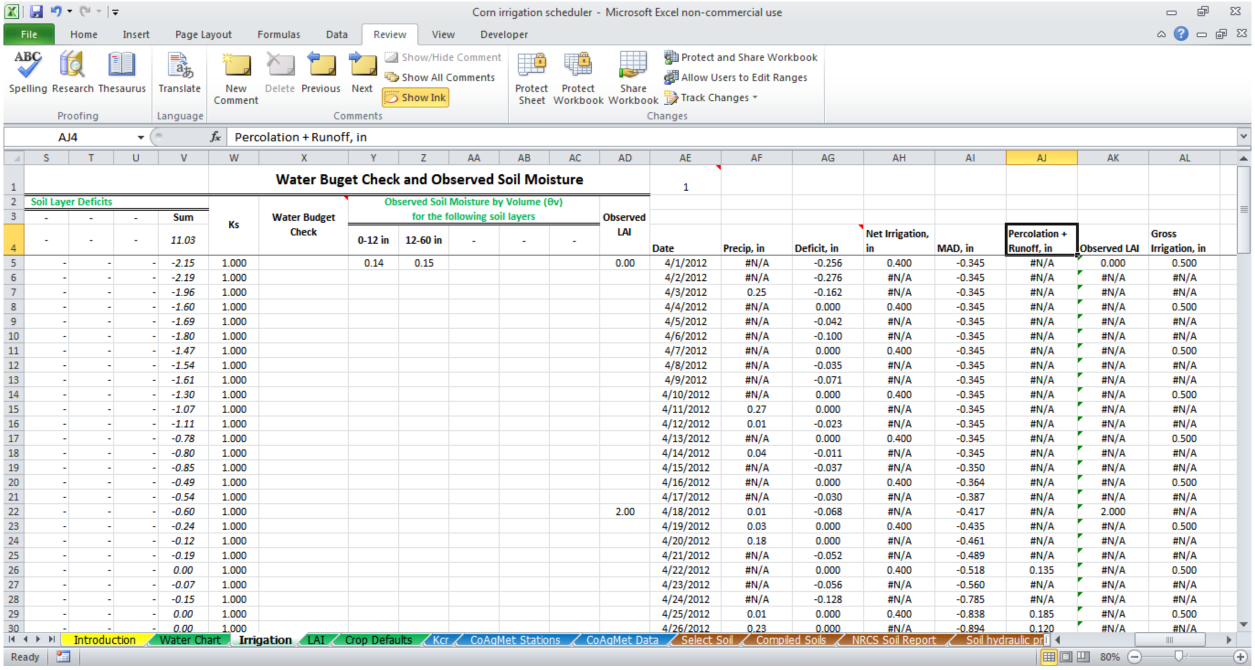
V. Analysis Pages

The Colorado Irrigation Scheduler uses several background analysis pages to store information that was queried from the NRCS Web Soil Survey and from CoAgMet and to perform calculations on this data. The user should not need to use these sheets, but they are described below for completeness.

These pages can be made visible with the ‘Show/Hide Analysis’ option buttons on the ‘Introduction’ sheet or the option buttons on the ‘Select Soil’ sheet. These sheets are described below.

1. Irrigation

Although the ‘Irrigation’ sheet is visible, columns AE:AL are hidden. These columns de-clutter the Water Chart by excluding zero values for precipitation, net irrigation and percolation + runoff points. For information about columns “X:AD” see Chapter IV.2.B Show/Hide Observed θv. The ‘Irrigation’ sheet with analysis columns unhidden is shown in Figure V.1 below.



AJ4 *fx* Percolation + Runoff, in

	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL
1					**Water Buget Check and Observed Soil Moisture**								1							
2	Soil Layer Deficits						Observed Soil Moisture by Volume (θv) for the following soil layers													
3	-	-	-	Sum	Ks	Water Budget Check						Observed LAI								
4	-	-	-	*11.03*			0-12 in	12-60 in	-	-	-		Date	Precip, in	Deficit, in	Net Irrigation, in	MAD, in	Percolation + Runoff, in	Observed LAI	Gross Irrigation, in
5	-	-	-	*-2.15*	1.000		0.14	0.15				0.00	4/1/2012	#N/A	-0.256	0.400	-0.345	#N/A	0.000	0.500
6	-	-	-	*-2.19*	1.000								4/2/2012	#N/A	-0.276	#N/A	-0.345	#N/A	#N/A	#N/A
7	-	-	-	*-1.96*	1.000								4/3/2012	0.25	-0.162	#N/A	-0.345	#N/A	#N/A	#N/A
8	-	-	-	*-1.60*	1.000								4/4/2012	#N/A	0.000	0.400	-0.345	#N/A	#N/A	0.500
9	-	-	-	*-1.69*	1.000								4/5/2012	#N/A	-0.042	#N/A	-0.345	#N/A	#N/A	#N/A
10	-	-	-	*-1.80*	1.000								4/6/2012	#N/A	-0.100	#N/A	-0.345	#N/A	#N/A	#N/A
11	-	-	-	*-1.47*	1.000								4/7/2012	#N/A	0.000	0.400	-0.345	#N/A	#N/A	0.500
12	-	-	-	*-1.54*	1.000								4/8/2012	#N/A	-0.035	#N/A	-0.345	#N/A	#N/A	#N/A
13	-	-	-	*-1.61*	1.000								4/9/2012	#N/A	-0.071	#N/A	-0.345	#N/A	#N/A	#N/A
14	-	-	-	*-1.30*	1.000								4/10/2012	#N/A	0.000	0.400	-0.345	#N/A	#N/A	0.500
15	-	-	-	*-1.07*	1.000								4/11/2012	0.27	0.000	#N/A	-0.345	#N/A	#N/A	#N/A
16	-	-	-	*-1.11*	1.000								4/12/2012	0.01	-0.023	#N/A	-0.345	#N/A	#N/A	#N/A
17	-	-	-	*-0.78*	1.000								4/13/2012	#N/A	0.000	0.400	-0.345	#N/A	#N/A	0.500
18	-	-	-	*-0.80*	1.000								4/14/2012	0.04	-0.011	#N/A	-0.345	#N/A	#N/A	#N/A
19	-	-	-	*-0.85*	1.000								4/15/2012	#N/A	-0.037	#N/A	-0.350	#N/A	#N/A	#N/A
20	-	-	-	*-0.49*	1.000								4/16/2012	#N/A	0.000	0.400	-0.364	#N/A	#N/A	0.500
21	-	-	-	*-0.54*	1.000								4/17/2012	#N/A	-0.030	#N/A	-0.387	#N/A	#N/A	#N/A
22	-	-	-	*-0.60*	1.000							2.00	4/18/2012	0.01	-0.068	#N/A	-0.417	#N/A	2.000	#N/A
23	-	-	-	*-0.24*	1.000								4/19/2012	0.03	0.000	0.400	-0.435	#N/A	#N/A	0.500
24	-	-	-	*-0.12*	1.000								4/20/2012	0.18	0.000	#N/A	-0.461	#N/A	#N/A	#N/A
25	-	-	-	*-0.19*	1.000								4/21/2012	#N/A	-0.052	#N/A	-0.489	#N/A	#N/A	#N/A
26	-	-	-	*0.00*	1.000								4/22/2012	#N/A	0.000	0.400	-0.518	0.135	#N/A	0.500
27	-	-	-	*-0.07*	1.000								4/23/2012	#N/A	-0.056	#N/A	-0.560	#N/A	#N/A	#N/A
28	-	-	-	*-0.15*	1.000								4/24/2012	#N/A	-0.128	#N/A	-0.785	#N/A	#N/A	#N/A
29	-	-	-	*0.00*	1.000								4/25/2012	0.01	0.000	0.400	-0.838	0.185	#N/A	0.500
30	-	-	-	*0.00*	1.000								4/26/2012	0.23	0.000	#N/A	-0.894	0.120	#N/A	#N/A

Figure V.1 Irrigation Sheet analysis columns

2. LAI

The ‘LAI’ sheet contains a graph that plots the leaf area indices entered on the ‘Irrigation’ sheet in column “AD” and the crop coefficient (Kc) curve. This can be used to evaluate the correctness of the shape of the crop coefficient curve, based on the fact that the Kc curve typically has a similar shape as the LAI curve. For information about entering LAI values see Chapter IV.2.B Show/Hide Observed θv. The LAI sheet with some LAI values entered is shown below in Figure V.2

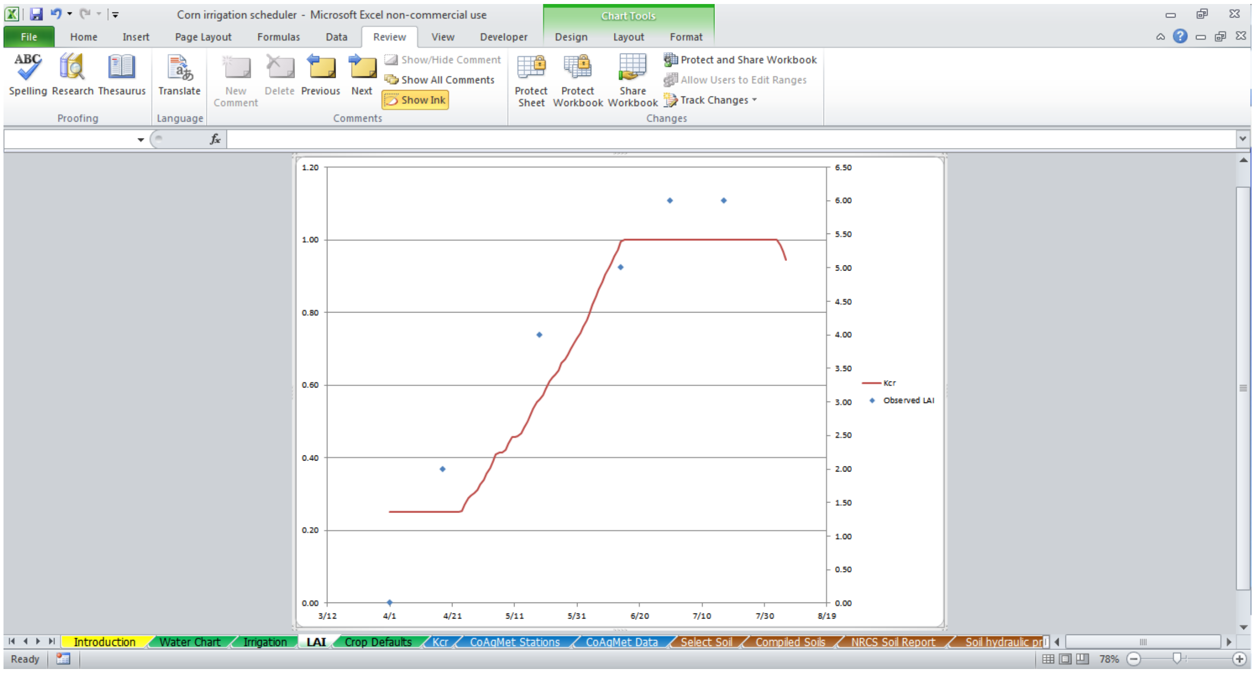
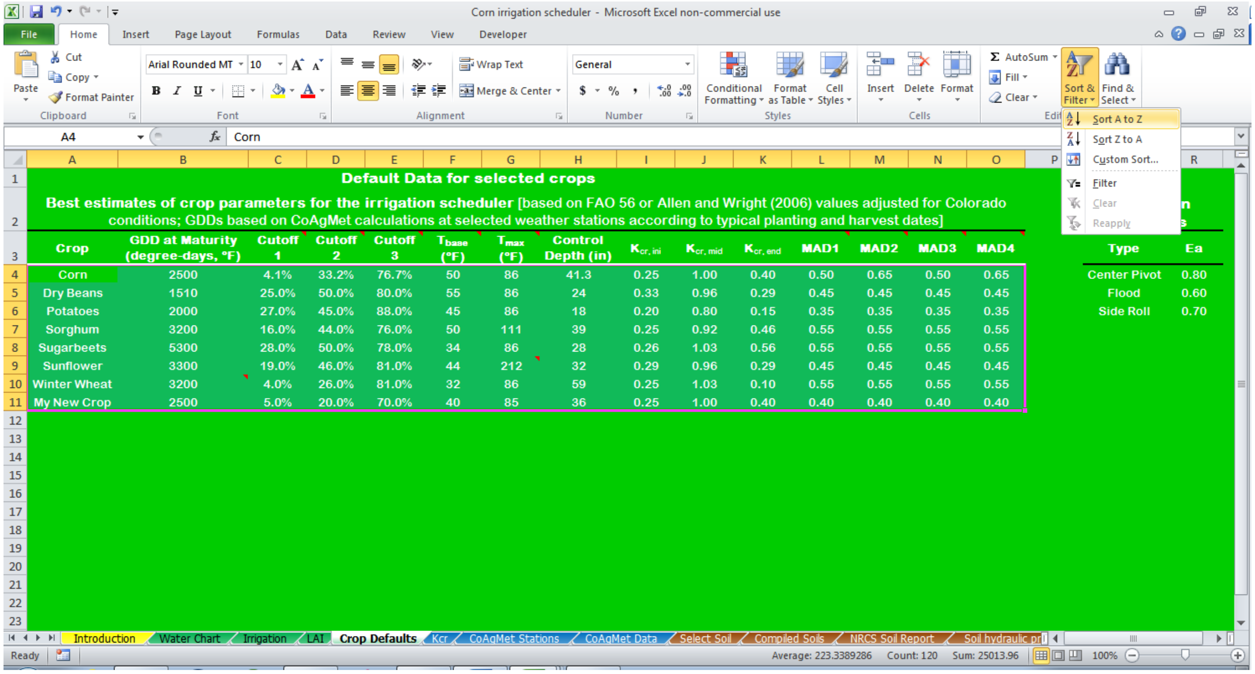


Figure V.2 LAI sheet

3. Crop Defaults

The ‘Crop Defaults’ sheet contains some default values for specified crops (in columns A:O) and default irrigation methods and efficiencies (in columns Q and R). Additional crops can be added by unprotecting the sheet (there is no password) and adding the new crop to the list with all of the required information. Do not skip a row when entering a new crop. To re-alphabetize the default crop list, highlight all of the crops and their parameters. Select the ‘Home’ ribbon and click on the ‘Sort & Filter’ then ‘Sort A to Z’ (see Figure V.3). New irrigation methods can be added in a similar way.



A4 Corn

Default Data for selected crops

Best estimates of crop parameters for the irrigation scheduler [based on FAO 56 or Allen and Wright (2006) values adjusted for Colorado conditions; GDDs based on CoAgMet calculations at selected weather stations according to typical planting and harvest dates]

Crop	GDD at Maturity (degree-days, °F)	Cutoff 1	Cutoff 2	Cutoff 3	T_{base} (°F)	T_{max} (°F)	Control Depth (in)	$K_{cr, ini}$	$K_{cr, mid}$	$K_{cr, end}$	MAD1	MAD2	MAD3	MAD4
Corn	2500	4.1%	33.2%	76.7%	50	86	41.3	0.25	1.00	0.40	0.50	0.65	0.50	0.65
Dry Beans	1510	25.0%	50.0%	80.0%	55	86	24	0.33	0.96	0.29	0.45	0.45	0.45	0.45
Potatoes	2000	27.0%	45.0%	88.0%	45	86	18	0.20	0.80	0.15	0.35	0.35	0.35	0.35
Sorghum	3200	16.0%	44.0%	76.0%	50	111	39	0.25	0.92	0.46	0.55	0.55	0.55	0.55
Sugarbeets	5300	28.0%	50.0%	78.0%	34	86	28	0.26	1.03	0.56	0.55	0.55	0.55	0.55
Sunflower	3300	19.0%	46.0%	81.0%	44	212	32	0.29	0.96	0.29	0.45	0.45	0.45	0.45
Winter Wheat	3200	4.0%	26.0%	81.0%	32	86	59	0.25	1.03	0.10	0.55	0.55	0.55	0.55
My New Crop	2500	5.0%	20.0%	70.0%	40	85	36	0.25	1.00	0.40	0.40	0.40	0.40	0.40

Type	Ea
Center Pivot	0.80
Flood	0.60
Side Roll	0.70

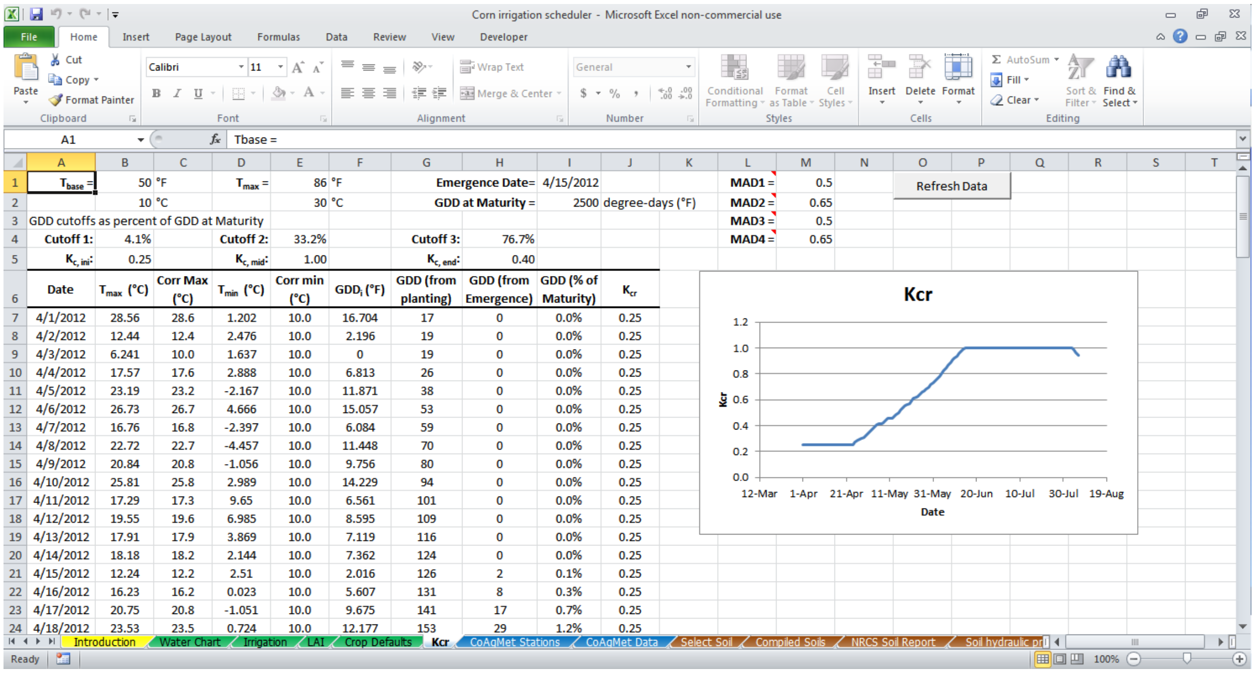
Figure V.3 Adding new default crops, and re-alphabetizing the crop default crop list

Once a new default crop is added it can be selected on the ‘CoAgMet and Farm Information’ form as described in Chapter III.

4. Kcr

The ‘Kcr’ sheet calculates the alfalfa-based crop coefficient for each day given the base temperature, max temperature, emergence date, GDD at maturity, MAD 1-4, Cutoff 1-3, Kcini, Kcmin and Kcend. These parameters were entered or verified with the ‘CoAgMet and Farm Information’ form. Any of these parameters can be changed on the Kcr sheet, but the changes will not come into effect until the ‘Refresh Data’ button is pressed on the Kcr sheet, the Irrigation sheet or the ‘Water Chart’ sheet.

The Kcr sheet also contains a graph of the calculated Kcr over time. See Figure V.4 below for a screen shot of the Kcr sheet.



Tbase =

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	T_{base} =	50	°F	T_{max} =	86	°F	Emergence Date=		4/15/2012			MAD1 =	0.5
2		10	°C		30	°C	GDD at Maturity =		2500	degree-days (°F)		MAD2 =	0.65
3	GDD cutoffs as percent of GDD at Maturity											MAD3 =	0.5
4	Cutoff 1:	4.1%		Cutoff 2:	33.2%		Cutoff 3:	76.7%				MAD4 =	0.65
5	$K_{c, ini}$:	0.25		$K_{c, mid}$:	1.00		$K_{c, end}$:	0.40					

6	Date	T_{max} (°C)	Corr Max (°C)	T_{min} (°C)	Corr min (°C)	GDD_i (°F)	GDD (from planting)	GDD (from Emergence)	GDD (% of Maturity)	K_{cr}
7	4/1/2012	28.56	28.6	1.202	10.0	16.704	17	0	0.0%	0.25
8	4/2/2012	12.44	12.4	2.476	10.0	2.196	19	0	0.0%	0.25
9	4/3/2012	6.241	10.0	1.637	10.0	0	19	0	0.0%	0.25
10	4/4/2012	17.57	17.6	2.888	10.0	6.813	26	0	0.0%	0.25
11	4/5/2012	23.19	23.2	-2.167	10.0	11.871	38	0	0.0%	0.25
12	4/6/2012	26.73	26.7	4.666	10.0	15.057	53	0	0.0%	0.25
13	4/7/2012	16.76	16.8	-2.397	10.0	6.084	59	0	0.0%	0.25
14	4/8/2012	22.72	22.7	-4.457	10.0	11.448	70	0	0.0%	0.25
15	4/9/2012	20.84	20.8	-1.056	10.0	9.756	80	0	0.0%	0.25
16	4/10/2012	25.81	25.8	2.989	10.0	14.229	94	0	0.0%	0.25
17	4/11/2012	17.29	17.3	9.65	10.0	6.561	101	0	0.0%	0.25
18	4/12/2012	19.55	19.6	6.985	10.0	8.595	109	0	0.0%	0.25
19	4/13/2012	17.91	17.9	3.869	10.0	7.119	116	0	0.0%	0.25
20	4/14/2012	18.18	18.2	2.144	10.0	7.362	124	0	0.0%	0.25
21	4/15/2012	12.24	12.2	2.51	10.0	2.016	126	2	0.1%	0.25
22	4/16/2012	16.23	16.2	0.023	10.0	5.607	131	8	0.3%	0.25
23	4/17/2012	20.75	20.8	-1.051	10.0	9.675	141	17	0.7%	0.25
24	4/18/2012	23.53	23.5	0.724	10.0	12.177	153	29	1.2%	0.25

Figure V.4 The Kcr page with example data for Corn

5. CoAgMet Stations

The ‘CoAgMet Stations’ sheet contains a list of all of the available CoAgMet stations and their location, latitude, longitude, elevation, first observed and last observed data. This list is updated when the ‘CoAgMet and Farm Information’ form is launched (by pressing the ‘Set Up Farm Using data from CoAgMet’ button on the ‘Introduction’ sheet).

6. CoAgMet Data

The ‘CoAgMet Data’ sheet contains the data that was most recently queried from CoAgMet in columns “A: G”. The etr_asce and the pp is in millimeters, columns “I:K” converts these values into inches and the date into the format used by the CIS.

7. Soil hydraulic properties

The ‘Soil hydraulic properties’ sheet contains a spreadsheet model (Ahuja et al., 1989; Brooks and Corey, 1964) that estimates the field capacity as well as other soil parameters from the percentage of sand and clay in the soil and the soil bulk density. This sheet is used to estimate the field capacity of different soils, from the information queried from the NRCS Web Soil Survey (the available water content given by the WSS is used instead of the AWC predicted by this spreadsheet model).

This model could also be used to estimate Available Water (in/in) (shown as Q_{AW}) and Field Capacity (in/in) (shown as Q_{FC}) on the ‘Select Soil’ sheet if the NRCS WSS will not be used.

8. Compiled Soils

The Compiled Soils sheet contains all of the soil properties that are used to calculate the soil available water capacity (AWC) and the Field Capacity (FC) for each of the soil types provided by the NRCS WSS. The soil survey provides the soil layer depths, available water content, percentage of sand, silt and clay in each layer, moist bulk density and several other soil parameters. The soil layer depths and an average of the available water content are used directly from the NRCS Web Soil Survey. Then the field capacity is estimated with a spreadsheet model developed by Allan Andales that uses the sand and clay percentage and the moist bulk density of each layer (Brooks and Corey, 1964; Ahuja et al., 1989). For more information see Chapter V.7 Soil hydraulic properties.

9. NRCS Soil Report

The ‘NRCS Soil Report’ sheet contains the WSS report as it was copied into Excel. This data was used to compile the ‘Compiled Soils’ sheet.

10. Map Data

The Map Data sheet shows the breakdown of the soil types, their acreage and the percent of the field that they cover. This data was copied from the NRCS Web Soil Survey. The drop down menu on the ‘Select Soil’ sheet references this page.

Index

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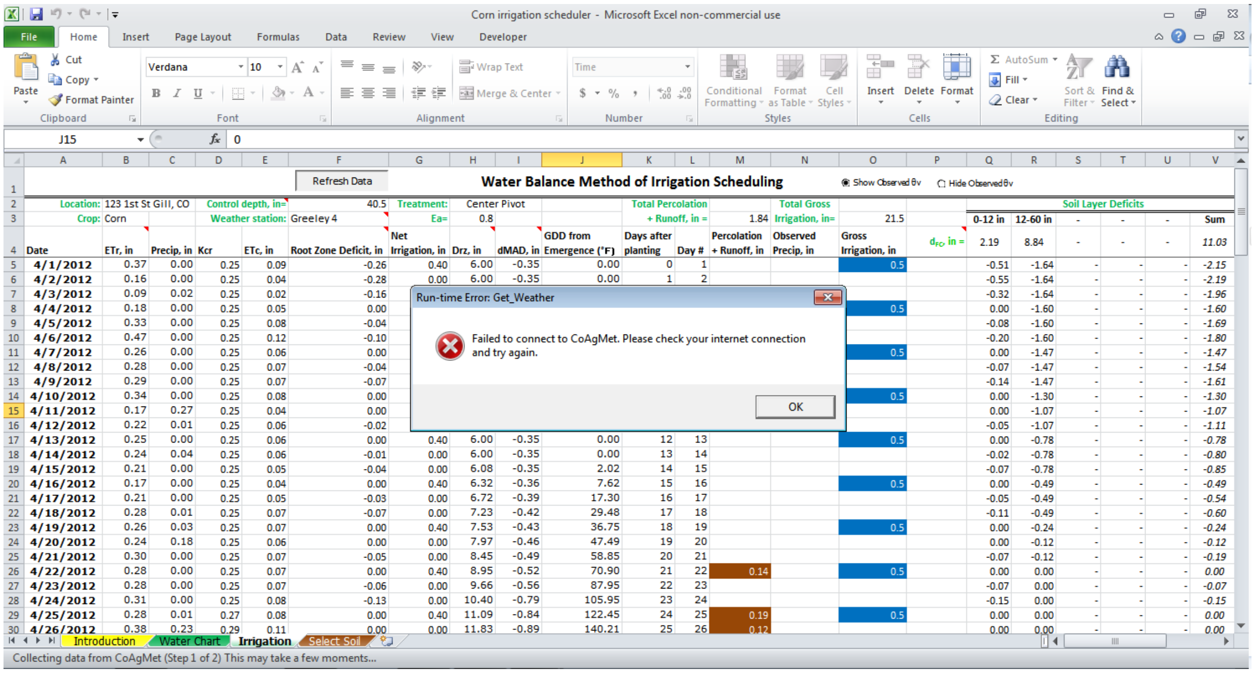
Appendix A: Common Errors

1. Internet Connection Problems

The most common errors that occur are related to internet connection problems. If the 'Refresh Data' button or the ' Set Up Farm Using data from CoAgMet' button is pressed without an internet connection an error similar to Figure App A.1 will likely appear.



J15 0

Water Balance Method of Irrigation Scheduling

Location: 123 1st St Gill, CO
Control depth, in= 40.5
Treatment: Center Pivot
Total Percolation + Runoff, in = 1.84
Total Gross Irrigation, in= 21.5
Crop: Corn
Weather station: Greeley 4
Ea= 0.8

Date	ETr, in	Precip, in	Kcr	ETc, in	Root Zone Deficit, in	Net Irrigation, in	Drz, in	dMAD, in	GDD from Emergence (°F)	Days after planting	Day #	Percolation + Runoff, in	Observed Precip, in	Gross Irrigation, in		Soil Layer Deficits 0-12 in	12-60 in	-	-	-	Sum
															d_{FC}, in =	2.19	8.84	-	-	-	11.03
4/1/2012	0.37	0.00	0.25	0.09	-0.26	0.40	6.00	-0.35	0.00	0	1			0.5		-0.51	-1.64	-	-	-	-2.15
4/2/2012	0.16	0.00	0.25	0.04	-0.28	0.00	6.00	-0.35	0.00	1	2					-0.55	-1.64	-	-	-	-2.19
4/3/2012	0.09	0.02	0.25	0.02	-0.16											-0.32	-1.64	-	-	-	-1.96
4/4/2012	0.18	0.00	0.25	0.05	0.00									0.5		0.00	-1.60	-	-	-	-1.60
4/5/2012	0.33	0.00	0.25	0.08	-0.04											-0.08	-1.60	-	-	-	-1.69
4/6/2012	0.47	0.00	0.25	0.12	-0.10											-0.20	-1.60	-	-	-	-1.80
4/7/2012	0.26	0.00	0.25	0.06	0.00									0.5		0.00	-1.47	-	-	-	-1.47
4/8/2012	0.28	0.00	0.25	0.07	-0.04											-0.07	-1.47	-	-	-	-1.54
4/9/2012	0.29	0.00	0.25	0.07	-0.07											-0.14	-1.47	-	-	-	-1.61
4/10/2012	0.34	0.00	0.25	0.08	0.00									0.5		0.00	-1.30	-	-	-	-1.30
4/11/2012	0.17	0.27	0.25	0.04	0.00											0.00	-1.07	-	-	-	-1.07
4/12/2012	0.22	0.01	0.25	0.06	-0.02											-0.05	-1.07	-	-	-	-1.11
4/13/2012	0.25	0.00	0.25	0.06	0.00	0.40	6.00	-0.35	0.00	12	13			0.5		0.00	-0.78	-	-	-	-0.78
4/14/2012	0.24	0.04	0.25	0.06	-0.01	0.00	6.00	-0.35	0.00	13	14					-0.02	-0.78	-	-	-	-0.80
4/15/2012	0.21	0.00	0.25	0.05	-0.04	0.00	6.08	-0.35	2.02	14	15					-0.07	-0.78	-	-	-	-0.85
4/16/2012	0.17	0.00	0.25	0.04	0.00	0.40	6.32	-0.36	7.62	15	16			0.5		0.00	-0.49	-	-	-	-0.49
4/17/2012	0.21	0.00	0.25	0.05	-0.03	0.00	6.72	-0.39	17.30	16	17					-0.05	-0.49	-	-	-	-0.54
4/18/2012	0.28	0.01	0.25	0.07	-0.07	0.00	7.23	-0.42	29.48	17	18					-0.11	-0.49	-	-	-	-0.60
4/19/2012	0.26	0.03	0.25	0.07	0.00	0.40	7.53	-0.43	36.75	18	19			0.5		0.00	-0.24	-	-	-	-0.24
4/20/2012	0.24	0.18	0.25	0.06	0.00	0.00	7.97	-0.46	47.49	19	20					0.00	-0.12	-	-	-	-0.12
4/21/2012	0.30	0.00	0.25	0.07	-0.05	0.00	8.45	-0.49	58.85	20	21					-0.07	-0.12	-	-	-	-0.19
4/22/2012	0.28	0.00	0.25	0.07	0.00	0.40	8.95	-0.52	70.90	21	22	0.14		0.5		0.00	0.00	-	-	-	0.00
4/23/2012	0.28	0.00	0.25	0.07	-0.06	0.00	9.66	-0.56	87.95	22	23					-0.07	0.00	-	-	-	-0.07
4/24/2012	0.31	0.00	0.25	0.08	-0.13	0.00	10.40	-0.79	105.95	23	24					-0.15	0.00	-	-	-	-0.15
4/25/2012	0.28	0.01	0.27	0.08	0.00	0.40	11.09	-0.84	122.45	24	25	0.19		0.5		0.00	0.00	-	-	-	0.00
4/26/2012	0.38	0.23	0.29	0.11	0.00	0.00	11.83	-0.89	140.21	25	26	0.12				0.00	0.00	-	-	-	0.00

Run-time Error: Get_Weather

Failed to connect to CoAgMet. Please check your internet connection and try again.

Collecting data from CoAgMet (Step 1 of 2) This may take a few moments...

Figure App A.1 Internet Connection Error

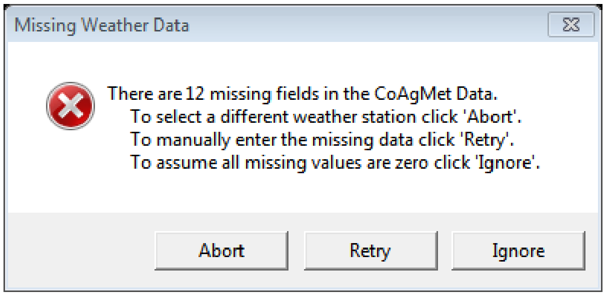
If this occurs, open your default internet browser, check that a website will load, close the browser and try again.

If no website will load try the following

1. Ensure that your computer has an active internet connection
2. Reset your internet modem and/or wireless router
3. Contact your internet provider

2. Missing Data

Sometimes CoAgMet stations go down and weather data is missing. If this occurs you will be prompted with an error message like the one shown in Figure A.2i below.



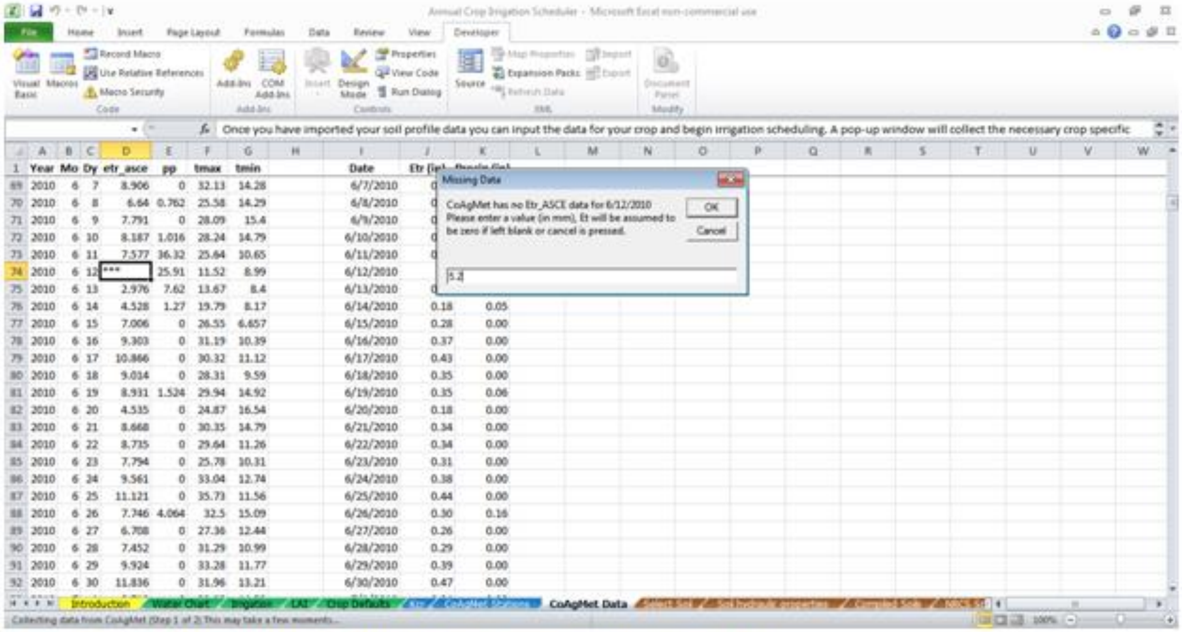
There are 12 missing fields in the CoAgMet Data.
To select a different weather station click 'Abort'.
To manually enter the missing data click 'Retry'.
To assume all missing values are zero click 'Ignore'.

Figure App A.2i: Missing Weather Data error message

Clicking 'Abort' will stop Excel from running analysis on the current weather data and return the user to the 'CoAgMet and Farm Information' form or the 'Irrigation' sheet (depending on what prompted the error).

Clicking 'Retry' allows the user to enter a value for each of the missing fields manually. This will select the 'CoAgMet Data' sheet and provide an input box for each missing field. An alternative is to fill missing data using the 'EYO Data' sheet. *Notice that Etr and precip values need to be entered in millimeters and maximum and minimum temperatures need to be entered in degrees Celsius.* See Figure A.2ii below for an example. Once all the missing values are entered the weather data will finish compiling.

Clicking 'Ignore' will replace all missing data value with zero. This neglects any Et or precip that occurred and any GDDs that may have accumulated, respectively, on the day with missing data.



Once you have imported your soil profile data you can input the data for your crop and begin irrigation scheduling. A pop-up window will collect the necessary crop specific

	Year	Mo	Dy	etr_asce	pp	tmax	tmin	Date	Etr (in)	Precip (in)
69	2010	6	7	8.906	0	32.13	14.28	6/7/2010		
70	2010	6	8	6.64	0.762	25.58	14.29	6/8/2010		
71	2010	6	9	7.791	0	28.09	15.4	6/9/2010		
72	2010	6	10	8.187	1.016	28.24	14.79	6/10/2010		
73	2010	6	11	7.577	36.32	25.64	10.65	6/11/2010		
74	2010	6	12	***	25.91	11.52	8.99	6/12/2010		
75	2010	6	13	2.976	7.62	13.67	8.4	6/13/2010		
76	2010	6	14	4.528	1.27	19.79	8.17	6/14/2010	0.18	0.05
77	2010	6	15	7.006	0	26.55	6.657	6/15/2010	0.28	0.00
78	2010	6	16	9.303	0	31.19	10.39	6/16/2010	0.37	0.00
79	2010	6	17	10.866	0	30.32	11.12	6/17/2010	0.43	0.00
80	2010	6	18	9.014	0	28.31	9.59	6/18/2010	0.35	0.00
81	2010	6	19	8.931	1.524	29.94	14.92	6/19/2010	0.35	0.06
82	2010	6	20	4.535	0	24.87	16.54	6/20/2010	0.18	0.00
83	2010	6	21	8.668	0	30.35	14.79	6/21/2010	0.34	0.00
84	2010	6	22	8.735	0	29.64	11.26	6/22/2010	0.34	0.00
85	2010	6	23	7.794	0	25.78	10.31	6/23/2010	0.31	0.00
86	2010	6	24	9.561	0	33.04	12.74	6/24/2010	0.38	0.00
87	2010	6	25	11.121	0	35.73	11.56	6/25/2010	0.44	0.00
88	2010	6	26	7.746	4.064	32.5	15.09	6/26/2010	0.30	0.16
89	2010	6	27	6.708	0	27.36	12.44	6/27/2010	0.26	0.00
90	2010	6	28	7.452	0	31.29	10.99	6/28/2010	0.29	0.00
91	2010	6	29	9.924	0	33.28	11.77	6/29/2010	0.39	0.00
92	2010	6	30	11.836	0	31.96	13.21	6/30/2010	0.47	0.00

Missing Data

CoAgMet has no Etr_ASCE data for 6/12/2010
Please enter a value (in mm), Et will be assumed to be zero if left blank or cancel is pressed.

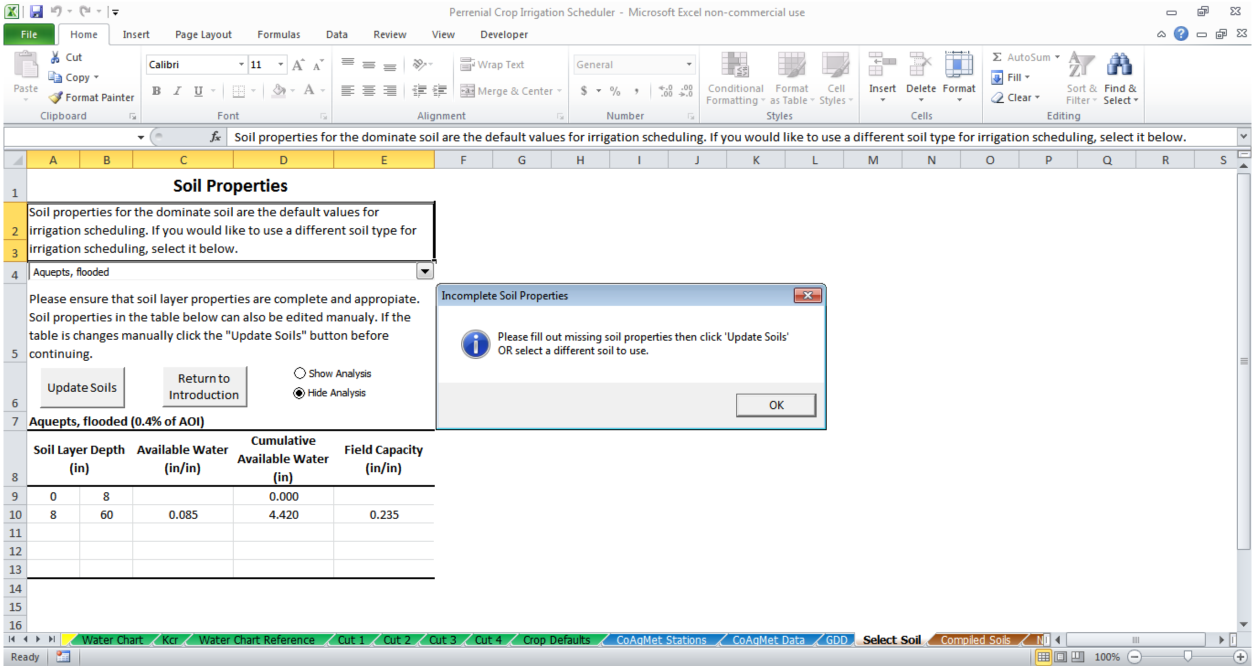
5.2

Collecting data from CoAgMet (Step 1 of 2) This may take a few moments...

Figure App A.2ii: An example of the input box used to enter missing weather data

3. Incomplete Soil Properties

Sometimes the NRCS WSS does not have soil properties for all soil layers for a specific soil type. If a soil type is selected that has missing soil properties an error message will be displayed as shown below in Figure App A.3. If this occurs fill in the missing fields or select a different soil type to use for irrigation scheduling.



Soil properties for the dominate soil are the default values for irrigation scheduling. If you would like to use a different soil type for irrigation scheduling, select it below.

Soil Properties

Soil properties for the dominate soil are the default values for irrigation scheduling. If you would like to use a different soil type for irrigation scheduling, select it below.

Aquepts, flooded

Please ensure that soil layer properties are complete and appropiate. Soil properties in the table below can also be edited manualy. If the table is changes manually click the "Update Soils" button before continuing.

Aquepts, flooded (0.4% of AOI)

Soil Layer Depth (in)		Available Water (in/in)	Cumulative Available Water (in)	Field Capacity (in/in)
0	8		0.000	
8	60	0.085	4.420	0.235

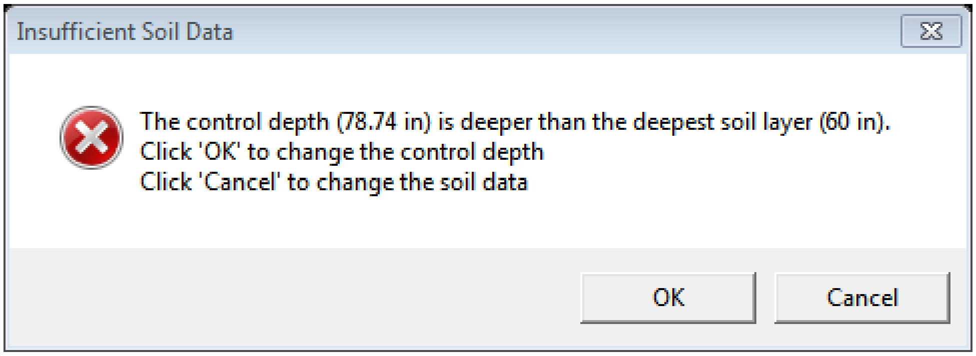
Incomplete Soil Properties

Please fill out missing soil properties then click 'Update Soils' OR select a different soil to use.

Figure App A.3: Incomplete Soil Properties Error Message, for this soil type there is no AWC or FC for the soil layer 0-8 in

4. Insufficient soil data

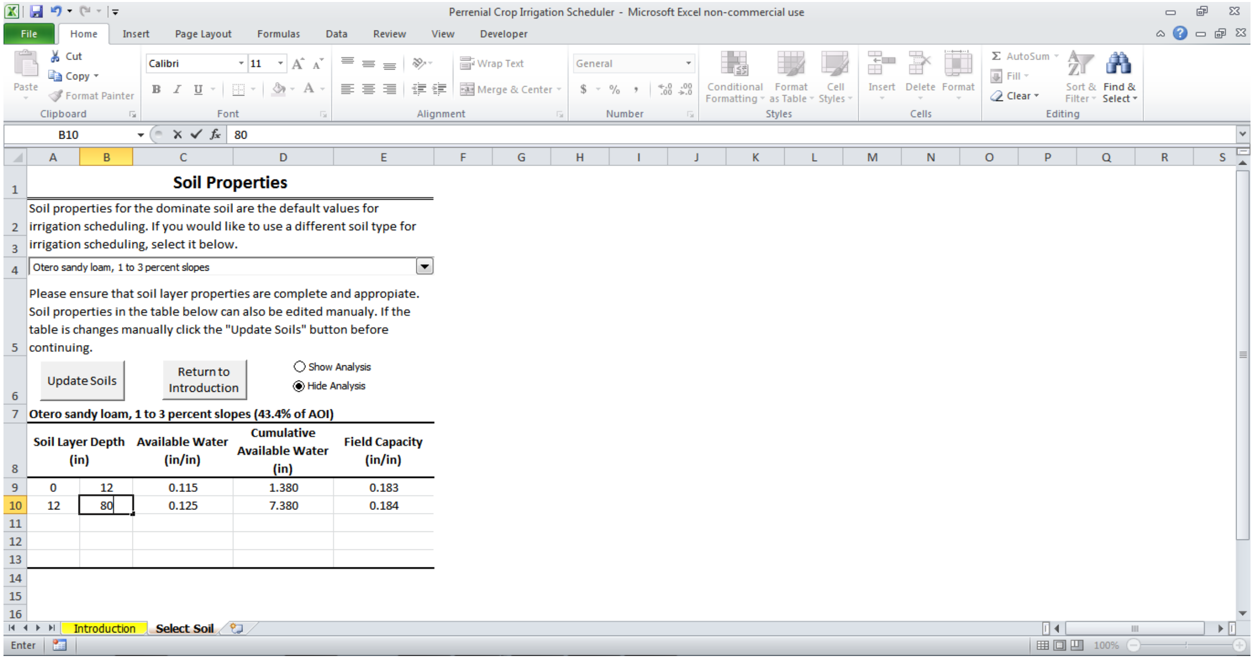
For soil layer scheduling purposes the control depth needs to shallower than the deepest soil layer. If a control depth is entered that is deeper than the deepest soil layer an error message will be displayed as below in Figure App A.4. This error is most likely to occur while using the ‘CoAgMet and Farm Information’ form. Clicking ‘OK’ will return you to the ‘CoAgMet and Farm Information’ form to change the Control Depth. Clicking ‘Cancel’ will close the ‘CoAgMet and Farm Information’ form and select the ‘Select Soil’ sheet so that the user can update the soil layers so that there is enough soil data for calculations, once the soils data is entered click the ‘Update Soils’ button.



The control depth (78.74 in) is deeper than the deepest soil layer (60 in).
Click 'OK' to change the control depth
Click 'Cancel' to change the soil data

Figure App A.4i: Insufficient Soil Data error message

For the example shown in Figure App A.4, we will assume that the soil properties at 60 in below the surface are the same from 60 in to 80 in below the surface. To do so, click ‘Cancel’. This will close the ‘CoAgMet and Farm Information’ form and select the ‘Select Soil’ sheets as shown below. The lower bound of the second soil layer was changed to 80 from 60. After this the ‘Update Soils’ button was clicked, and this allowed the data to finish compiling.



B10 80

Soil Properties

Soil properties for the dominate soil are the default values for irrigation scheduling. If you would like to use a different soil type for irrigation scheduling, select it below.

Otero sandy loam, 1 to 3 percent slopes

Please ensure that soil layer properties are complete and appropiate. Soil properties in the table below can also be edited manualy. If the table is changes manually click the "Update Soils" button before continuing.

○ Show Analysis
● Hide Analysis

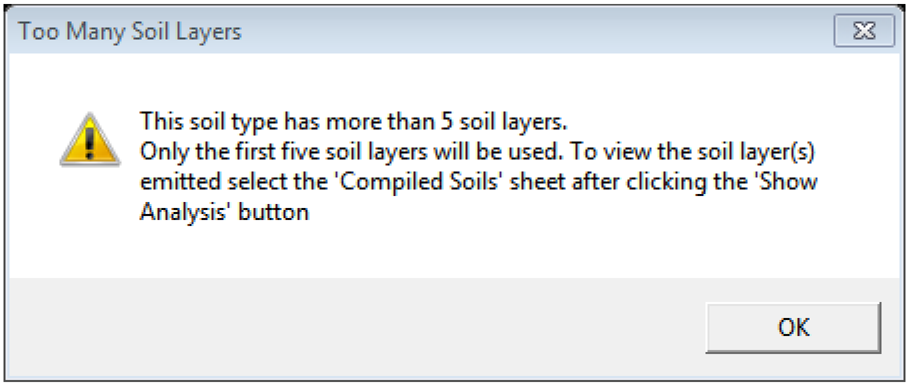
Otero sandy loam, 1 to 3 percent slopes (43.4% of AOI)

Soil Layer Depth (in)		Available Water (in/in)	Cumulative Available Water (in)	Field Capacity (in/in)
0	12	0.115	1.380	0.183
12	80	0.125	7.380	0.184

Figure App A.4ii: Updating the soil layers so that the maximum soil depth exceeds the control depth

5. Too Many Soil Layers

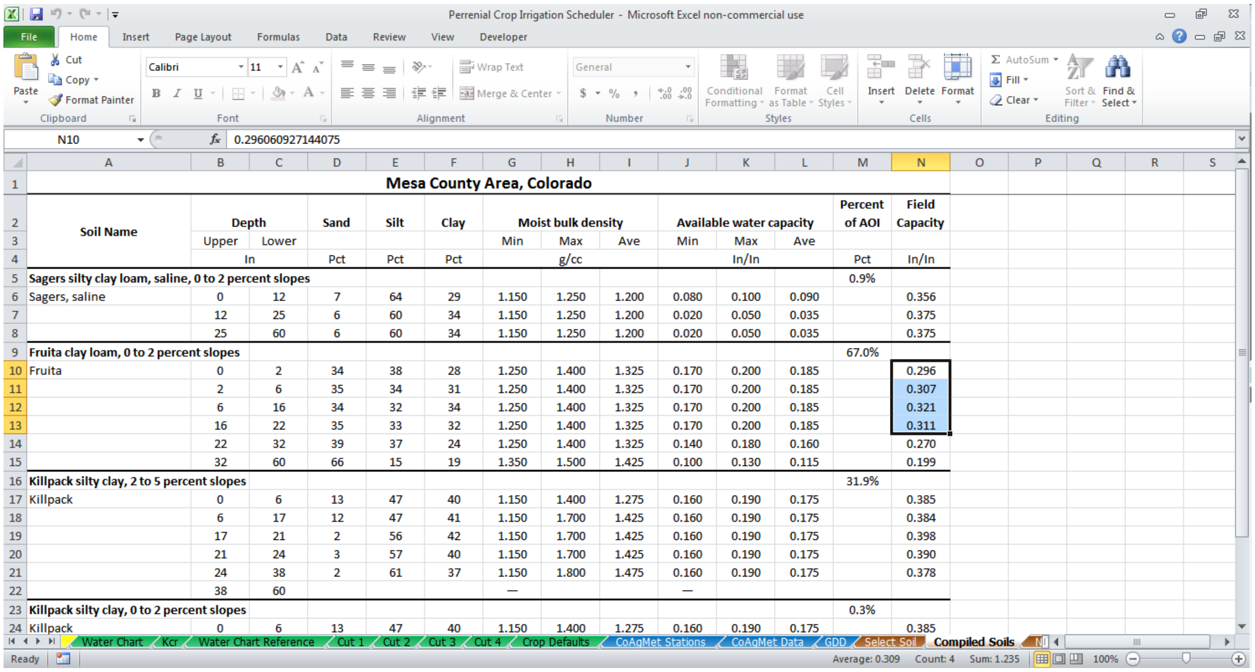
The CIS is limited to calculate soil layer deficits for five or less layers. Sometimes the WSS has more than five layers. If this occurs the user will be prompted with an error message similar to Figure App A.5i below. There are several suggestions on how to deal with this error as shown below.



This soil type has more than 5 soil layers.
Only the first five soil layers will be used. To view the soil layer(s) emitted select the 'Compiled Soils' sheet after clicking the 'Show Analysis' button

Figure App A.5i: Too Many Soil Layers error message

1. If the first five layers are sufficient to cover the root-zone then only use the first five layers.
2. Choose a different soil type
3. Combine soil layers by
    a. Click the ‘Show Analysis’ button
    b. Select the ‘Compiled Soils’ sheet.
    c. Using the data on this sheet as a reference, combine soil layers with similar AWC and FC so that there are five or less total layers.
    d. Enter these new layers manually on the ‘Select Soil’ sheet, it may be helpful to write down the soil properties. In the example shown in Figure App A.5ii, the first four layers have the same AWC so an average of their FC was used (0.309 in/in).
    e. Click the ‘Hide Analysis’ button
    f. Click the ‘Update Soils’ button
    g. An example of the new soil properties table is shown in Figure App A.5iii

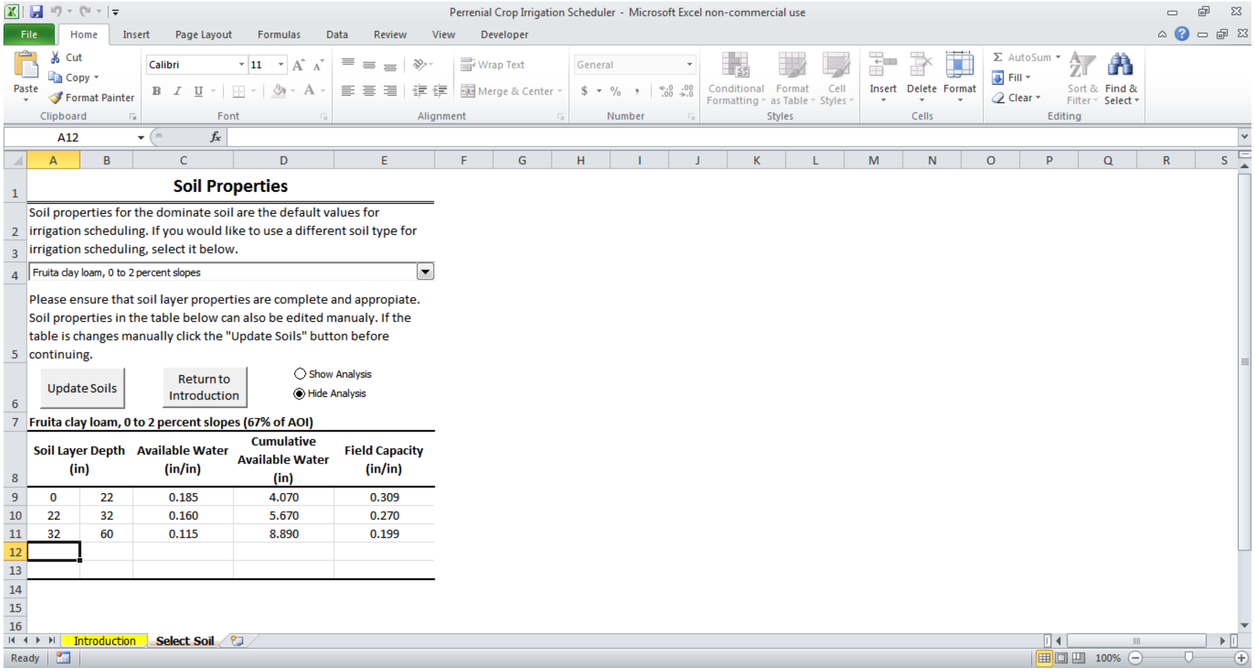


N10 0.296060927144075

Mesa County Area, Colorado

Soil Name	Depth		Sand	Silt	Clay	Moist bulk density			Available water capacity			Percent of AOI	Field Capacity
	Upper	Lower				Min	Max	Ave	Min	Max	Ave		
	In		Pct	Pct	Pct	g/cc			In/In			Pct	In/In
Sagers silty clay loam, saline, 0 to 2 percent slopes												0.9%	
Sagers, saline	0	12	7	64	29	1.150	1.250	1.200	0.080	0.100	0.090		0.356
	12	25	6	60	34	1.150	1.250	1.200	0.020	0.050	0.035		0.375
	25	60	6	60	34	1.150	1.250	1.200	0.020	0.050	0.035		0.375
Fruita clay loam, 0 to 2 percent slopes												67.0%	
Fruita	0	2	34	38	28	1.250	1.400	1.325	0.170	0.200	0.185		0.296
	2	6	35	34	31	1.250	1.400	1.325	0.170	0.200	0.185		0.307
	6	16	34	32	34	1.250	1.400	1.325	0.170	0.200	0.185		0.321
	16	22	35	33	32	1.250	1.400	1.325	0.170	0.200	0.185		0.311
	22	32	39	37	24	1.250	1.400	1.325	0.140	0.180	0.160		0.270
	32	60	66	15	19	1.350	1.500	1.425	0.100	0.130	0.115		0.199
Killpack silty clay, 2 to 5 percent slopes												31.9%	
Killpack	0	6	13	47	40	1.150	1.400	1.275	0.160	0.190	0.175		0.385
	6	17	12	47	41	1.150	1.700	1.425	0.160	0.190	0.175		0.384
	17	21	2	56	42	1.150	1.700	1.425	0.160	0.190	0.175		0.398
	21	24	3	57	40	1.150	1.700	1.425	0.160	0.190	0.175		0.390
	24	38	2	61	37	1.150	1.800	1.475	0.160	0.190	0.175		0.378
	38	60				—			—				
Killpack silty clay, 0 to 2 percent slopes												0.3%	
Killpack	0	6	13	47	40	1.150	1.400	1.275	0.160	0.190	0.175		0.385

Figure App A.5ii: Compiled Soils sheet showing all of the soil layers



Soil Properties

Soil properties for the dominate soil are the default values for irrigation scheduling. If you would like to use a different soil type for irrigation scheduling, select it below.

Fruita clay loam, 0 to 2 percent slopes

Please ensure that soil layer properties are complete and appropiate. Soil properties in the table below can also be edited manually. If the table is changes manually click the "Update Soils" button before continuing.

○ Show Analysis
● Hide Analysis

Fruita clay loam, 0 to 2 percent slopes (67% of AOI)

Soil Layer Depth (in)		Available Water (in/in)	Cumulative Available Water (in)	Field Capacity (in/in)
0	22	0.185	4.070	0.309
22	32	0.160	5.670	0.270
32	60	0.115	8.890	0.199

Figure App A.5iii: Updated soil properties table

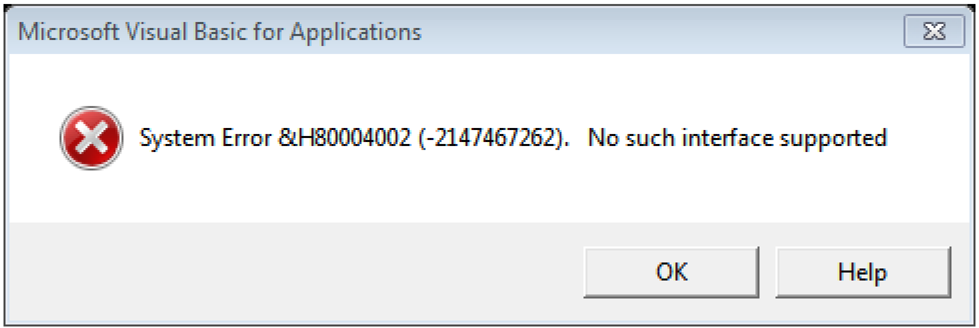
6. Protection

The CIS does not require a password to unprotect sheets and make changes; however doing so may cause errors.

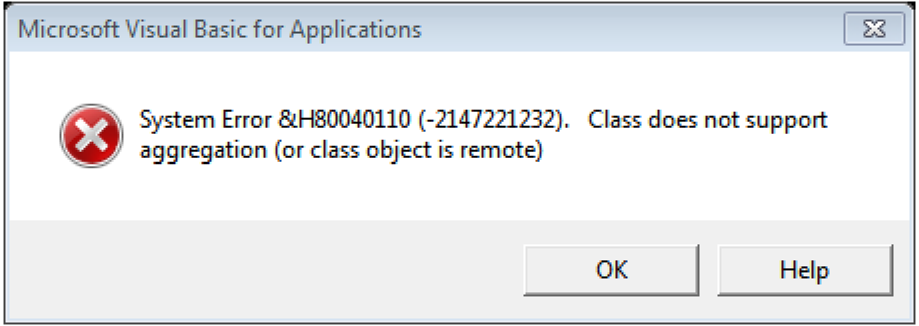
IF A PASSWORD IS ASSIGNED TO ANY SHEET THE CIS WILL NO LONGER FUNCTION PROPERLY. To password protect the CIS see the ‘Workbook_Macros’ module in the VBA editor.

7. System Errors

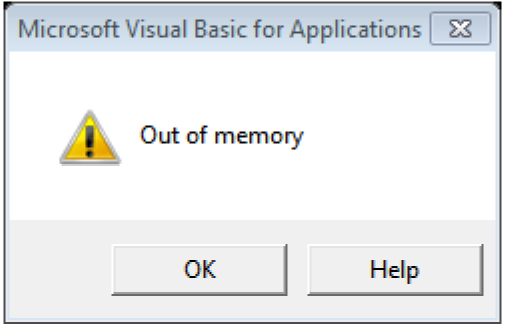
If several irrigation schedulers or similar Excel files are open at once, the following (or similar) dialogue boxes may be displayed. A fix is to press ‘Ok’ until messages stop appearing, then close all open Excel files and reopen only the necessary Excel files.



System Error &H80004002 (-2147467262). No such interface supported



System Error &H80040110 (-2147221232). Class does not support aggregation (or class object is remote)



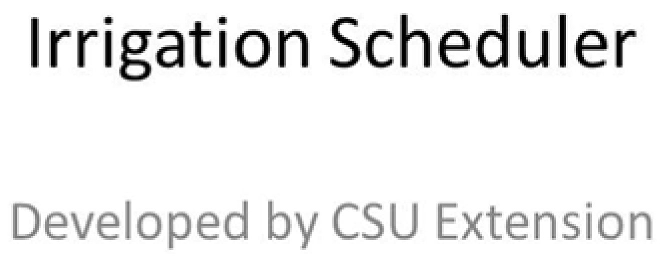
Out of memory

8. Other Problems

If any of the parameters on the ‘Irrigation’ sheet, the ‘Kcr’ sheet or the ‘Select Soil’ sheet are deleted the CIS will stop functioning properly.

1. Check that all fields are entered (See the respective section in this manual for more information.)
2. Use either the ‘Reset All’ or ‘Reset Crop’ button on the ‘Introduction’ sheet and re-setup the farm

Appendix B: Web Soil Survey Slides



Irrigation Scheduler

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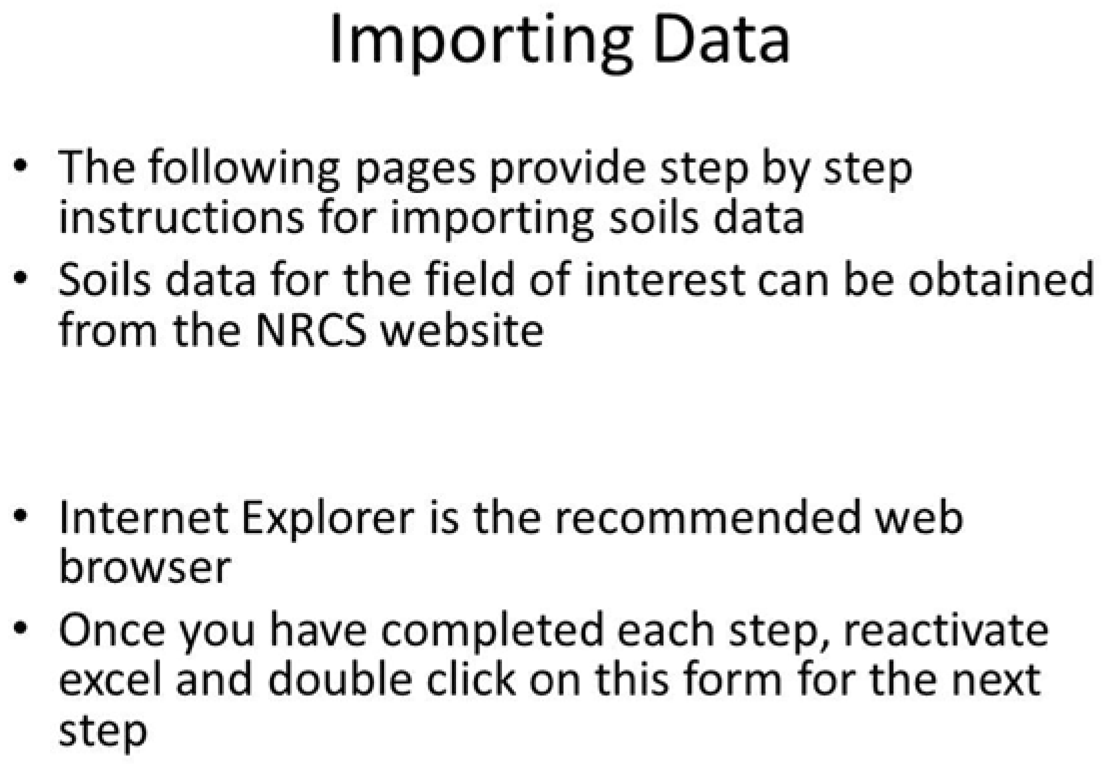


Importing Data

- The following pages provide step by step instructions for importing soils data
- Soils data for the field of interest can be obtained from the NRCS website

- Internet Explorer is the recommended web browser
- Once you have completed each step, reactivate excel and double click on this form for the next step

Step 1: Click "Start WSS" to begin Web Soil Survey

Welcome to Web Soil Survey (WSS)

Web Soil Survey (WSS) provides soil data and information produced by the National Cooperative Soil Survey. It is operated by the USDA Natural Resources Conservation Service (NRCS) and provides access to the largest natural resource information system in the world. NRCS has soil maps and data available online for more than 95 percent of the nation's counties and anticipates having 100 percent in the near future. The site is updated and maintained online as the single authoritative source of soil survey information.

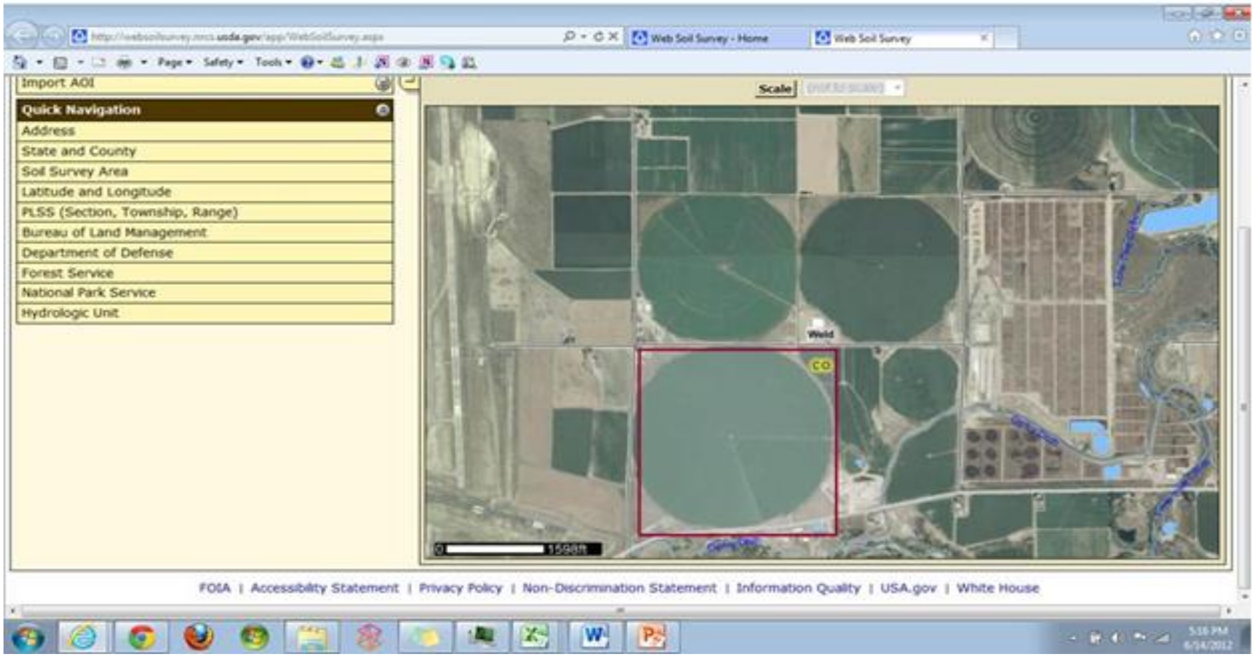
Four Basic Steps

1 Define...

Area of Interest (AOI)

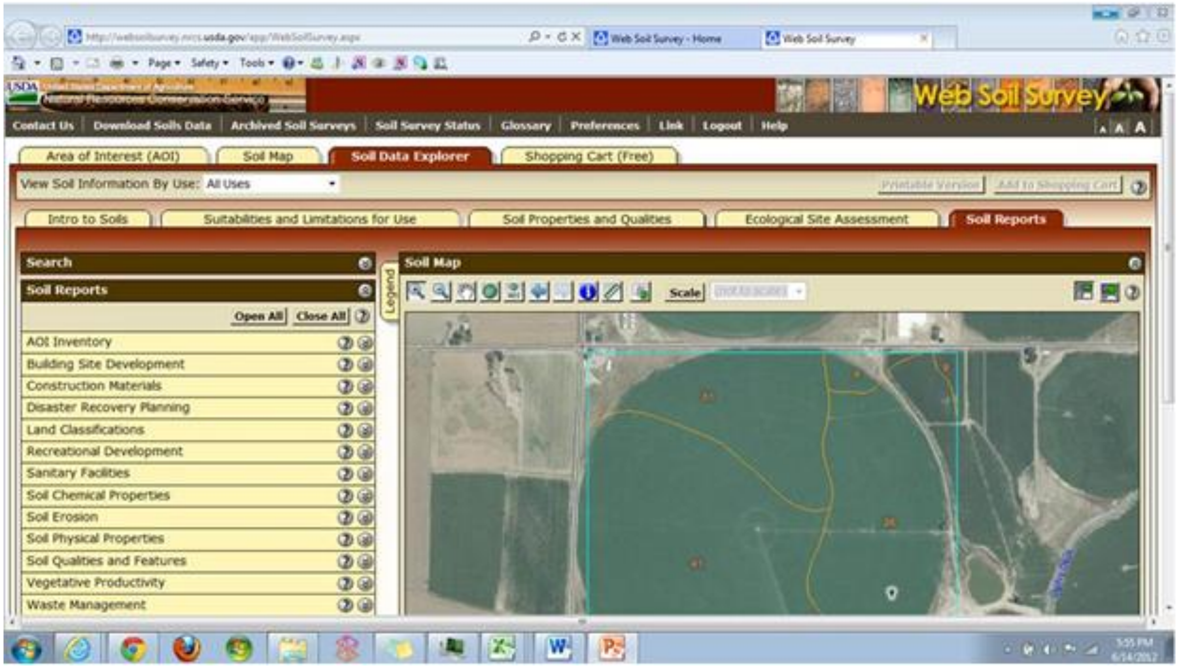
Use the Area of Interest tab to define your area of interest.

Step 2: Select an Area of Interest (AOI) using the website's interface

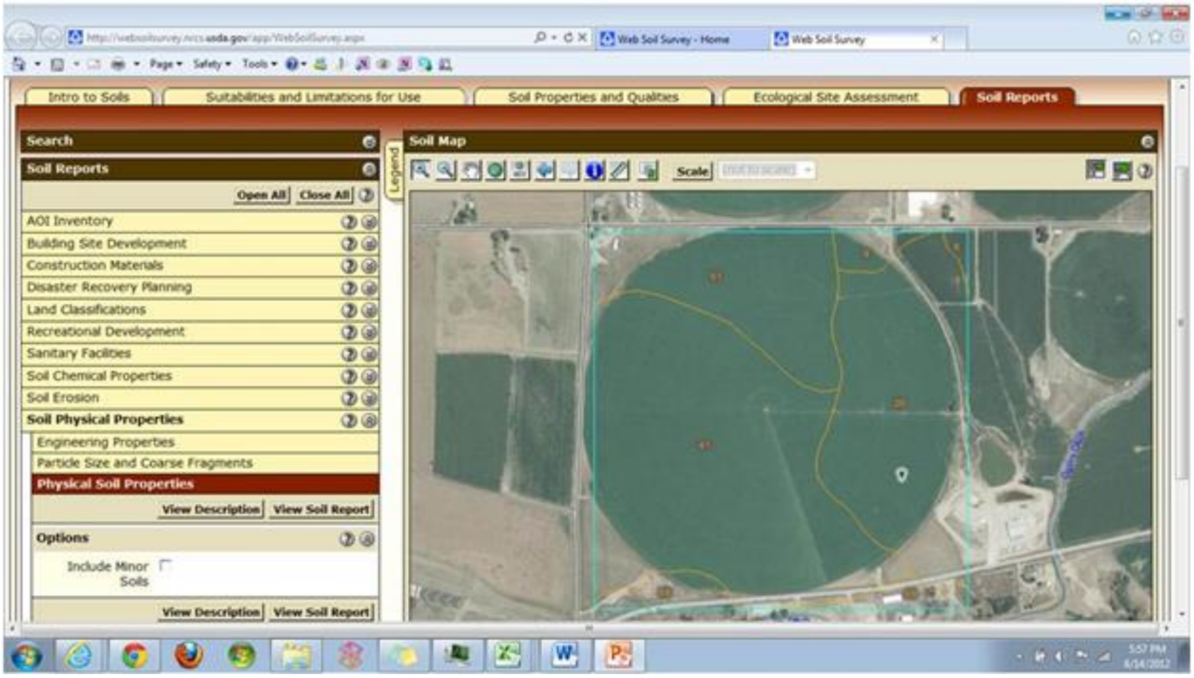


Step 3: Select the Soil Map Tab and Copy the Map Unit Legend

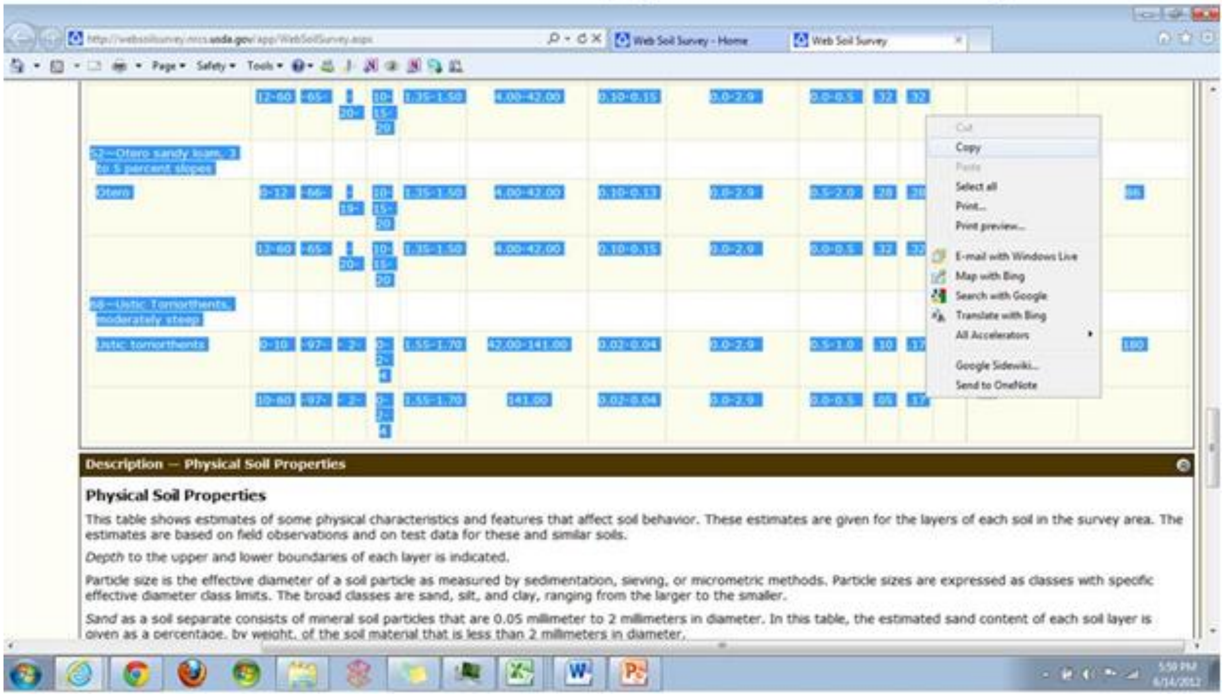
Step 4: Select the "Soil Data Explorer" Tab Then Select the "Soils Report" Secondary Tab



Step 5: Select “Soil Physical Properties” Then Select “Physical Soil Properties”



Step 6: Click “View Soil Report” Scroll Down and Copy the Entire Report



Physical Soil Properties

This table shows estimates of some physical characteristics and features that affect soil behavior. These estimates are given for the layers of each soil in the survey area. The estimates are based on field observations and on test data for these and similar soils.

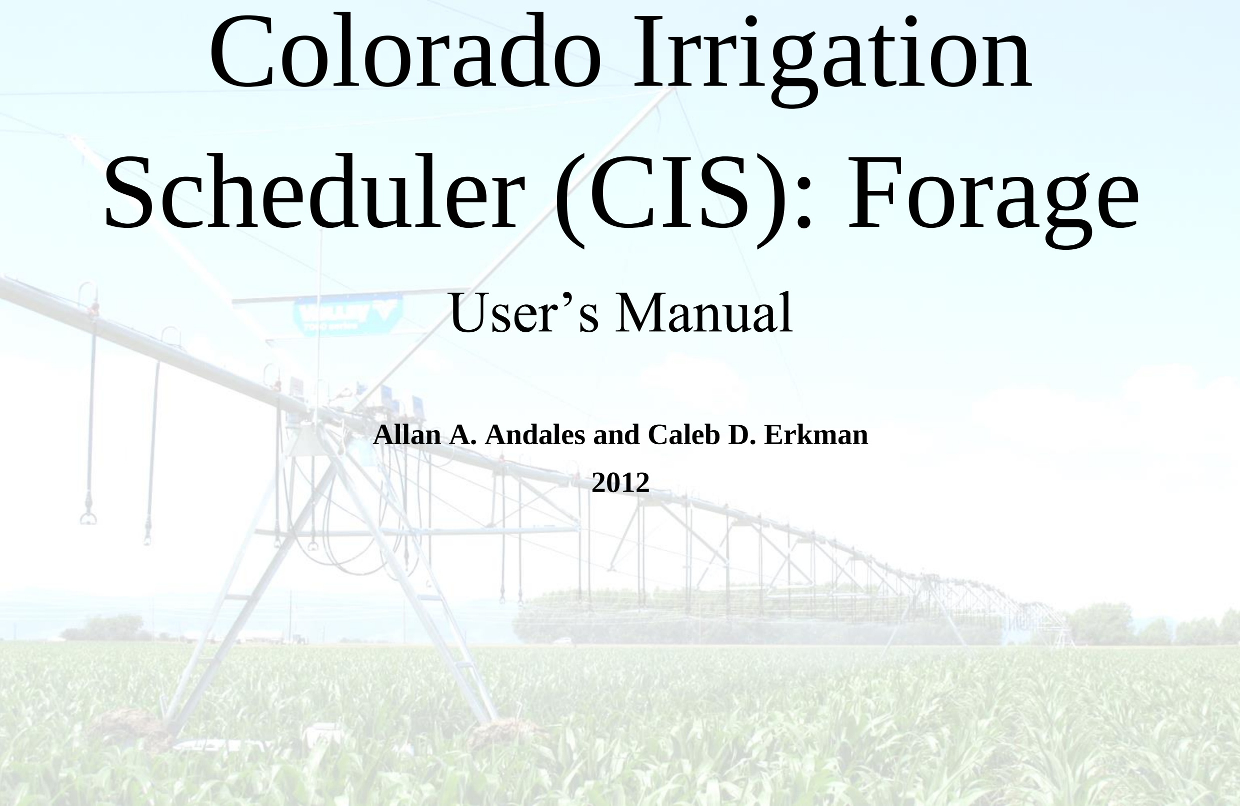
Depth to the upper and lower boundaries of each layer is indicated.

Particle size is the effective diameter of a soil particle as measured by sedimentation, sieving, or micrometric methods. Particle sizes are expressed as classes with specific effective diameter class limits. The broad classes are sand, silt, and clay, ranging from the larger to the smaller.

Sand as a soil separate consists of mineral soil particles that are 0.05 millimeter to 2 millimeters in diameter. In this table, the estimated sand content of each soil layer is given as a percentage, by weight, of the soil material that is less than 2 millimeters in diameter.

Please wait while your soils data is complied…

APPENDIX II: “COLORADO IRRIGATION SCHEDULER (CIS): FORAGE” USER’S MANUAL



Colorado Irrigation Scheduler (CIS): Forage

User’s Manual

Allan A. Andales and Caleb D. Erkman

2012

The Colorado Irrigation Scheduler (CIS) uses soils data from the Natural Resources Conservation Service (NRCS) Web Soil Survey and weather data from the Colorado Agricultural Meteorological Network (CoAgMet) to estimate daily total soil water deficit for up to five different soil layers for an individual field. The soil water deficit can be compared to a management allowed depletion value for scheduling irrigations (amount and timing) for common irrigated crops grown in Colorado. The CIS has parallel spreadsheet and graphical interfaces to input gross irrigation, observed precipitation and soil moisture measurements that are used to calculate the soil water balance. It is recommended that the user first read ‘Irrigation Scheduling: The Water Balance Approach’ by Andales et al. (2011) to become familiar with concepts used in this manual. See http://www.ext.colostate.edu/pubs/crops/04707.pdf

Acknowledgement

This project was funded by the U.S. Department of Agriculture – Natural Resources Conservation Service – Colorado Conservation Innovation Grant no. 69-8B05-A-09-09 and by the Colorado Agricultural Experiment Station.

Table of Contents

I. Setting up Excel

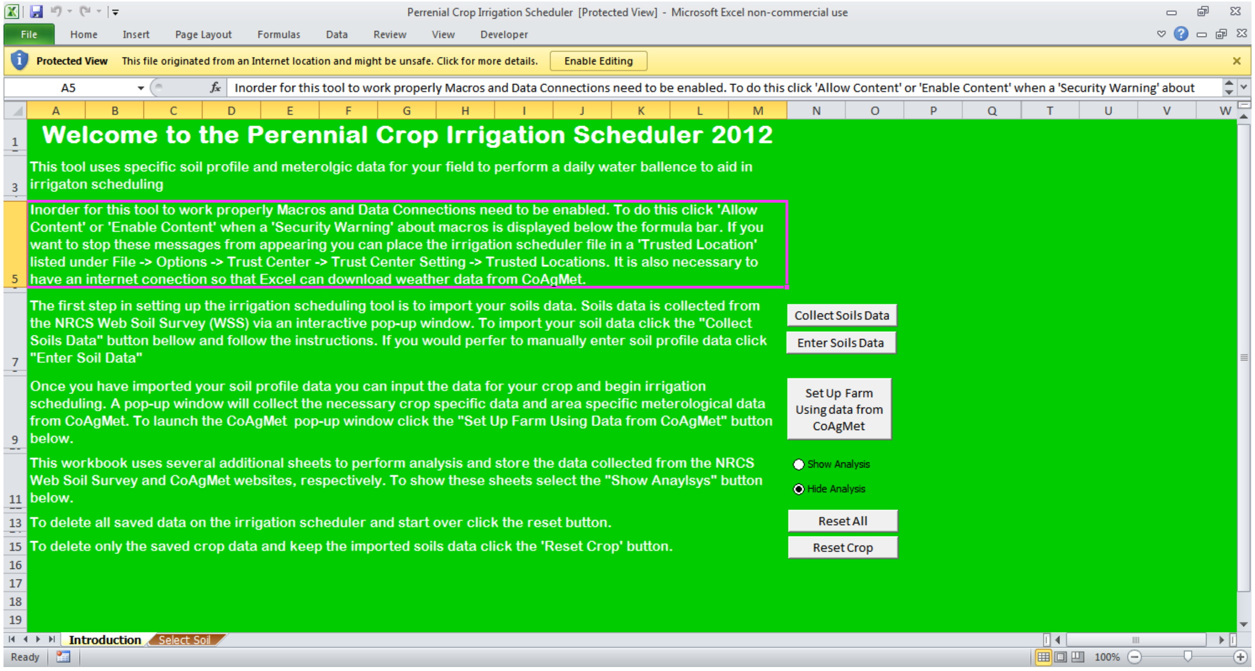
Requirements for the CIS Tool

5) Microsoft Excel 2007 or newer
6) Macros need to be enabled
7) Data connection need to be enabled
8) An active internet connection

The procedures for initializing these settings in Microsoft Excel 2010 are described below. The interface for Microsoft Excel 2007 is slightly different, but the same settings are available.

1. Protected View

If you downloaded the CIS Tool from an internet source it will likely open in protected view, and a message will be displayed above the formula bar as shown in Figure 1a below. If this occurs click ‘Enable Editing’ to continue.



Protected View This file originated from an Internet location and might be unsafe. Click for more details.

Inorder for this tool to work properly Macros and Data Connections need to be enabled. To do this click 'Allow Content' or 'Enable Content' when a 'Security Warning' about

Welcome to the Perennial Crop Irrigation Scheduler 2012

This tool uses specific soil profile and meterolgic data for your field to perform a daily water ballence to aid in irrigaton scheduling

Inorder for this tool to work properly Macros and Data Connections need to be enabled. To do this click 'Allow Content' or 'Enable Content' when a 'Security Warning' about macros is displayed below the formula bar. If you want to stop these messages from appearing you can place the irrigation scheduler file in a 'Trusted Location' listed under File -> Options -> Trust Center -> Trust Center Setting -> Trusted Locations. It is also necessary to have an internet conection so that Excel can download weather data from CoAgMet.

The first step in setting up the irrigation scheduling tool is to import your soils data. Soils data is collected from the NRCS Web Soil Survey (WSS) via an interactive pop-up window. To import your soil data click the "Collect Soils Data" button bellow and follow the instructions. If you would perfer to manually enter soil profile data click "Enter Soil Data"

Once you have imported your soil profile data you can input the data for your crop and begin irrigation scheduling. A pop-up window will collect the necessary crop specific data and area specific meterological data from CoAgMet. To launch the CoAgMet pop-up window click the "Set Up Farm Using Data from CoAgMet" button below.

This workbook uses several additional sheets to perform analysis and store the data collected from the NRCS Web Soil Survey and CoAgMet websites, respectively. To show these sheets select the "Show Anaylsys" button below.

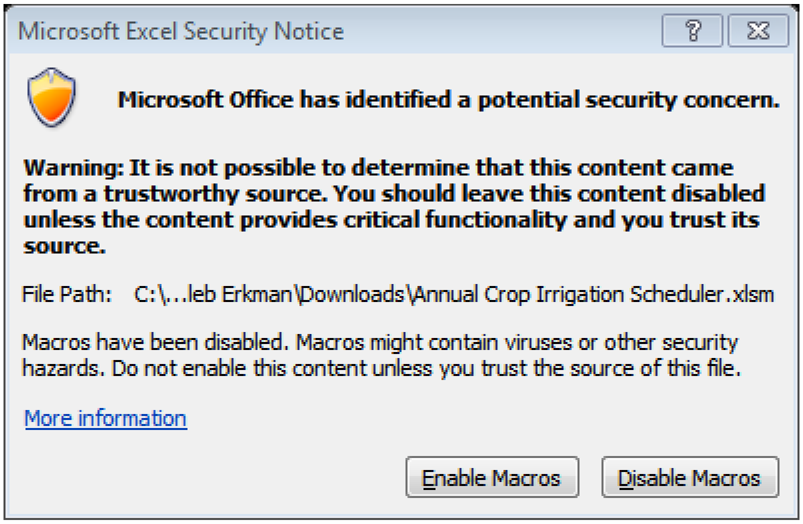
To delete all saved data on the irrigation scheduler and start over click the reset button.

To delete only the saved crop data and keep the imported soils data click the 'Reset Crop' button.

Figure 2a: Protected View Warning message in Excel 2010

2. Macros

Enabling macros allows the necessary background programs to run. However macros can be dangerous if from an untrusted source, because of this Excel may display a security warning when the CIS opens such as in Figure I.2.A or Figure I.2.B below.



Microsoft Excel Security Notice

Microsoft Office has identified a potential security concern.

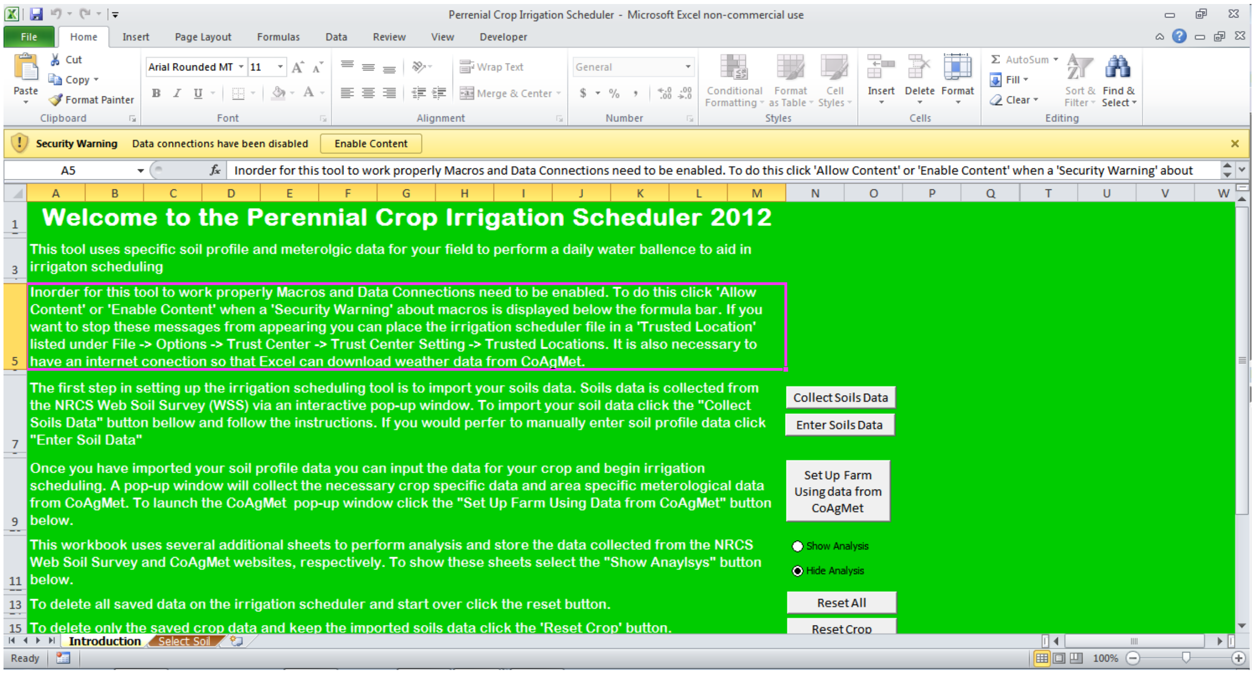
Warning: It is not possible to determine that this content came from a trustworthy source. You should leave this content disabled unless the content provides critical functionality and you trust its source.

File Path: C:\...leb Erkman\Downloads\Annual Crop Irrigation Scheduler.xlsm

Macros have been disabled. Macros might contain viruses or other security hazards. Do not enable this content unless you trust the source of this file.

Figure I.2.A: A possible macro security warning for Excel 2010

If this security warning is displayed click ‘Enable Macros’ before continuing.



Perennial Crop Irrigation Scheduler - Microsoft Excel non-commercial use

Security Warning Data connections have been disabled

A5: Inorder for this tool to work properly Macros and Data Connections need to be enabled. To do this click 'Allow Content' or 'Enable Content' when a 'Security Warning' about

Welcome to the Perennial Crop Irrigation Scheduler 2012

This tool uses specific soil profile and meterolgic data for your field to perform a daily water ballence to aid in irrigaton scheduling

Inorder for this tool to work properly Macros and Data Connections need to be enabled. To do this click 'Allow Content' or 'Enable Content' when a 'Security Warning' about macros is displayed below the formula bar. If you want to stop these messages from appearing you can place the irrigation scheduler file in a 'Trusted Location' listed under File -> Options -> Trust Center -> Trust Center Setting -> Trusted Locations. It is also necessary to have an internet conection so that Excel can download weather data from CoAgMet.

The first step in setting up the irrigation scheduling tool is to import your soils data. Soils data is collected from the NRCS Web Soil Survey (WSS) via an interactive pop-up window. To import your soil data click the "Collect Soils Data" button bellow and follow the instructions. If you would perfer to manually enter soil profile data click "Enter Soil Data"

Once you have imported your soil profile data you can input the data for your crop and begin irrigation scheduling. A pop-up window will collect the necessary crop specific data and area specific meterological data from CoAgMet. To launch the CoAgMet pop-up window click the "Set Up Farm Using Data from CoAgMet" button below.

This workbook uses several additional sheets to perform analysis and store the data collected from the NRCS Web Soil Survey and CoAgMet websites, respectively. To show these sheets select the "Show Anaylsys" button below.

To delete all saved data on the irrigation scheduler and start over click the reset button.

To delete only the saved crop data and keep the imported soils data click the 'Reset Crop' button.

Figure I.2.B: Macro Security Warning for Excel 2010

When this security warning is displayed click ‘Enable Content’ to continue.

3. Data Connections

The CIS uses data connections to collect the appropriate weather data for the farm in question from the CoAgMet website. A security warning similar to the one shown in Figure I.2.B may also be displayed that warns the user that the file contains data connections. If this happens allow the content in a similar way as before.

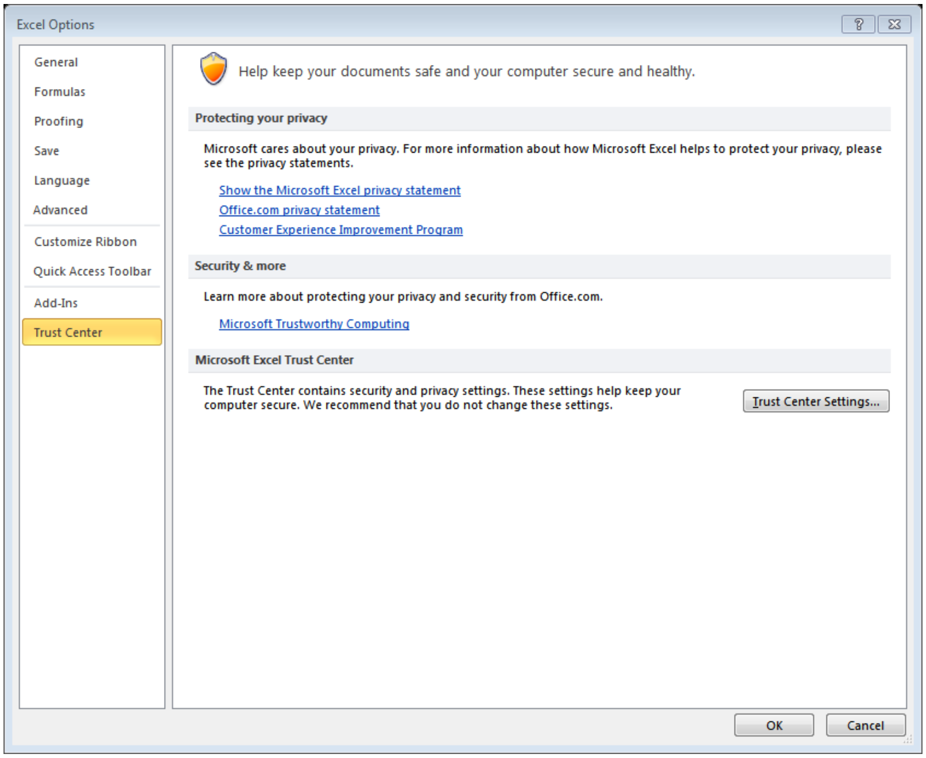
4. Secure Locations

The macro security warning and the data connections security warning will likely be displayed each time that the CIS Tool is opened. To keep this from occurring, the folder that contains the CIS file can be added to Excel's trusted locations. *Doing this is not necessary to run the CIS, but it will eliminate the need to allow content each time the CIS is opened.*

To do add a secure location, Open Excel and Select 'File' --> 'Excel Options' and select 'Trust Center' on the message box that is displayed (see Figure I.4.A).

Next click 'Trust Center Settings…' and select 'Trusted Locations' and click 'Add new location…' (see Figure I.4.B). Now click 'Add new location…' and use the browse button to select the folder where you will store the CIS file. Click Ok twice, to exit both input boxes.

Warning: It is not recommended that you put a folder that contains many files as Trusted Locations, because a file from an untrusted source could be inadvertently placed there and cause damage to your computer.



Help keep your documents safe and your computer secure and healthy.

Protecting your privacy

Microsoft cares about your privacy. For more information about how Microsoft Excel helps to protect your privacy, please see the privacy statements.

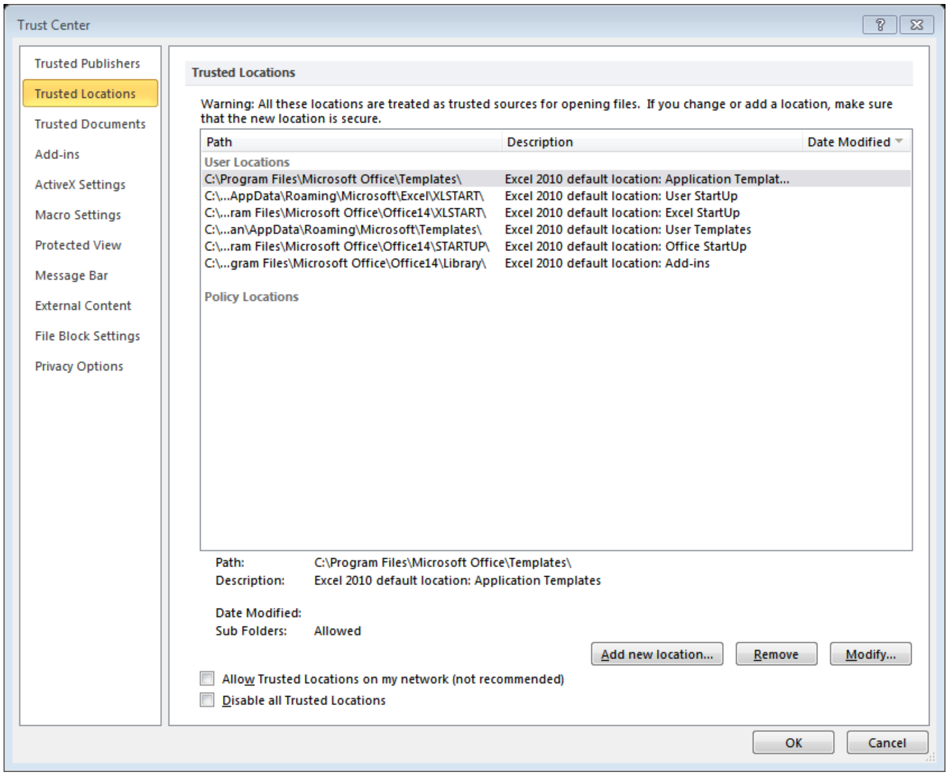
Security & more

Learn more about protecting your privacy and security from Office.com.

Microsoft Excel Trust Center

The Trust Center contains security and privacy settings. These settings help keep your computer secure. We recommend that you do not change these settings.

Figure I.4.A: Excel Options -> Trust Center



Trusted Locations

Warning: All these locations are treated as trusted sources for opening files. If you change or add a location, make sure that the new location is secure.

Path	Description	Date Modified
User Locations		
C:\Program Files\Microsoft Office\Templates\	Excel 2010 default location: Application Templat...	
C:\...AppData\Roaming\Microsoft\Excel\XLSTART\	Excel 2010 default location: User StartUp	
C:\...ram Files\Microsoft Office\Office14\XLSTART\	Excel 2010 default location: Excel StartUp	
C:\...an\AppData\Roaming\Microsoft\Templates\	Excel 2010 default location: User Templates	
C:\...ram Files\Microsoft Office\Office14\STARTUP\	Excel 2010 default location: Office StartUp	
C:\...gram Files\Microsoft Office\Office14\Library\	Excel 2010 default location: Add-ins	
Policy Locations		

Path: C:\Program Files\Microsoft Office\Templates\
Description: Excel 2010 default location: Application Templates

Date Modified:
Sub Folders: Allowed

☐ Allow Trusted Locations on my network (not recommended)
☐ Disable all Trusted Locations

Figure I.4.B: Trust Center ->Trusted Locations

II. Soil Data

Before beginning irrigation scheduling the soils data for the field of interest needs to be inputted. There are two options for entering soils data: the ‘Collect Soils Data’ and the ‘Enter Soils Data’ buttons.

The ‘Collect Soils Data’ button gives step-by-step instructions for querying the NRCS Web Soil Survey and copying the necessary tables into the CIS tool. The dominant soil type will be used for irrigation scheduling with the option of selecting a different soil type if desired.

The ‘Enter Soils Data’ button allows the user to directly enter the soil profile data that will be used for irrigation scheduling namely: depths, the available water content and field capacity for each soil layer.

Each of these methods has a button on the ‘Introduction’ sheet, more information and specific steps required for these options is provided below.

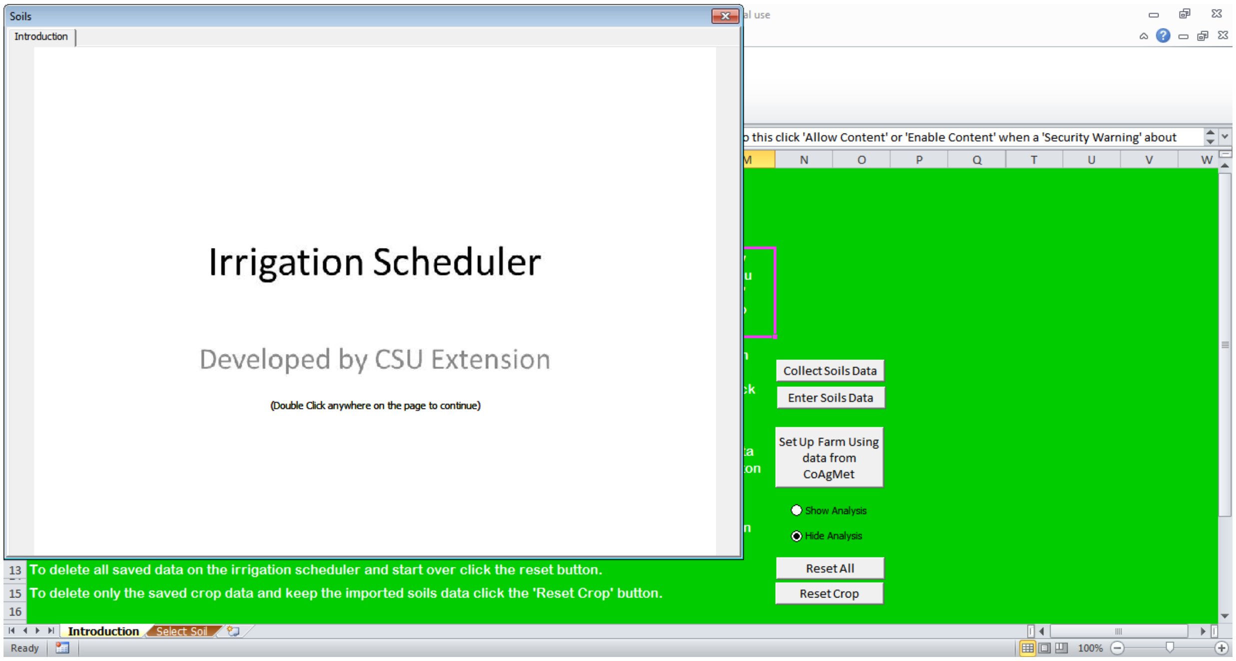
1. Collect Soils Data

The Web Soil Survey works best when used with Internet Explorer.

The ‘Collect Soils Data’ button on the Introduction Sheet will launch a form that gives step by step instructions for collecting the Soil Survey information from the NRCS Web Soil Survey. (See Appendix: B Web Soil Survey Slides for higher resolution versions of the instruction slides.) More detailed instructions for collecting soils data from the NRCS Web Soil Survey follow.

A. Starting the Soil Collection Form

When ‘Collect Soils Data’ is clicked the following introduction page will be displayed.



Irrigation Scheduler

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(Double Click anywhere on the page to continue)

o this click 'Allow Content' or 'Enable Content' when a 'Security Warning' about

To delete all saved data on the irrigation scheduler and start over click the reset button.

To delete only the saved crop data and keep the imported soils data click the 'Reset Crop' button.

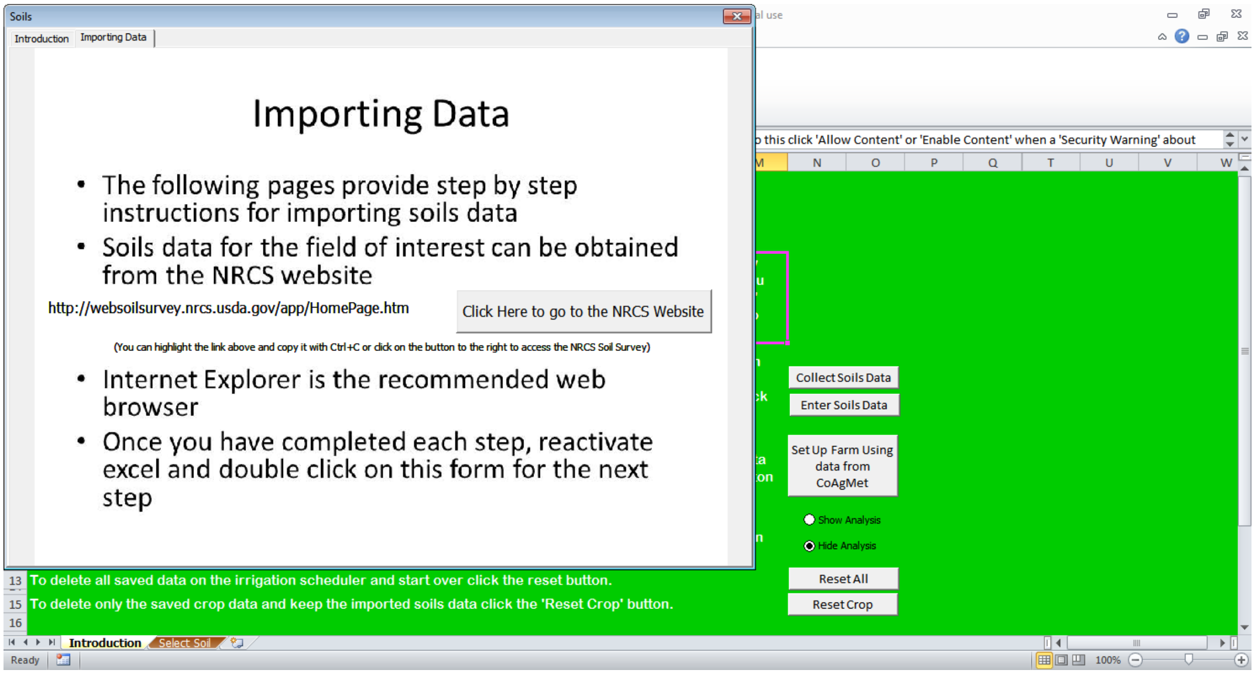
Figure II.1.A: Collecting Soils data Introduction.

Double-click anywhere on this form to advance to the first set of instructions.

B. Importing Data Instructions

The slide that is now displayed will explain how to go to the NRCS website. To ensure that the soils data copies correctly into Excel, it is recommended that Internet Explorer is used to conduct the Web Soil Survey. The use of another web browser such as Google Chrome or Firefox may cause formatting related errors when soils data is copied into Excel and may take several tries to get the soil data to copy correctly.

If Internet Explorer is your default web browser then click the button provided. If Internet Explorer is not your default web browser then open Internet Explorer and copy-and-paste or type the web address shown in the form (http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm) into the Internet Explorer address bar. The usual drop-down menu will not be displayed if you right-click on the form in Excel, but Ctrl+C will still copy the highlighted text.



Importing Data

- The following pages provide step by step instructions for importing soils data
- Soils data for the field of interest can be obtained from the NRCS website

http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm

(You can highlight the link above and copy it with Ctrl+C or click on the button to the right to access the NRCS Soil Survey)

- Internet Explorer is the recommended web browser
- Once you have completed each step, reactivate excel and double click on this form for the next step

13 To delete all saved data on the irrigation scheduler and start over click the reset button.

15 To delete only the saved crop data and keep the imported soils data click the 'Reset Crop' button.

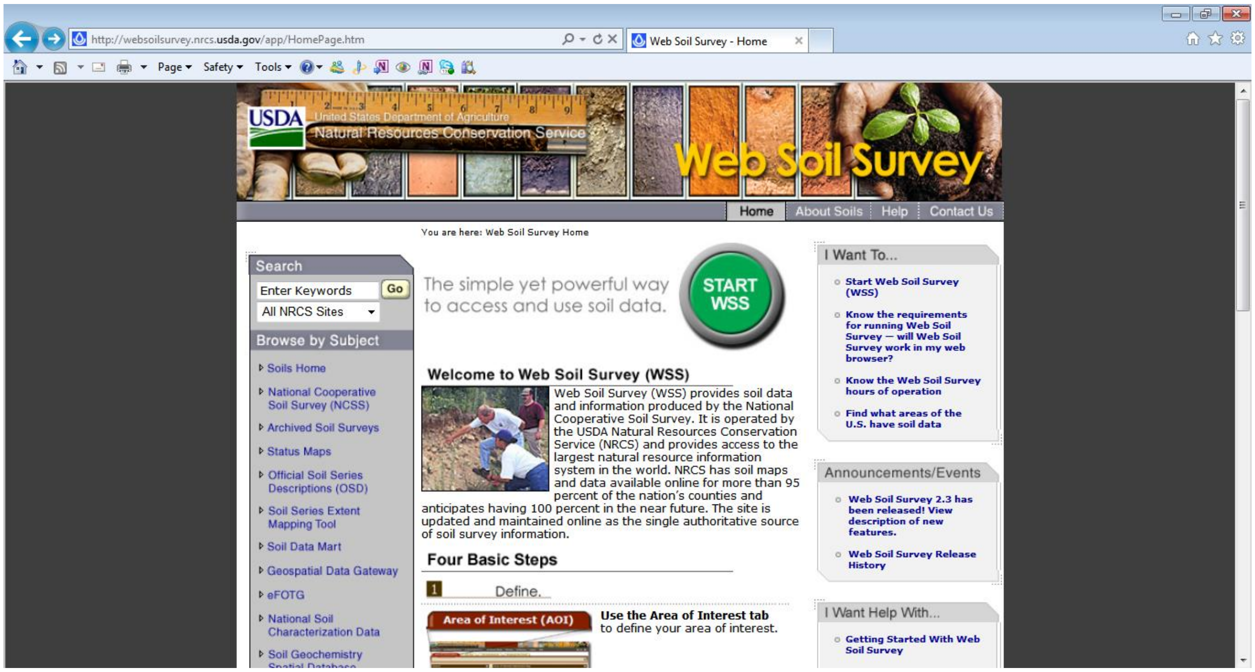
Figure II.3.B: Importing Data

Now, double-click anywhere on the slide to continue to the next instruction page.

At this point this manual will describe how to collect soils data from the NRCS Web Soil Survey in detail. Following this manual will avoid switching between Excel and Internet Explorer as each step is completed

C. Starting the Web Soil Survey

The link provided above will open the introduction page of the NRCS Web Soil Survey. This page provides some information about the Web Soil Survey. To begin the Web Soil Survey click the green “Start WSS” button shown below in Figure II.1.C.



Welcome to Web Soil Survey (WSS)

Web Soil Survey (WSS) provides soil data and information produced by the National Cooperative Soil Survey. It is operated by the USDA Natural Resources Conservation Service (NRCS) and provides access to the largest natural resource information system in the world. NRCS has soil maps and data available online for more than 95 percent of the nation’s counties and anticipates having 100 percent in the near future. The site is updated and maintained online as the single authoritative source of soil survey information.

Four Basic Steps

Use the Area of Interest tab to define your area of interest.

Figure II.1.C: Starting the Web Soil Survey

D. Selecting an Area of Interest (AOI)

Once the Web Soil Survey loads, select an Area of Interest (AOI). For the AOI, select the field that you want to schedule irrigation for. The WSS provides several methods to select an AOI. Two of these are entering the street address of the field of interest or to successively zoom into the area where your farm is located until the field of interest fills most of the screen.

Once the field of interest fills most of the screen, select either the rectangle or the polygon AOI button in the Area of Interest Interactive Map tool bar. If the field of interest is non-rectangular then using the polygon tool will give more precise soil properties for your field.

To use the polygon tool, click on a starting point on the perimeter of the field. Now move around the field’s perimeter clicking to add points as necessary to reflect the perimeter of the actual irrigated area. Once the field’s perimeter is adequately selected, double-click to finalize the polygon. An example of selecting an area of interest with the polygon AOI tool is shown below in Figure II.1.D.

Once an AOI is selected a few message boxes will be displayed as WSS compiles the soil and spatial data for the selected field.

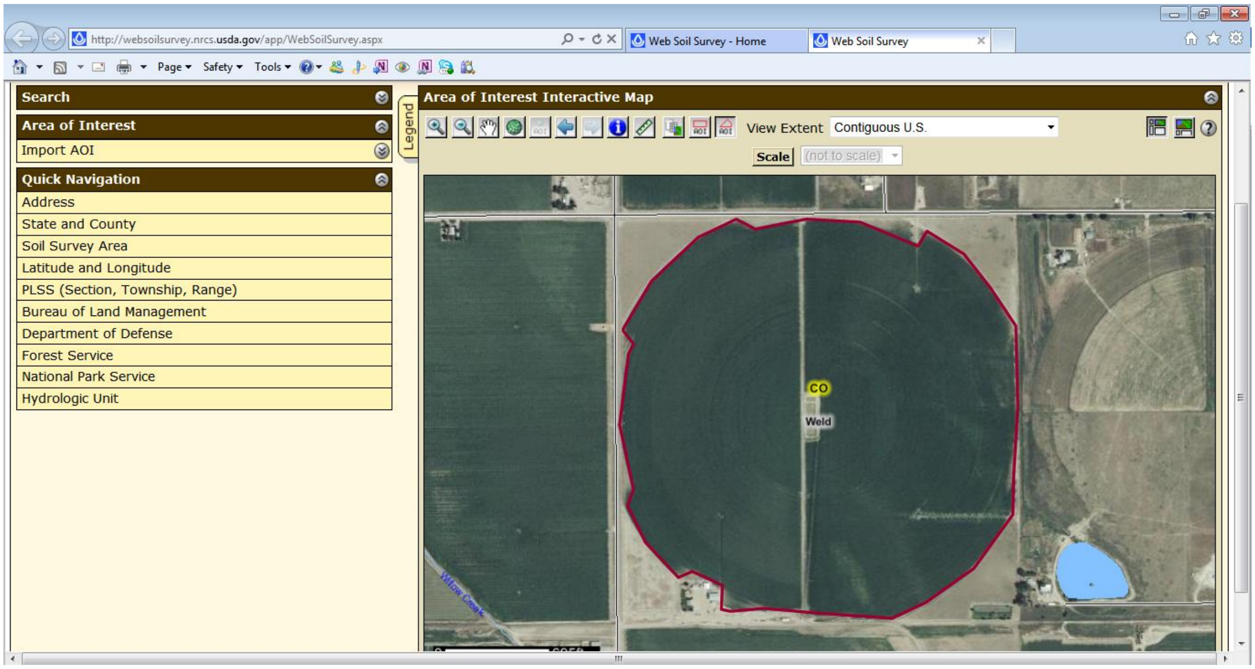
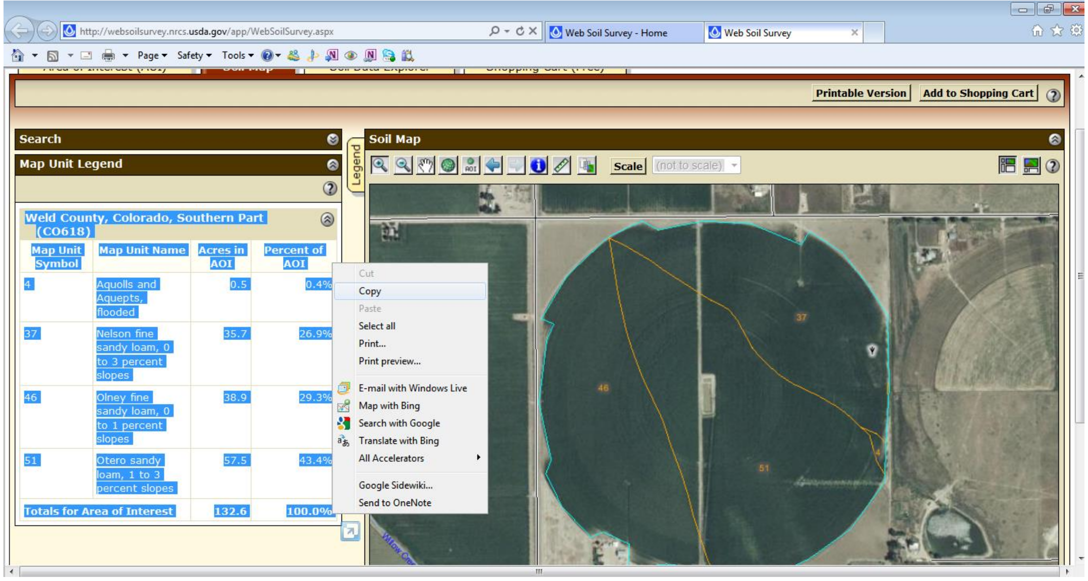


Figure II.1.D: Selecting an Area of Interest

E. Copying the Map Unit Legend

Now that an AOI is selected, click on the "Soil Map" tab near the top of the screen.

Next highlight the Map Unit Legend Table as shown below in Figure II.1.E.i , and copy it by right-clicking and selecting copy (as shown below) or pressing 'Ctrl' + 'C'.



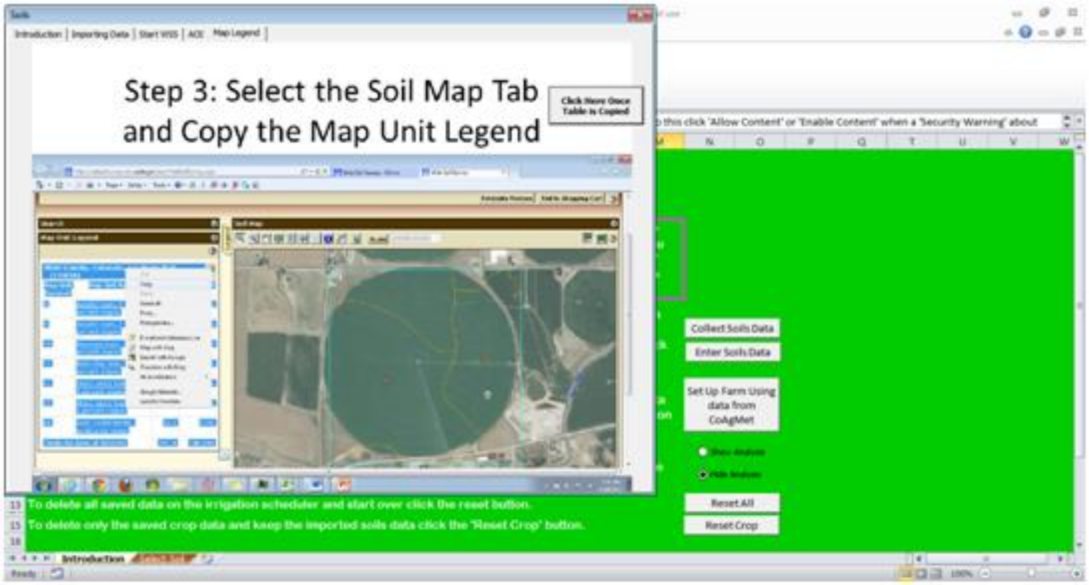
Weld County, Colorado, Southern Part (CO618)

Map Unit Symbol	Map Unit Name	Acres in AOI	Percent of AOI
4	Aquolls and Aquepts, flooded	0.5	0.4%
37	Nelson fine sandy loam, 0 to 3 percent slopes	35.7	26.9%
46	Olney fine sandy loam, 0 to 1 percent slopes	38.9	29.3%
51	Otero sandy loam, 1 to 3 percent slopes	57.5	43.4%
Totals for Area of Interest		132.6	100.0%

Figure II.1.E.i: Copying the Map Unit Legend Table

Now, activate Excel by clicking on the Excel Icon on the Windows Taskbar.

This will display Excel and the Soils form. Double click on the Soils form until the page shown in Figure II.1.E.ii is displayed. Now click the 'Click Here Once Table is Copied' button and wait until the next page is displayed. This may take a few minutes and may cause Excel or the Soil form to read (Not Responding). If this occurs continue to wait for the program to respond without taking any action.



Step 3: Select the Soil Map Tab and Copy the Map Unit Legend

this click 'Allow Content' or 'Enable Content' when a 'Security Warning' about

To delete all saved data on the irrigation scheduler and start over click the reset button.

To delete only the saved crop data and keep the imported soils data click the 'Reset Crop' button.

Figure II.1.E.ii: Importing Map Unit Legend table into Excel

F. Collecting Soil Data

Now activate Internet Explorer using the Windows Taskbar.

On the WSS page select the “Soil Data Explorer” tab near the top of the page.

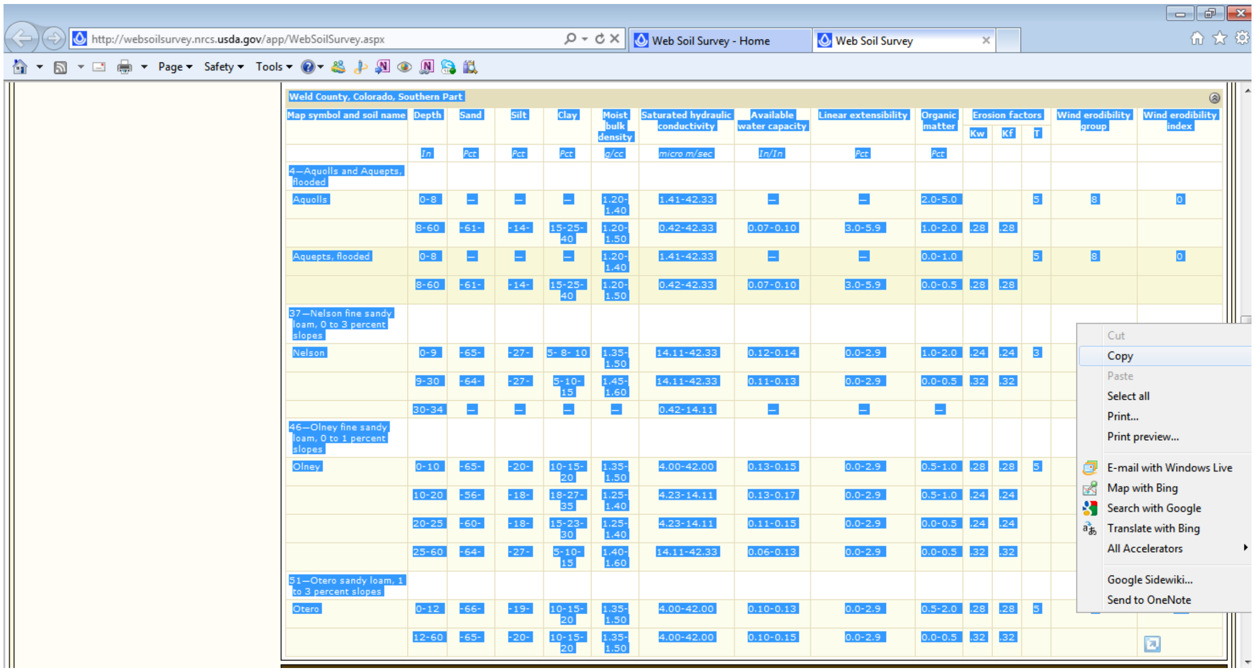
This will open a page with another tab strip below the tab strip at the top of the page. Select the “Soil Reports” tab on this secondary tab strip.

On the left hand side of the page there should now be a list of several soil reports that are available. Click on “Soil Physical Properties” located about two-thirds of the way down the list.

This will display a sub-list. On this list select “Physical Soil Properties”.

Now click the ‘View Soil Report’ button, and scroll down to “Report—Physical Soil Properties”

Next, highlight the entire table as shown below in Figure II.1.A



Weld County, Colorado, Southern Part

Map symbol and soil name	Depth	Sand	Silt	Clay	Moist bulk density	Saturated hydraulic conductivity	Available water capacity	Linear extensibility	Organic matter	Erosion factors			Wind erodibility group	Wind erodibility index
										Kw	Kf	T		
	In	Pct	Pct	Pct	g/cc	micro m/sec	In/In	Pct	Pct					
4—Aquolls and Aquepts, flooded														
Aquolls	0-8	—	—	—	1.20-1.40	1.41-42.33	—	—	2.0-5.0			5	8	0
	8-60	-61-	-14-	15-25-40	1.20-1.50	0.42-42.33	0.07-0.10	3.0-5.9	1.0-2.0	.28	.28			
Aquepts, flooded	0-8	—	—	—	1.20-1.40	1.41-42.33	—	—	0.0-1.0			5	8	0
	8-60	-61-	-14-	15-25-40	1.20-1.50	0.42-42.33	0.07-0.10	3.0-5.9	0.0-0.5	.28	.28			
37—Nelson fine sandy loam, 0 to 3 percent slopes														
Nelson	0-9	-65-	-27-	5- 8- 10	1.35-1.50	14.11-42.33	0.12-0.14	0.0-2.9	1.0-2.0	.24	.24	3		
	9-30	-64-	-27-	5-10-15	1.45-1.60	14.11-42.33	0.11-0.13	0.0-2.9	0.0-0.5	.32	.32			
	30-34	—	—	—	—	0.42-14.11	—	—	—					
46—Olney fine sandy loam, 0 to 1 percent slopes														
Olney	0-10	-65-	-20-	10-15-20	1.35-1.50	4.00-42.00	0.13-0.15	0.0-2.9	0.5-1.0	.28	.28	5		
	10-20	-56-	-18-	18-27-35	1.25-1.40	4.23-14.11	0.13-0.17	0.0-2.9	0.5-1.0	.24	.24			
	20-25	-60-	-18-	15-23-30	1.25-1.40	4.23-14.11	0.11-0.15	0.0-2.9	0.0-0.5	.24	.24			
	25-60	-64-	-27-	5-10-15	1.40-1.60	14.11-42.33	0.06-0.13	0.0-2.9	0.0-0.5	.32	.32			
51—Otero sandy loam, 1 to 3 percent slopes														
Otero	0-12	-66-	-19-	10-15-20	1.35-1.50	4.00-42.00	0.10-0.13	0.0-2.9	0.5-2.0	.28	.28	5		
	12-60	-65-	-20-	10-15-20	1.35-1.50	4.00-42.00	0.10-0.15	0.0-2.9	0.0-0.5	.32	.32			

Figure II.1.A: Copying the Report –Physical Soil Properties Table. Note that the zoom on the WSS Page was adjusted so that the entire table fit in the screen. This is not necessary, but can be accomplished by holding the control key and scrolling on the mouse.

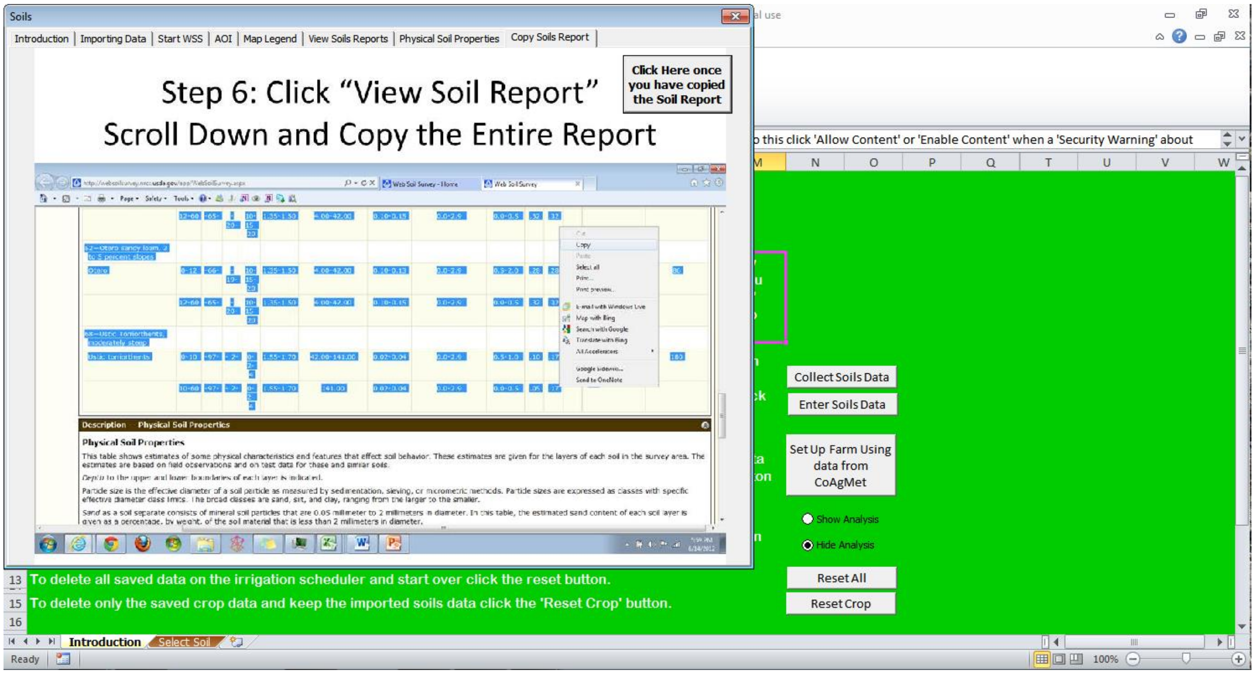
It is important that the highlighted area looks very similar to what is shown above, or else the table may not paste into Excel correctly.

Right-click and click ‘Click’ copy or press Ctrl+C to copy the table at this point.

G. Importing the Soil Table

Activate Excel using the Windows Taskbar.

Double-Click on the Soils form until the ‘Step 6: Click “View Soil Report”’ is displayed as shown below in Figure II.1.G.



Step 6: Click “View Soil Report”
Scroll Down and Copy the Entire Report

this click 'Allow Content' or 'Enable Content' when a 'Security Warning' about

Description Physical Soil Properties

Physical Soil Properties

This table shows estimates of some physical characteristics and features that effect soil behavior. These estimates are given for the layers of each soil in the survey area. The estimates are based on field observations and on test data for these and similar soils.

Depth to the upper and lower boundaries of each layer is indicated.

Particle size is the effective diameter of a soil particle as measured by sedimentation, sieving, or micrometric methods. Particle sizes are expressed as classes with specific effective diameter class limits. The broad classes are sand, silt, and clay, ranging from the larger to the smaller.

Sand as a soil separate consists of mineral soil particles that are 0.05 millimeter to 2 millimeters in diameter. In this table, the estimated sand content of each soil layer is given as a percentage, by weight, of the soil material that is less than 2 millimeters in diameter.

13 To delete all saved data on the irrigation scheduler and start over click the reset button.
15 To delete only the saved crop data and keep the imported soils data click the 'Reset Crop' button.

Figure II.1.G: Importing the Soil Report into Excel

Now click the ‘Click Here once you have copied the Soil Report’ button.

This will compile the soil report. Compiling the soil report may take several minutes and in this process Excel may read Not Responding. If this occurs, wait for Excel to respond without taking any action. If Excel takes more than two or three minutes to respond, use Windows Task Manager (Ctrl+Alt+Delete) to terminate Excel, and restart the program, copying the necessary tables as before.

If the soils report did not copy correctly, a message will prompt you to try again. If this happens repeat steps F and G.

When the soils data is finished compiling the ‘Soils’ form will disappear and the ‘Select Soil’ sheet will be selected (as shown in Figure II.1.H). At this point the WSS is no longer needed and Internet Explorer can be closed.

H. Verifying Soil Information

The soils data on this sheet should be checked to ensure that all values were available and appropriate. The most prominent soil type in the area of interest will be selected by default. This soil type will be used for irrigation scheduling purposes, and the soil layer depths shown will be used as the control volumes for each respective soil layer.

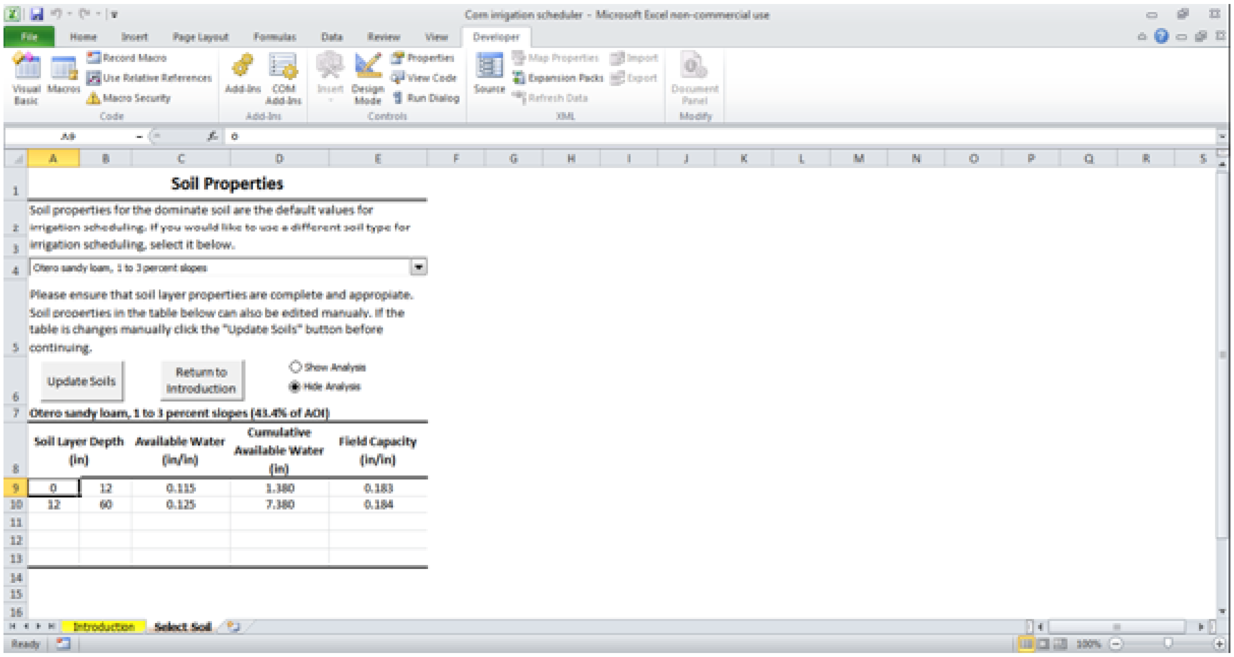
To use a different soil type for irrigation scheduling, select it using the drop down menu near the top of the page. (The percentage of the field that the selected soil type covers is shown in parentheses above the soil properties table.)

Once a soil type is selected, the user should verify that:

3. The deepest soil layer is at least as deep as the control depth (maximum rooting depth). If you believe that the deepest soil layer represents the deepest soil that the plant's roots can penetrate and this is less than the crop's control depth, then set the control depth equal to this deepest soil depth. Otherwise increase the maximum soil depth to be at least a deep as the control depth or add additional soil layers that cover the entire control depth.
4. There is an Available Water and a Field Capacity entered for each soil layer

The depths, available water capacity, and field capacity in the soil properties table can be changed manually if necessary. Click the 'Update Soils' button to save any manual changes to the Soil Properties table.

Once the soil properties table has been reviewed; click the 'Return to Introduction' button or select the 'Introduction' sheet to continue.



Soil Properties

Soil properties for the dominate soil are the default values for irrigation scheduling. If you would like to use a different soil type for irrigation scheduling, select it below.

Otero sandy loam, 1 to 3 percent slopes

Please ensure that soil layer properties are complete and appropiate. Soil properties in the table below can also be edited manualy. If the table is changes manually click the "Update Soils" button before continuing.

○ Show Analysis
● Hide Analysis

Otero sandy loam, 1 to 3 percent slopes (43.4% of AOI)

Soil Layer Depth (in)		Available Water (in/in)	Cumulative Available Water (in)	Field Capacity (in/in)
0	12	0.115	1.380	0.183
12	60	0.125	7.380	0.184

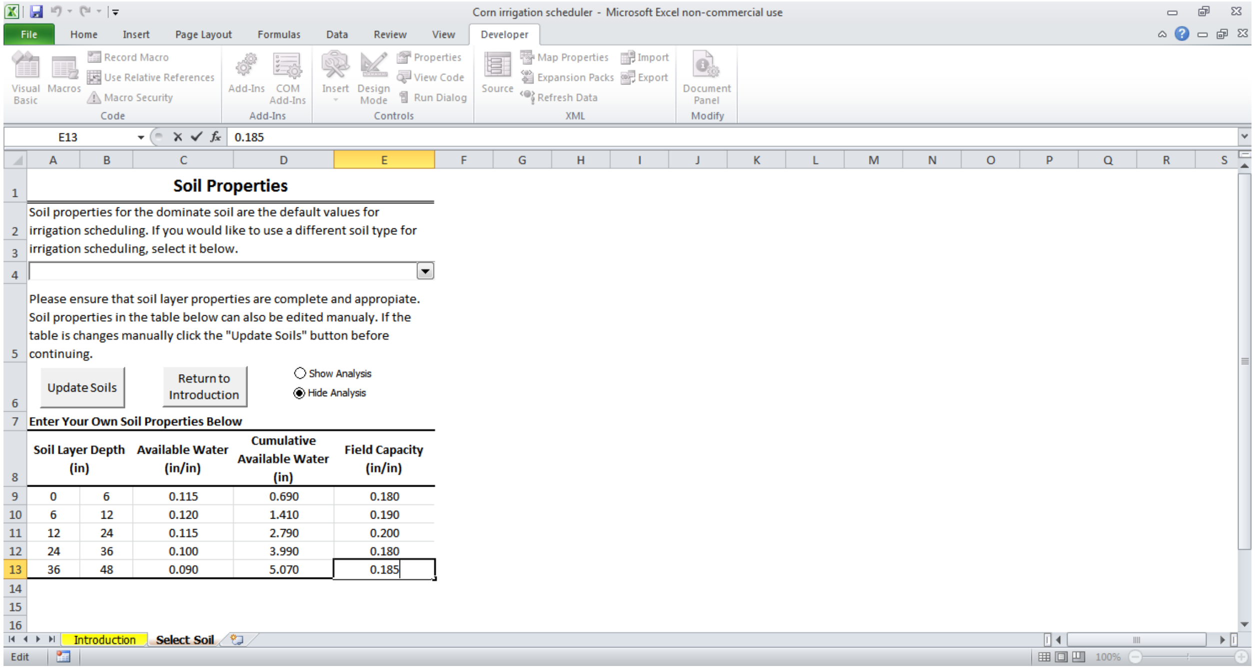
Figure II.1.H: Verifying Soil Properties

2. Enter Soils Data

The ‘Enter Soils Data’ button allows the users to enter their own soil layer depths and properties without using the NRCS Web Soil Survey. The following steps explain how to enter your own soil data.

5. When the ‘Enter Soils Data’ button is selected default soil layer depths will be populated. These layer depths can be changed if desired.
6. Enter the available water content (in/in) for each layer
7. Enter the field capacity (in/in) for each layer
8. A spreadsheet model that estimates the field capacity and the available water content for a soil given the percent sand, percent clay and soil bulk density is included in the Analysis sheets. For more information about this model see “Soil hydraulic properties” in section V.7 Soil hydraulic properties.

Figure II.2 below shows a filled out Soil Properties table



E13 0.185

Soil Properties

Soil properties for the dominate soil are the default values for irrigation scheduling. If you would like to use a different soil type for irrigation scheduling, select it below.

Please ensure that soil layer properties are complete and appropiate. Soil properties in the table below can also be edited manualy. If the table is changes manually click the "Update Soils" button before continuing.

○ Show Analysis
● Hide Analysis

Enter Your Own Soil Properties Below

Soil Layer Depth (in)		Available Water (in/in)	Cumulative Available Water (in)	Field Capacity (in/in)
0	6	0.115	0.690	0.180
6	12	0.120	1.410	0.190
12	24	0.115	2.790	0.200
24	36	0.100	3.990	0.180
36	48	0.090	5.070	0.185

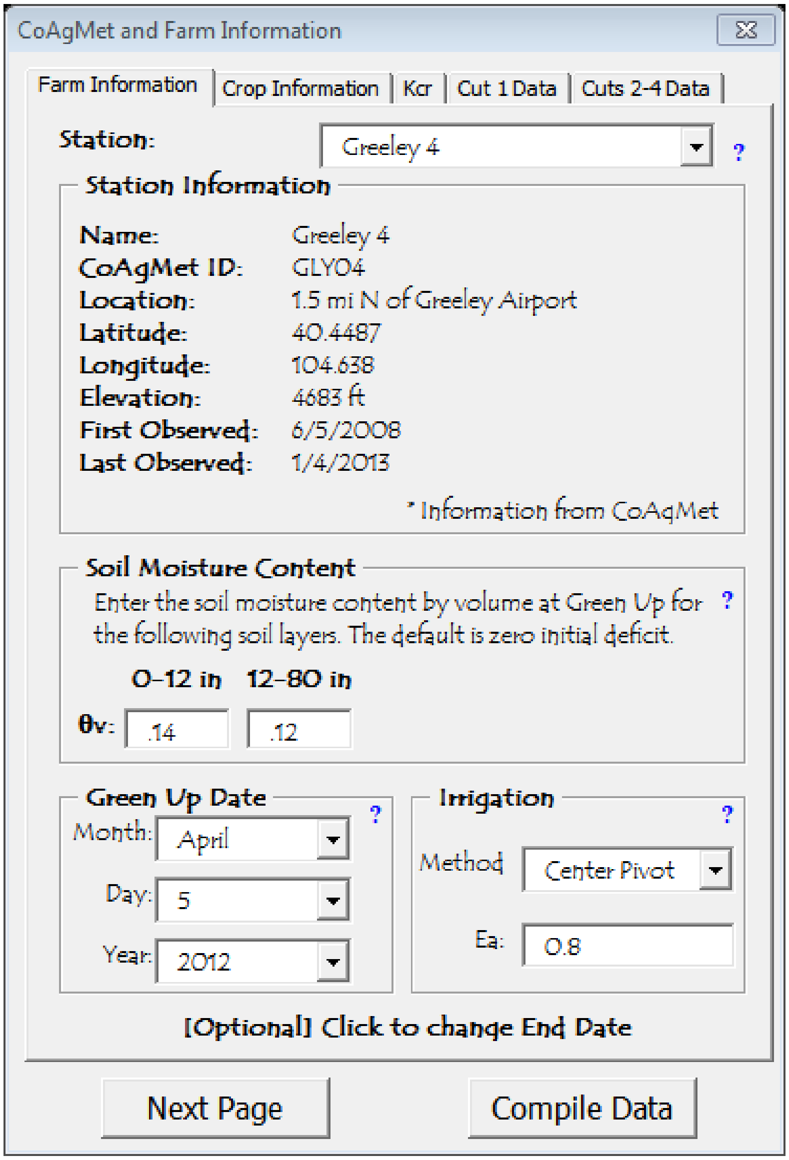
Figure II.2: Enter your own soil properties, filled out

III. Getting Weather Data

Once soils data is either collected or entered the farm can be set up by selecting a weather station and entering crop and irrigation information. To do so click the ‘Set Up Farm Using data from CoAgMet’ on the ‘Introduction’ sheet. This will start the ‘CoAgMet and Farm Information’ form to get weather data from CoAgMet and to enter your crop properties. This form has two tabs where crop and farm information are entered, and three tabs with information about crop parameters. An explanation of these tabs follows.

1. Farm Information

A description of the editable fields on the ‘Farm Information’ tab (shown in Figure III.1 below) are listed below, each of these explanations can also be viewed by clicking on the question mark next to the respective field on the ‘CoAgMet and Farm Information’ form.



Station: Greeley 4

Station Information

Name: Greeley 4
CoAgMet ID: GLY04
Location: 1.5 mi N of Greeley Airport
Latitude: 40.4487
Longitude: 104.638
Elevation: 4683 ft
First Observed: 6/5/2008
Last Observed: 1/4/2013

* Information from CoAgMet

Soil Moisture Content

Enter the soil moisture content by volume at Green Up for the following soil layers. The default is zero initial deficit.

	0-12 in	12-80 in
θv:	.14	.12

Green Up Date
Month: April
Day: 5
Year: 2012

Irrigation
Method: Center Pivot
Ea: 0.8

[Optional] Click to change End Date

Figure III.1: Example of the first tab of the ‘CoAgMet and Farm Information’ Form filled out

A. Select a Station

Select the weather station listed that is closest to your farm's location. Ensure that the dates that you want to collect data for fall within the first observed and last observed dates shown. If the last observed date for the station nearest your farm is older than acceptable, choose the next closest station.

B. Enter the Soil Moisture Content if available

Enter the volumetric soil moisture content (in/in) for each layer. The soil moisture content is used in conjunction with the soil layer data to determine the initial deficit for each soil layer.

If the soil moisture content is not entered the initial deficit is assumed to be zero, which corresponds to the soil being at field capacity.

C. Enter the green up date

Enter the green up date for the crop that irrigation will be scheduled for.

D. Irrigation Method

Irrigation application efficiencies for some common irrigation methods are provided.

Please select one from the list, or enter your own irrigation application efficiency (Ea) in the appropriate box. Typical values of Ea for different irrigation systems have been summarized by Barta et al. (2004).

E. [Optional] Change End Date

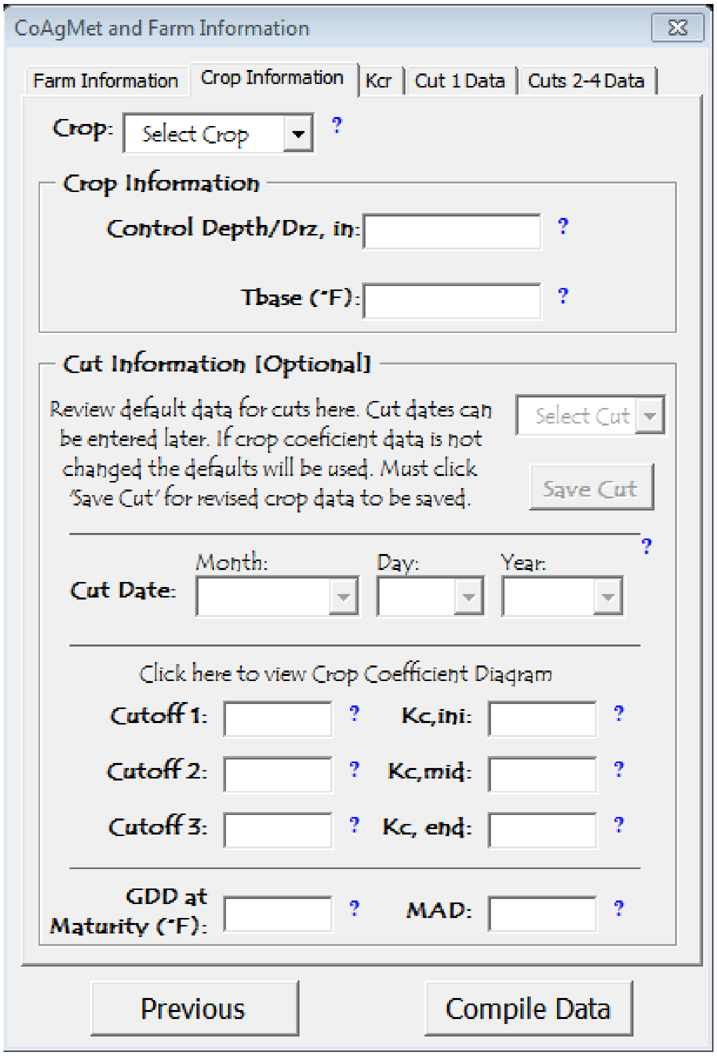
Weather data will be collected until the end of the calendar year following the green-up date, the day before the current date, or the date entered when this text is clicked, whichever comes first.

2. Next Page

The ‘Next Page’ button will open the second tab of the ‘CoAgMet and Farm Information’ form as shown in Figure III.3

3. Crop Information

A description of the editable fields on the ‘Crop Information’ tab (shown in Figure III.3) are listed below, each of these explanations can also be viewed by clicking on the question mark next to the respective field.



Review default data for cuts here. Cut dates can be entered later. If crop coeficient data is not changed the defaults will be used. Must click 'Save Cut' for revised crop data to be saved.

Figure III.3: The ‘Crop Information’ tab on the ‘CoAgMet and Farm Information’ form

A. Crop

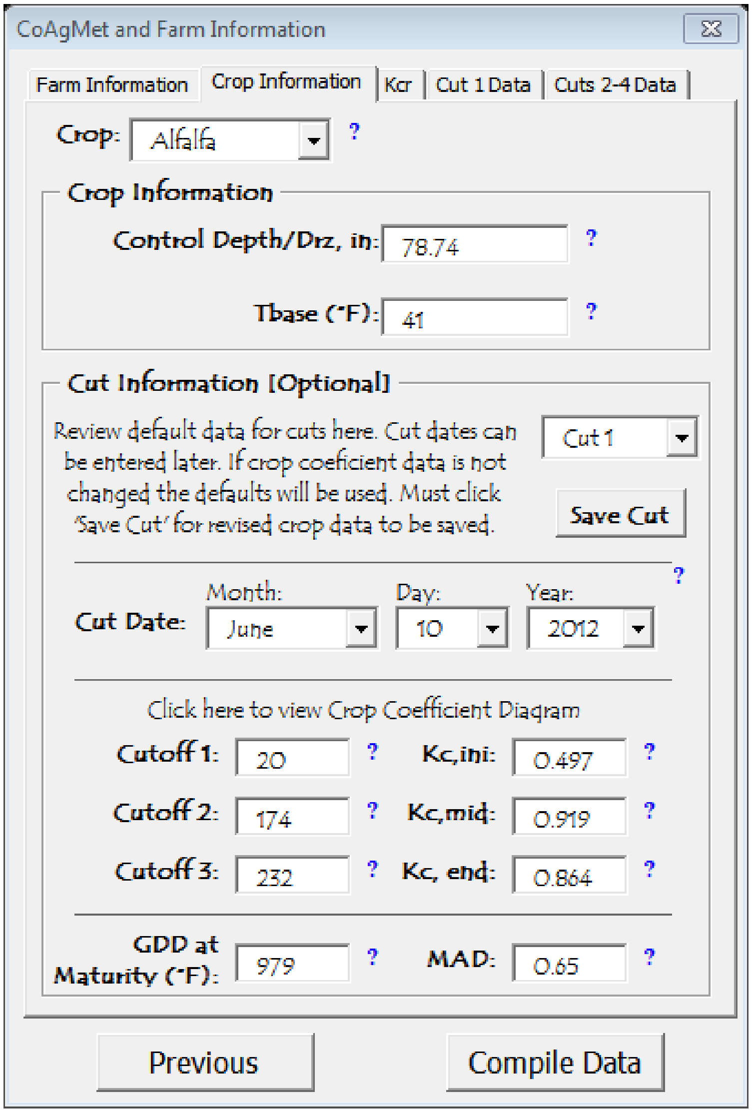
Select the crop that you want to schedule irrigation for. Default crop coefficients (Kc ini, Kc mid, Kc end, Cutoff 1, Cutoff 2, Cutoff 3, Tbase and Control depth) will be shown by cut. Adjust these as appropriate. For definitions of these variables see the Kcr page and for data that supports them see the Cut 1 Data and Cuts 2-4 Data pages, respectively. If you have more than one type of crop you will need to run a separate CIS for each crop.

B. Control Depth/Drz

Control depth is used for calculated and observed root-zone soil water deficits, also known as the root zone depth. For forage crops it is assumed that the control depth does not change over the course of the growing season.

C. Base Temperature (Tbase)

The base temperature is the lowest temperature at which the selected crop can grow and is used to calculate the growing degree days (GDD) accumulated each day. A default value taken from peer-reviewed articles or online GDD calculators (e.g., State Extension services) for the selected crop is shown.



Crop: Alfalfa

Crop Information

Control Depth/Drz, in: 78.74

Tbase (°F): 41

Cut Information [Optional]

Review default data for cuts here. Cut dates can be entered later. If crop coeficient data is not changed the defaults will be used. Must click 'Save Cut' for revised crop data to be saved.

Cut 1

Cut Date: Month: June Day: 10 Year: 2012

Cutoff 1: 20
Kc,ini: 0.497
Cutoff 2: 174
Kc,mid: 0.919
Cutoff 3: 232
Kc, end: 0.864
GDD at Maturity (°F): 979
MAD: 0.65

Figure III.3.D: Saving Cut Information

D. Select Cut

This drop-down menu allows the user to review and adjust as necessary default crop coefficient information for each cutting cycle.

Any changes to the default data will not be recorded until the 'Save Cut' button is clicked.

An example of reviewing crop coefficient data and entering a cut date is shown below in Figure III.3.D.

i. Cut Date

If the selected cut has not occurred yet leave this date blank. Otherwise enter the date that the selected cut was performed.

ii. Cutoff 1-3

Cutoff 1, 2 and 3 are the number of GDDs from green up that mark the end of the seedling phase, beginning of the full canopy phase, and the beginning of senescence phase, respectively. Default values are based on lengths of crop development phases from FAO-56 (Allen et al., 1998).

A diagram of the crop coefficient (Kcr) curve is provided in Figure III.4.

iii. Kc ini, mid, and end

Kc ini, Kc, mid, and Kc end are the crop coefficients at emergence, full cover and maturity, respectively. Default values for Cut 1 are based on data shown in Figure III.5 and default values for cuts 2-4 are based on data shown in Figure III.6. A diagram of the crop coefficient (Kcr) curve is provided in Figure III.4.

iv. GDD at Maturity

Enter the number of growing degree days (GDD, in degrees Fahrenheit) from emergence until you expect your crop to reach maturity/harvest age.

Default values are based on CoAgMet calculations at selected weather stations according to typical green-up and harvest dates.

v. MAD

Enter the management allowed depletion (MAD) as a decimal fraction of available water capacity, for each of the crop developmental phases. MAD1 is the MAD for the seedling phase, MAD2 is the MAD for the rapid development phase, MAD3 is the MAD for the full canopy phase, and MAD4 is the MAD for the senescence phase.

Default values are taken from FAO-56 (Allen et al., 1998) and CSU Extension Fact Sheet No 4.715 (Al-Kaisi and Boner, 2009).

4. Kcr

The Kcr tab contains a definition of the crop coefficient terms used including: Kcini, Kcmid, Kcend, cutoffs 1-3, and the seedling, rapid development, full canopy and senescence phases. This is also shown below in Figure III.4

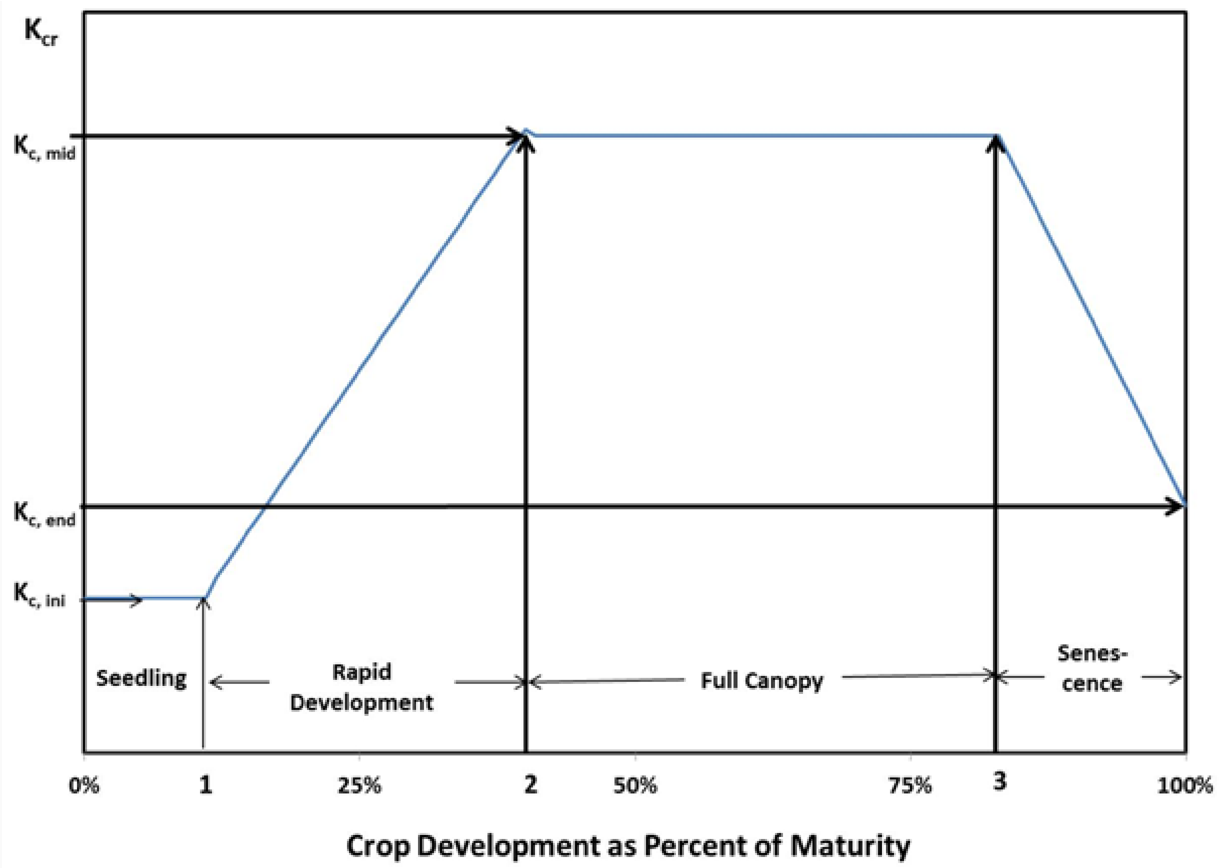


Figure III.4: Crop Coefficient Diagram with definitions of crop coefficient terms

5. Cut 1 Data

The data shown on the Cut 1 tab is crop coefficient data collected in the year 2010 for alfalfa at Rocky Ford, Colorado. This is included for reference in Figure III.5 below

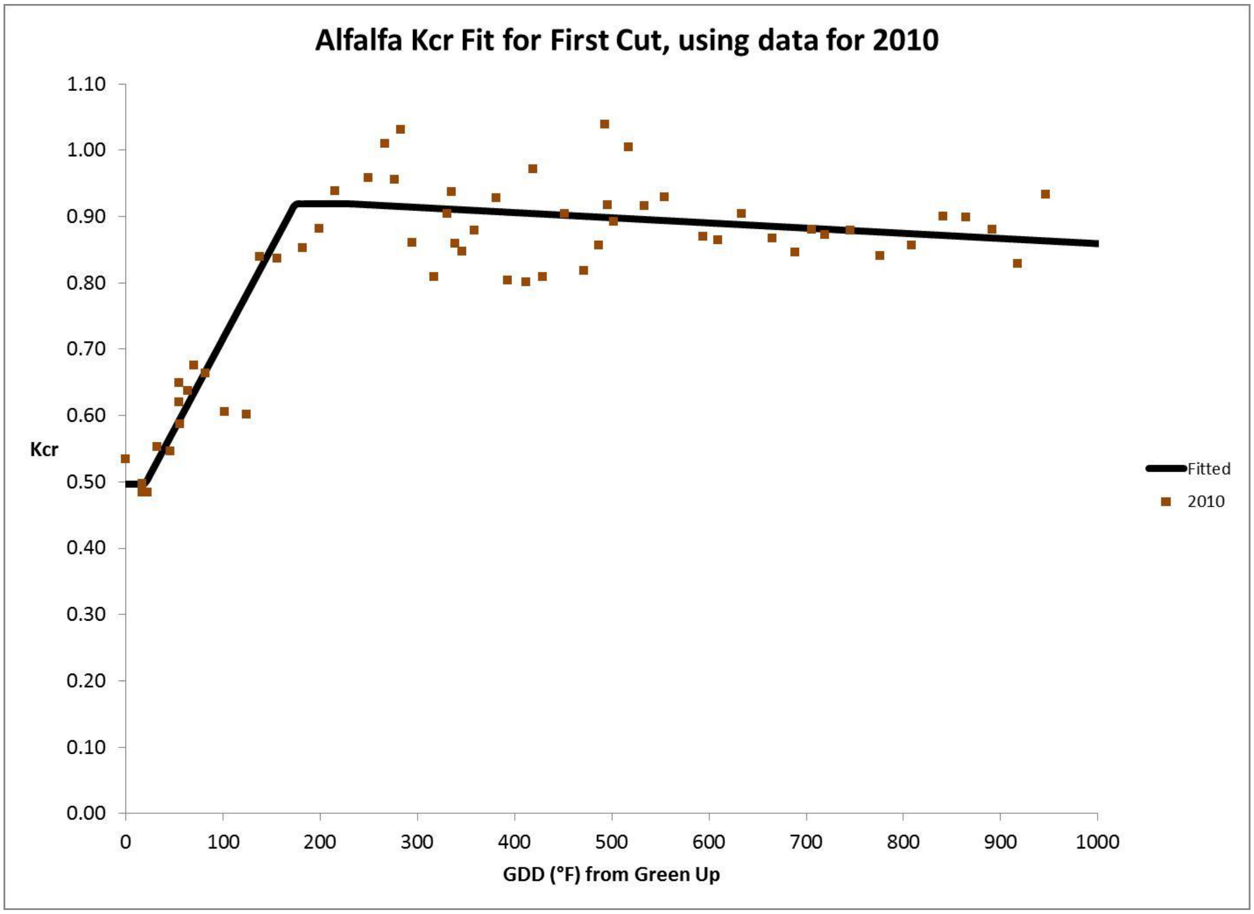


Figure III.5: Crop Coefficient data for alfalfa, default parameters used for fitted line

6. Cuts 2-4 Data

The data shown on the Cut 2-4 tab is crop coefficient data collected in the years 2008, 2009 and 2010 for alfalfa at Rocky Ford, Colorado. This is included for reference in Figure III.6 below

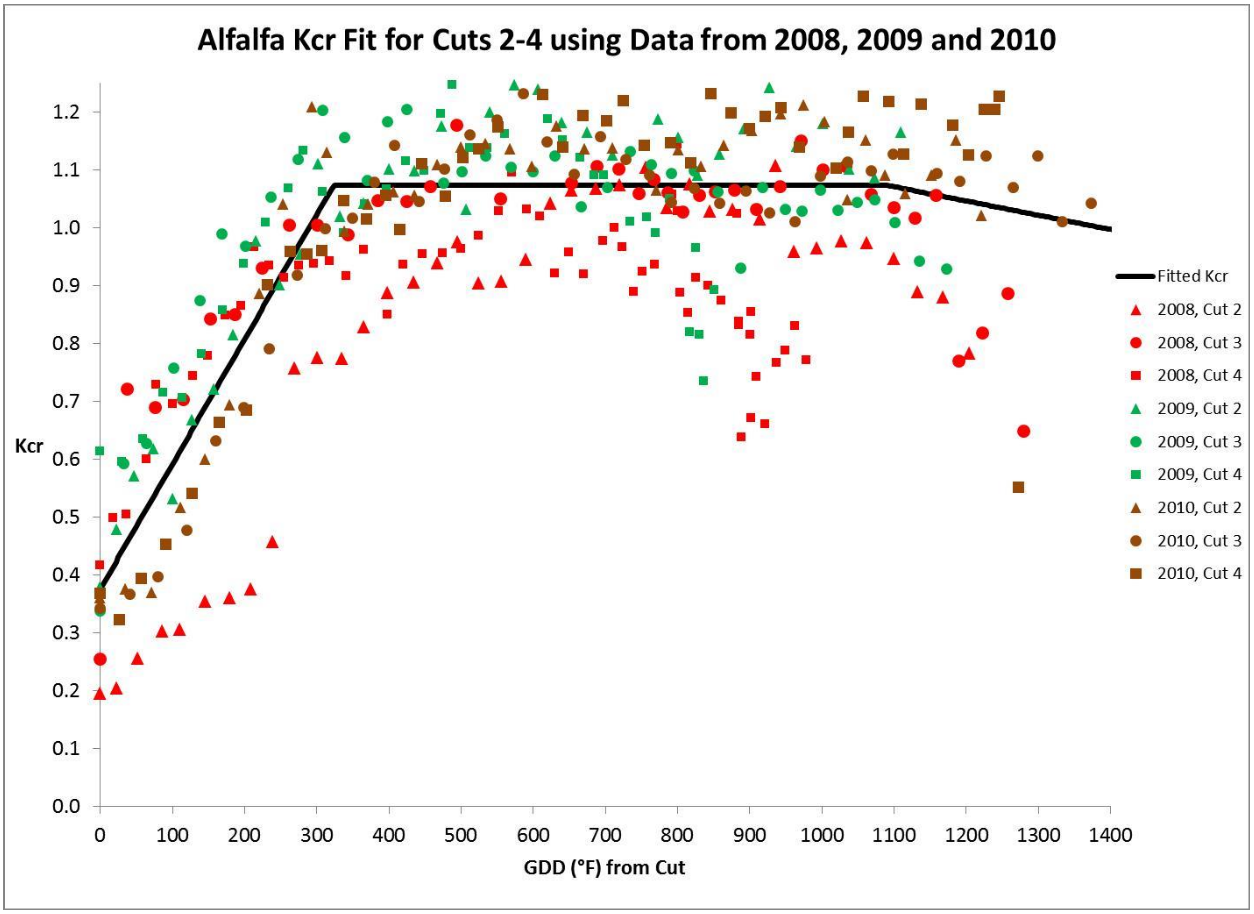
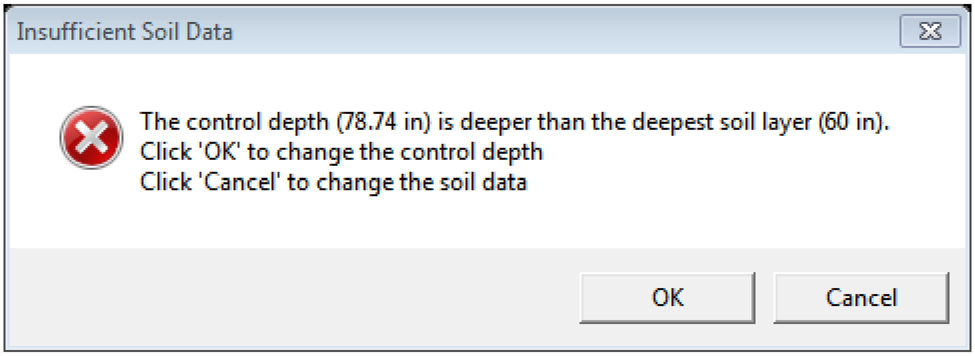


Figure III.6: Crop coefficient data for alfalfa, default values give the fitted line.

7. Click Compile Data

When the compile button is clicked, Excel will query CoAgMet for the daily values of: alfalfa reference evapotranspiration (ETr) calculated from the ASCE standardized reference ET equation (Allen et al., 2005), precipitation, maximum temperature, and minimum temperature for dates up to two years after the plant date. Occasionally come CoAgMet stations are non-operational, and data is missing. If any data is missing you will be prompted to either enter a value for each missing field or neglect any contribution to the ET, precipitation or GDD (depending on which field is missing) for that day. Occasionally stations are non-operational for long periods of time. If this occurs, either enter all of your own data, or select the second closest station to your farm. Alternatively, you can enter missing data using the 'EYO Data' sheet. EYO stands for 'enter your own' data. All weather data that are manually entered are saved in this sheet. Instructions for using the 'EYO Data' sheet are given at the top of the sheet. See Appendix A: Common Errors: Missing Data for more information about dealing with missing information.

NRCS WSS data usually does not go deeper than 60 in. If your crop has a control depth greater than 60 in an 'Insufficient Soil Data' error similar to Figure III.7.B may appear. See Appendix A.4 Insufficient Soil Data for more information about this error. The 'Water Chart' sheet should now be selected, and irrigation scheduling can now begin.



The control depth (78.74 in) is deeper than the deepest soil layer (60 in).
Click 'OK' to change the control depth
Click 'Cancel' to change the soil data

Figure III.7.B: Insufficient Soil Data error message

In this example 'Cancel' was clicked and the lower bound of the deepest soil layer was changed from '60' to '80' then 'Update Soils' was clicked.

When the 'Update Soils' button is clicked, the 'Water Chart' sheet will be selected, and irrigation scheduling can begin.

IV. Irrigation Management

The CIS has two parallel methods for entering irrigation data: the graphical and the spreadsheet method.

1. The Graphical Method

The graphical method of irrigation scheduling operates off of the ‘Water Chart’ sheet. Any information that is entered using the graphical method will be available for the spreadsheet method and vice-versa.

The Water Chart Sheet shows a graph of the root-zone deficit, precipitation, depth of management allowed depletion of the root-zone, net irrigation, and runoff and percolation for dates since the crop was planted. An example of the water chart page (after crop data is entered) is shown below in Figure IV.1

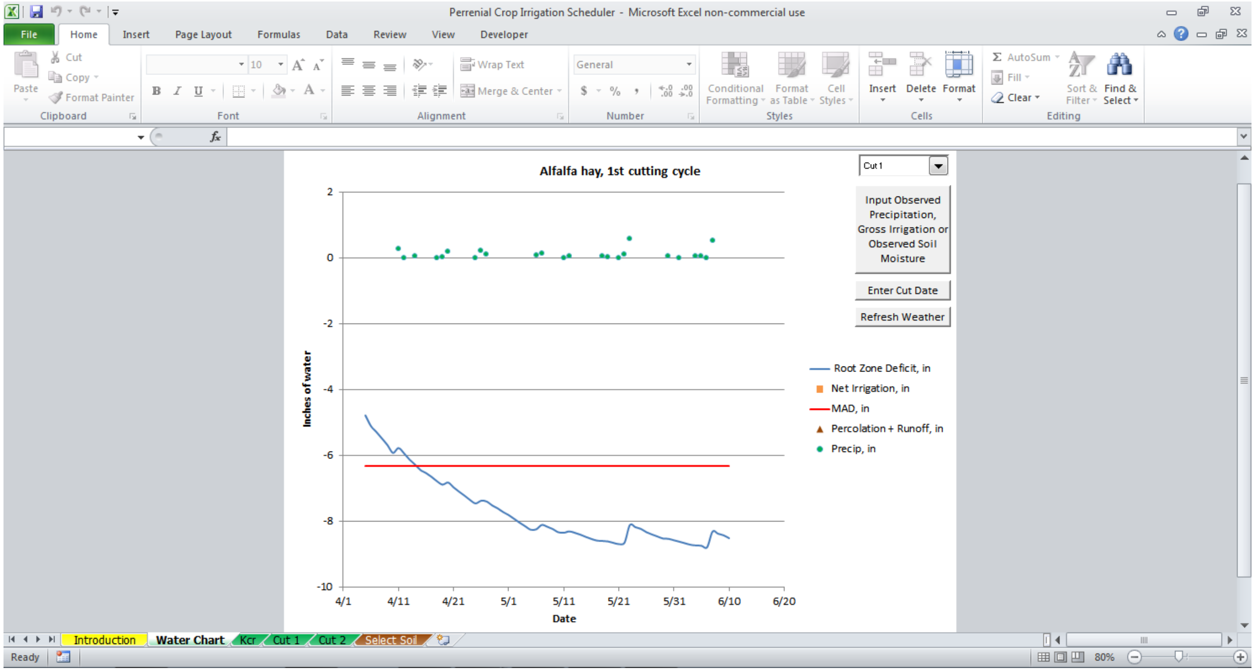


Figure IV.1: Default water chart before irrigation is entered

The Water Chart has a drop down menu to select the cutting cycle, and three buttons: ‘Enter Observed Precipitation, Gross Irrigation or Soil Moisture’, ‘Enter Cut Date’ and ‘Refresh Weather’.

A. Select a Cut

Irrigation data can only be entered for one cut at a time. The first cut will be selected by default. Since we entered a cut date for cut 1, the second cut is also available. To enter data for a different cut select the desired cut from the cut drop down menu as shown in Figure IV.1.A

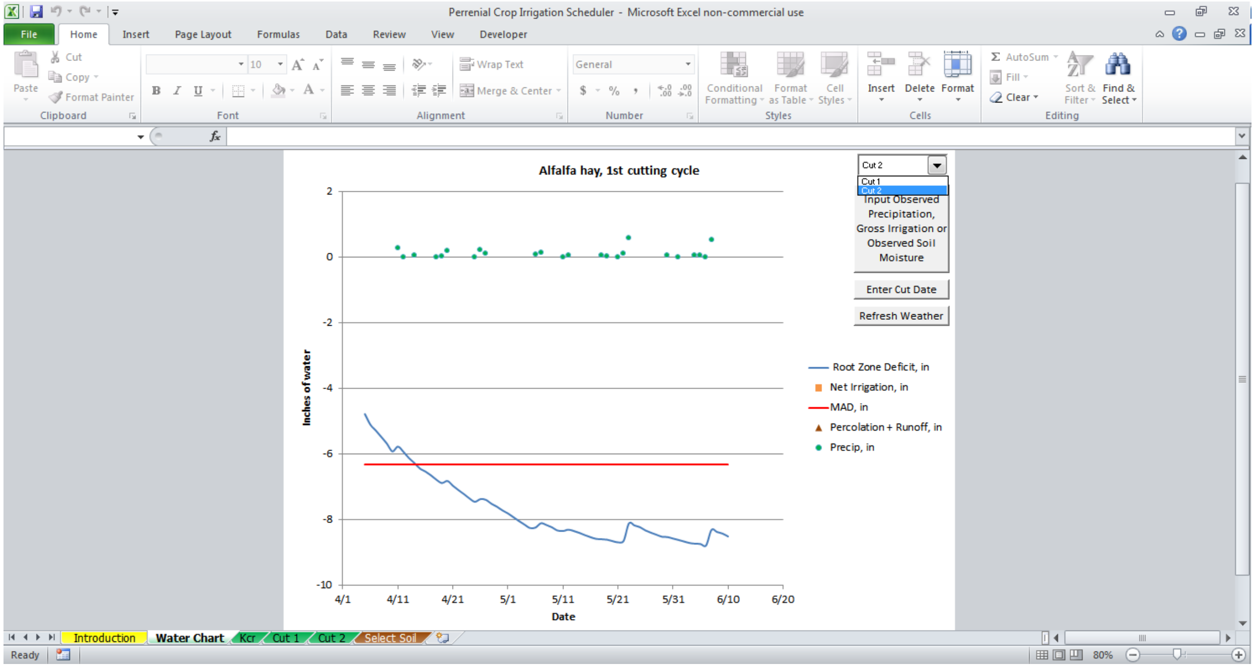


Figure IV.1.A: Changing the cut that is selected for irrigation scheduling

The soil layer deficit will carry over from one cut to the next, and the cut date can be assigned when the initial farm information is entered, or by using the ‘Enter Cut Date’ button on either the ‘Water Chart’ sheet or the respective cut sheet.

B. Enter Observed Precipitation, Gross Irrigation or Soil Moisture

This button will launch a form where observed precipitation, gross irrigation and observed soil moisture can be entered for any date. An empty version of the 'Irrigation Scheduler' form is shown below in Figure IV.1.A. This form has a list box containing the dates when irrigation could be applied, a multi-tab box where observed precipitation, gross irrigation and soil moisture can be entered and 'Input' and 'Quit' buttons. These features are described below.

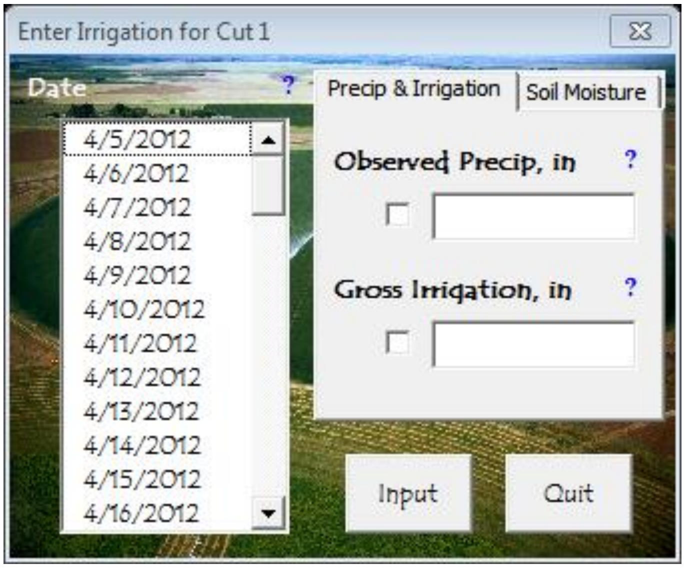


Figure IV.1.A: The 'Irrigation Scheduler' form

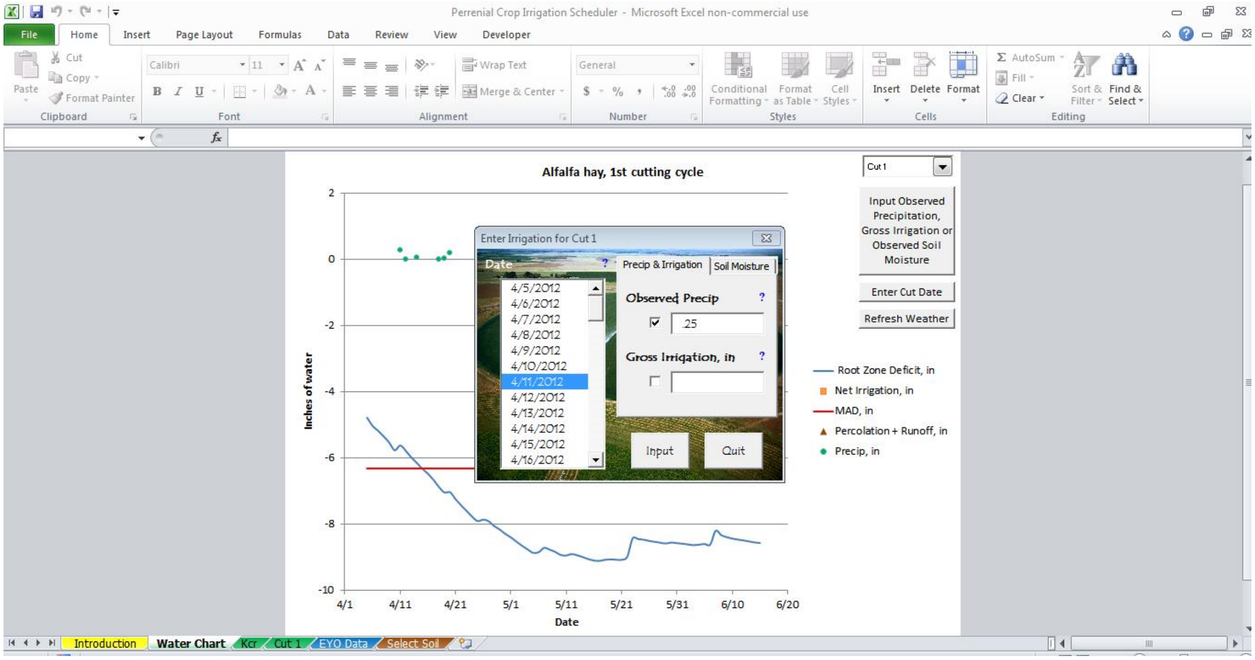
Dates

The form allows the user to enter data for any single date or for several dates at once where the same gross Irrigation, precipitation or soil moisture were observed. Click on the date to select it. Clicking on a selected date will unselect the date.

Observed Precipitation

If the precipitation at your field differs from the precipitation at the CoAgMet station where weather data was selected, the measured precipitation can be entered in the Observed Precipitation Box. To enter the observed precipitation click the check box, under the Observed Precipitation label and enter the observed value in the box. Then click 'Input' as shown below in Figure IV.1.Ai. Each time 'Input' is clicked all selected and entered fields will be cleared, so that the form is ready for more information to be entered.

There is no graphical difference between observed precipitation and default precipitation from CoAgMet, but the observed precipitation will override the CoAgMet precipitation value.



Cut 1

Enter Irrigation for Cut 1

Date: 4/5/2012, 4/6/2012, 4/7/2012, 4/8/2012, 4/9/2012, 4/10/2012, **4/11/2012**, 4/12/2012, 4/13/2012, 4/14/2012, 4/15/2012, 4/16/2012

Observed Precip ☑ .25

Gross Irrigation, in ☐

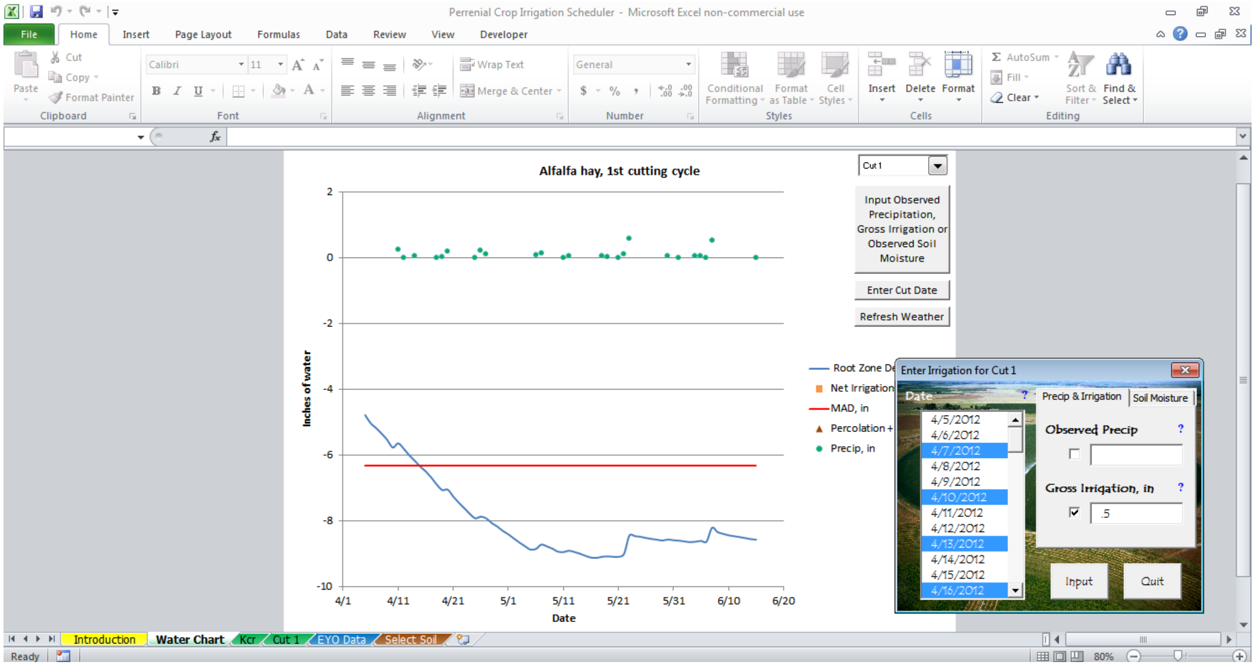
Figure IV.1.Ai: Entering Observed Precipitation

Gross Irrigation

Gross irrigation can be entered for each day separately or for several days at once if the same amount of gross irrigation is applied for each of the days. To enter gross irrigation values select the appropriate dates in the date list box, click the irrigation check box and enter the gross irrigation value (in inches) in the textbox under the Gross Irrigation label.

Click the Input button to enter the data.

Figure IV.1.Aii shows the irrigation form with 0.5 inch of gross irrigation applied every three days.



Observed Precip ☐

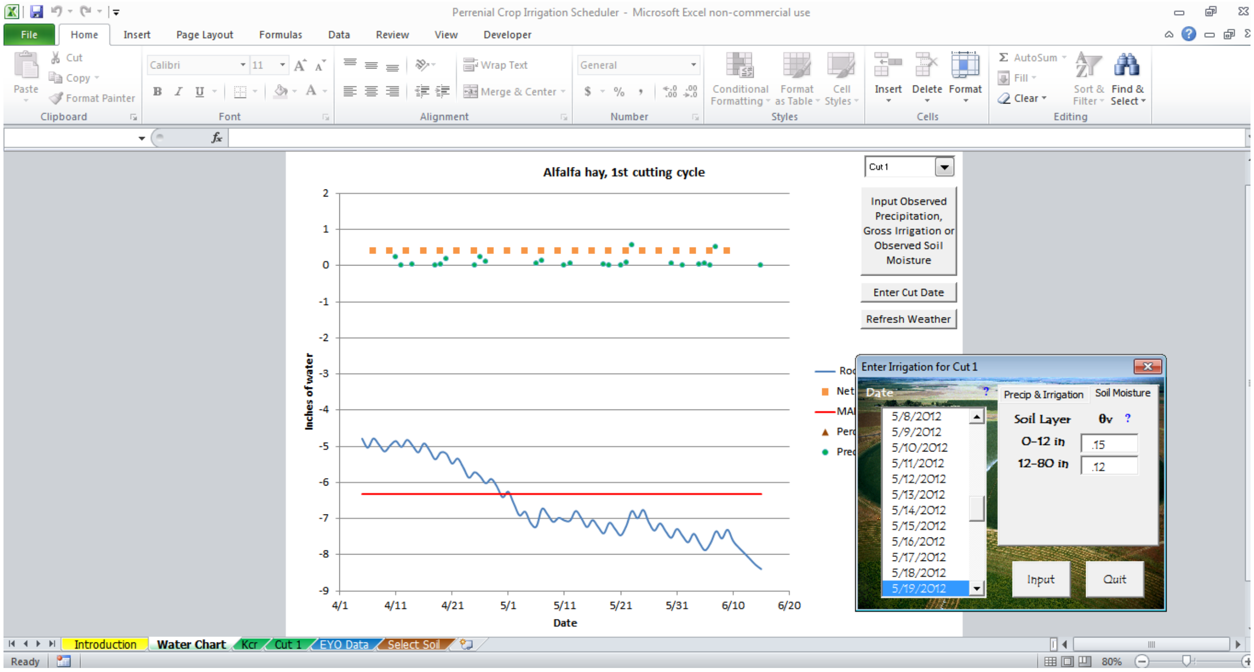
Gross Irrigation, in ☑ .5

Figure IV.1.Aii: Entering Gross Irrigation with the form

Observed Soil Moisture

To enter observed soil moisture, select the soil moisture tab on the Input Gross Irrigation form. Select the date when the soil moisture measurements were made, enter the soil moisture content (θv) (in inches per inch of soil), and click the ‘Input’ button.

Figure IV.1.Aiii shows the irrigation scheduler form filled out with some possible observed soil moisture contents.



Cut 1

Soil Layer	θv
0-12 in	.15
12-80 in	.12

Figure IV.1.Aiii Entering Soil Moisture Content

Entering observed moisture content for a day will override the calculated deficit for that day.

Input Button

The Input button enters the observed precipitation and/or gross irrigation values that have been entered for the date(s) selected if the ‘Precip & Irrigation’ tab is selected. If the ‘Soil Moisture’ tab is selected then only the soil moisture data will be entered for the selected day(s).

Each time the Input button is clicked, the daily deficit is calculated for each soil layer, the graph is updated, and the irrigation form is reset.

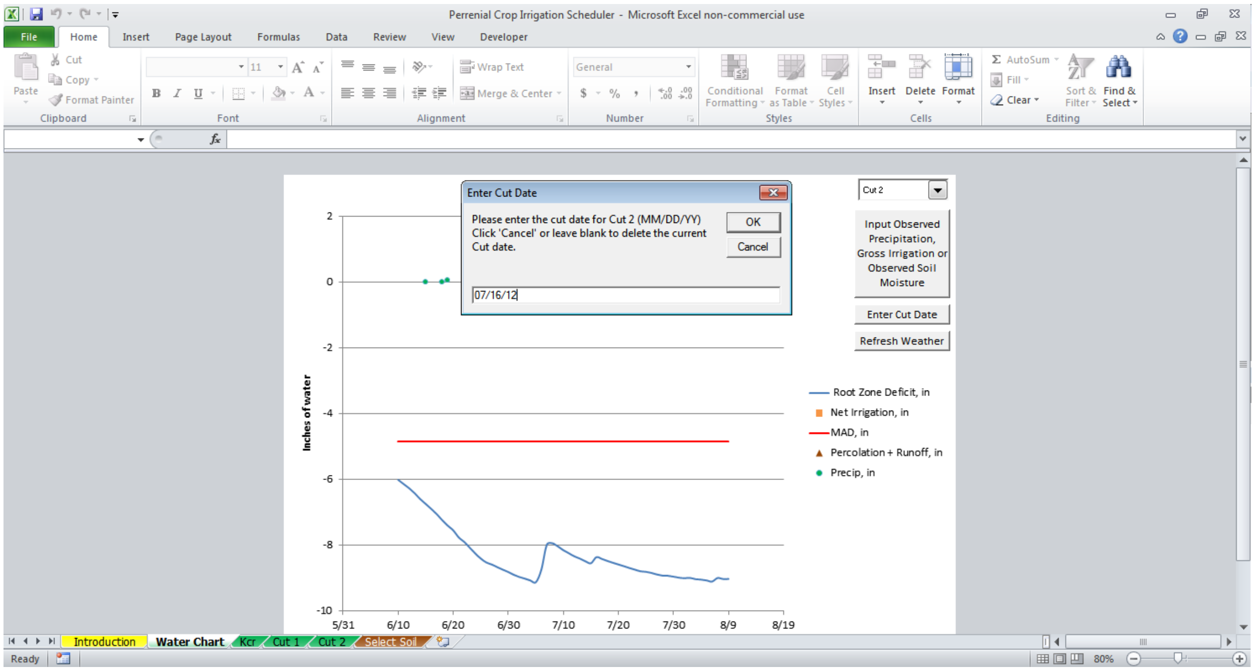
Quit Button

Use either the Quit button or the “x” on the Irrigation form to stop entering data using the irrigation form when finished.

C. Enter Cut Date

The ‘Enter Cut Date’ button allows the user to enter or change the cut date for the selected cutting cycle. If the ‘Cut 1’ sheet is selected and a cut date is entered, the ‘Cut 1’ sheet will now contain dates from Green Up to Cut 1, and the ‘Cut 2’ sheet will contain dates after Cut 1. If a cut date is entered with ‘Cut 2’ selected, the ‘Cut 2’ sheet will then contain dates from the Cut 1 date to the Cut 2 date, and so on for the ‘Cut 3’ and ‘Cut 4’ sheets.

The ‘Enter Cut Date’ button will display a dialogue box similar to Figure IV.1.C, if a cut date has already been entered it will be displayed as in Figure IV.2.B, *changing this date or clicking ‘Cancel’ will erase all observed precipitation, gross irrigation, and soil moisture data that has been entered.* When entering a new cut date use a valid date format such as MM/DD/YY, and click ‘OK’.



Please enter the cut date for Cut 2 (MM/DD/YY)
Click 'Cancel' or leave blank to delete the current Cut date.

07/16/12

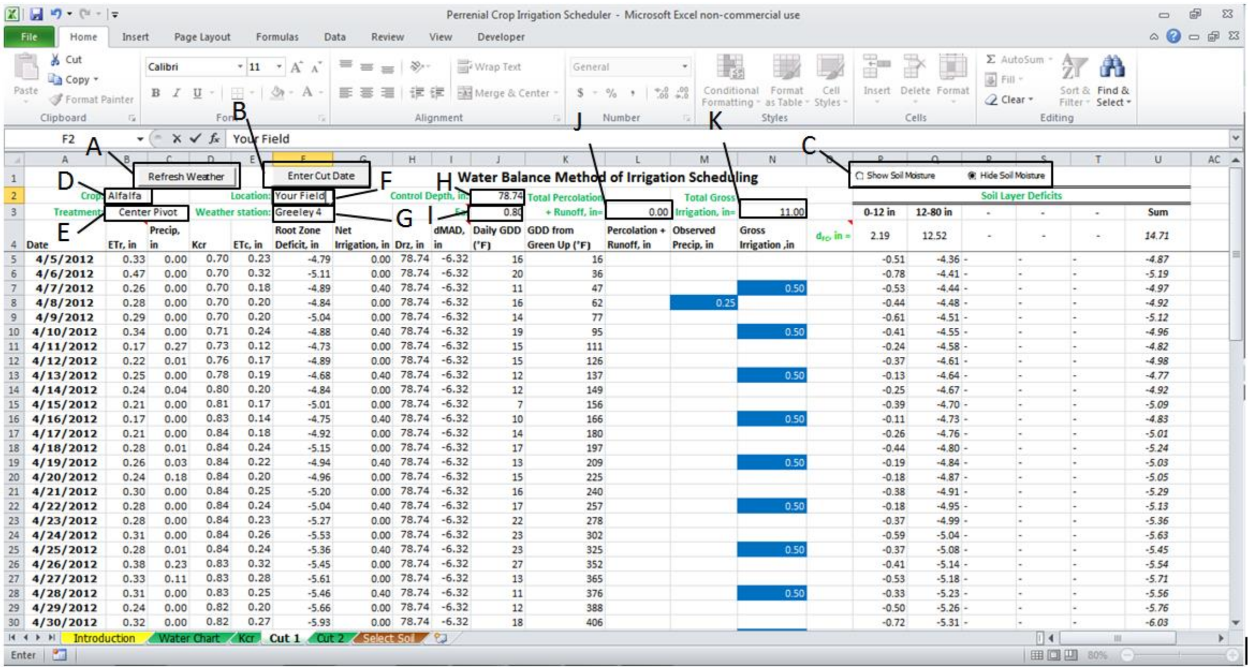
Figure IV.1.C: Enter Cut date dialogue box

D. Refresh Weather

The refresh data button on the Water Chart Page will query CoAgMet for the most recent weather data, usually up to one day old. See Appendix B.2 Missing Data for more information about missing weather data.

2. The Spreadsheet Method

The spreadsheet method uses the cut sheets. Each Cut sheet shows numerical values for Date, ETr, Precip, Kcr, ETc, Root Zone Deficit, Net Irrigation, Drz, dMAD, GDD from Emergence (°F), Days after planting, Day #, Percolation + Runoff, Observed Precip, Gross Irrigation, and deficits for each layer for every day. All depths are in inches. Figure IV.2 shows the 'Cut 1' sheet with the data that was entered above using the Graphical Method.



F2 Your Field

Water Balance Method of Irrigation Scheduling

Crop: Alfalfa
Location: Your Field
Control Depth, in: 78.74
Total Percolation + Runoff, in= 0.00
Total Gross Irrigation, in= 11.00
Treatment: Center Pivot
Weather station: Greeley 4
F= 0.80

Date	ETr, in	Precip, in	Kcr	ETc, in	Root Zone Deficit, in	Net Irrigation, in	Drz, in	dMAD, in	Daily GDD (°F)	GDD from Green Up (°F)	Percolation + Runoff, in	Observed Precip, in	Gross Irrigation ,in		Soil Layer Deficits 0-12 in	12-80 in	-	-	-	Sum
														d_{FC}, in =	2.19	12.52	-	-	-	*14.71*
4/5/2012	0.33	0.00	0.70	0.23	-4.79	0.00	78.74	-6.32	16	16					-0.51	-4.36	-	-	-	*-4.87*
4/6/2012	0.47	0.00	0.70	0.32	-5.11	0.00	78.74	-6.32	20	36					-0.78	-4.41	-	-	-	*-5.19*
4/7/2012	0.26	0.00	0.70	0.18	-4.89	0.40	78.74	-6.32	11	47			0.50		-0.53	-4.44	-	-	-	*-4.97*
4/8/2012	0.28	0.00	0.70	0.20	-4.84	0.00	78.74	-6.32	16	62		0.25			-0.44	-4.48	-	-	-	*-4.92*
4/9/2012	0.29	0.00	0.70	0.20	-5.04	0.00	78.74	-6.32	14	77					-0.61	-4.51	-	-	-	*-5.12*
4/10/2012	0.34	0.00	0.71	0.24	-4.88	0.40	78.74	-6.32	19	95			0.50		-0.41	-4.55	-	-	-	*-4.96*
4/11/2012	0.17	0.27	0.73	0.12	-4.73	0.00	78.74	-6.32	15	111					-0.24	-4.58	-	-	-	*-4.82*
4/12/2012	0.22	0.01	0.76	0.17	-4.89	0.00	78.74	-6.32	15	126					-0.37	-4.61	-	-	-	*-4.98*
4/13/2012	0.25	0.00	0.78	0.19	-4.68	0.40	78.74	-6.32	12	137			0.50		-0.13	-4.64	-	-	-	*-4.77*
4/14/2012	0.24	0.04	0.80	0.20	-4.84	0.00	78.74	-6.32	12	149					-0.25	-4.67	-	-	-	*-4.92*
4/15/2012	0.21	0.00	0.81	0.17	-5.01	0.00	78.74	-6.32	7	156					-0.39	-4.70	-	-	-	*-5.09*
4/16/2012	0.17	0.00	0.83	0.14	-4.75	0.40	78.74	-6.32	10	166			0.50		-0.11	-4.73	-	-	-	*-4.83*
4/17/2012	0.21	0.00	0.84	0.18	-4.92	0.00	78.74	-6.32	14	180					-0.26	-4.76	-	-	-	*-5.01*
4/18/2012	0.28	0.01	0.84	0.24	-5.15	0.00	78.74	-6.32	17	197					-0.44	-4.80	-	-	-	*-5.24*
4/19/2012	0.26	0.03	0.84	0.22	-4.94	0.40	78.74	-6.32	13	209			0.50		-0.19	-4.84	-	-	-	*-5.03*
4/20/2012	0.24	0.18	0.84	0.20	-4.96	0.00	78.74	-6.32	15	225					-0.18	-4.87	-	-	-	*-5.05*
4/21/2012	0.30	0.00	0.84	0.25	-5.20	0.00	78.74	-6.32	16	240					-0.38	-4.91	-	-	-	*-5.29*
4/22/2012	0.28	0.00	0.84	0.24	-5.04	0.40	78.74	-6.32	17	257			0.50		-0.18	-4.95	-	-	-	*-5.13*
4/23/2012	0.28	0.00	0.84	0.23	-5.27	0.00	78.74	-6.32	22	278					-0.37	-4.99	-	-	-	*-5.36*
4/24/2012	0.31	0.00	0.84	0.26	-5.53	0.00	78.74	-6.32	23	302					-0.59	-5.04	-	-	-	*-5.63*
4/25/2012	0.28	0.01	0.84	0.24	-5.36	0.40	78.74	-6.32	23	325			0.50		-0.37	-5.08	-	-	-	*-5.45*
4/26/2012	0.38	0.23	0.83	0.32	-5.45	0.00	78.74	-6.32	27	352					-0.41	-5.14	-	-	-	*-5.54*
4/27/2012	0.33	0.11	0.83	0.28	-5.61	0.00	78.74	-6.32	13	365					-0.53	-5.18	-	-	-	*-5.71*
4/28/2012	0.31	0.00	0.83	0.25	-5.46	0.40	78.74	-6.32	11	376			0.50		-0.33	-5.23	-	-	-	*-5.56*
4/29/2012	0.24	0.00	0.82	0.20	-5.66	0.00	78.74	-6.32	12	388					-0.50	-5.26	-	-	-	*-5.76*
4/30/2012	0.32	0.00	0.82	0.27	-5.93	0.00	78.74	-6.32	18	406					-0.72	-5.31	-	-	-	*-6.03*

Figure IV.2 Filled out 'Cut 1' sheet, labeled fields are discussed below

The 'Cut 1' sheet contains several editable fields and gives the ability to change values that were assigned in either the 'CoAgMet and Farm Information' form or the 'Irrigation Scheduler' form.

All of the Crop and Farm information fields should be already filled out; however they can be changed on this page as necessary. These fields will be the same on the sheet for Cut 1-4, so any changes need to be made on the 'Cut 1' sheet. A summary of each of these fields follows:

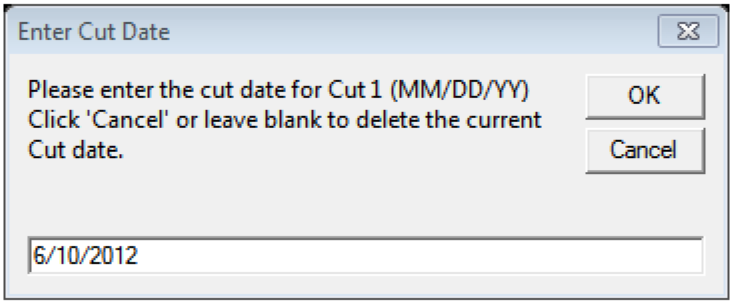
A. Refresh Data

The 'Refresh Data' button will get the most recent weather data from CoAgMet using the date shown in cell 'A5' as the green up date and the weather station in cell 'F3'. This will get up to one day old weather data. Any observed precipitation, gross irrigations, soil moistures or LAI values that have been entered will be saved, but if CoAgMet had missing data for your station that missing data will need to be filled in each time that the weather data is refreshed. See Appendix B.2 Missing Data for more information about missing data in CoAgMet.

B. Enter Cut Date

The 'Enter Cut Date' button allows the user to enter or change the cut date for the selected cut. If the 'Cut 1' sheet is selected and a cut date is entered, the 'Cut 1' sheet will now contain dates from Green Up to Cut 1, and the 'Cut 2' sheet will contain dates after Cut 1. If a cut date is entered with the 'Cut 2' sheet selected the 'Cut 2' sheet will now contain dates from the Cut 1 date to the Cut 2 date, and so on for the 'Cut 3' and 'Cut 4' sheets.

The 'Enter Cut Date' button will display a dialogue box similar to Figure IV.1.C, if a cut date has already been entered it will be displayed as it in Figure IV.2.B, *changing this date or clicking 'Cancel' will erase all observed precipitation, gross irrigation, and soil moisture data that has been entered.* When entering a new cut date use a valid date format such as MM/DD/YY, and click 'OK'.



Please enter the cut date for Cut 1 (MM/DD/YY)
Click 'Cancel' or leave blank to delete the current Cut date.

6/10/2012

Figure IV.2.B: Enter Cut Date dialogue box

C. Show/Hide Observed θv

The show / hide observed θv buttons show or hide columns that allow the user to enter soil moisture measurements for the soil layers specified on the 'Select Soil' sheet as shown in Figure IV.2.C. When a soil moisture value is entered the soil layer deficits will be automatically updated.

Column "V" contains the stress coefficient (Ks) that is calculated for the root-zone by the root-zone deficit algorithm. In general Ks is calculated as follows:

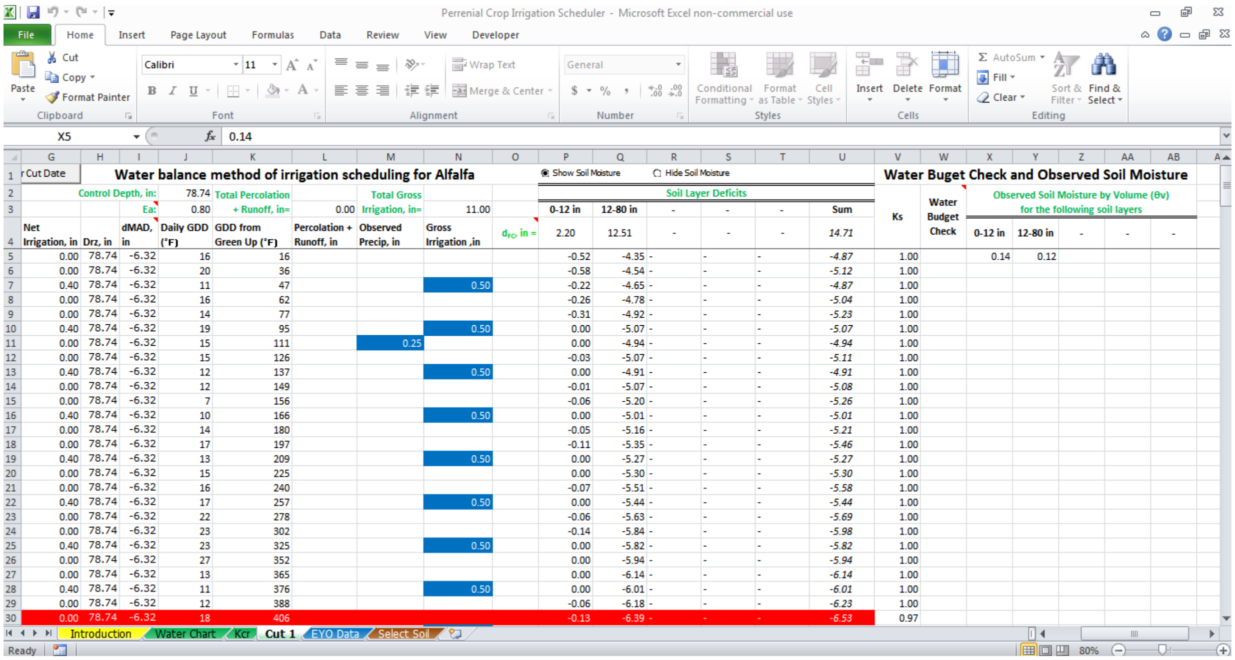
$$Ks = \frac{TAW - |D|}{(1 - MAD) * TAW}$$

where,

TAW is the total available water capacity in the root-zone (inches)
D is the root-zone deficit (inches)
MAD is the management allowed depletion, given as a fraction of the available water capacity

Column "W" contains a daily water budget check. If the water did not balance then "False" will be displayed in the respective row of column "W", the water budget reading false when soil moisture values are entered indicates that the measured deficit differed from the calculated deficit by at least ±0.0001 in. The following water balance was used:

$$\Delta Total\ Deficit = Net\ Irrigation + Precip - ETc * Ks - (Percolation + Runoff)$$



X5 = 0.14

	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB
1	r Cut Date	Water balance method of irrigation scheduling for Alfalfa								● Show Soil Moisture		○ Hide Soil Moisture				Water Buget Check and Observed Soil Moisture						
2		Control Depth, in:		78.74	Total Percolation		Total Gross			Soil Layer Deficits						Ks	Water Budget Check	Observed Soil Moisture by Volume (θv) for the following soil layers				
3			Ea:	0.80	+ Runoff, in=	0.00	Irrigation, in=	11.00		0-12 in	12-80 in	-	-	-	Sum							
4	Net Irrigation, in	Drz, in	dMAD, in	Daily GDD (°F)	GDD from Green Up (°F)	Percolation + Runoff, in	Observed Precip, in	Gross Irrigation ,in	d_{FC}, in =	2.20	12.51	-	-	-	14.71			0-12 in	12-80 in	-	-	-
5	0.00	78.74	-6.32	16	16					-0.52	-4.35	-	-	-	-4.87	1.00		0.14	0.12			
6	0.00	78.74	-6.32	20	36					-0.58	-4.54	-	-	-	-5.12	1.00						
7	0.40	78.74	-6.32	11	47			0.50		-0.22	-4.65	-	-	-	-4.87	1.00						
8	0.00	78.74	-6.32	16	62					-0.26	-4.78	-	-	-	-5.04	1.00						
9	0.00	78.74	-6.32	14	77					-0.31	-4.92	-	-	-	-5.23	1.00						
10	0.40	78.74	-6.32	19	95			0.50		0.00	-5.07	-	-	-	-5.07	1.00						
11	0.00	78.74	-6.32	15	111		0.25			0.00	-4.94	-	-	-	-4.94	1.00						
12	0.00	78.74	-6.32	15	126					-0.03	-5.07	-	-	-	-5.11	1.00						
13	0.40	78.74	-6.32	12	137			0.50		0.00	-4.91	-	-	-	-4.91	1.00						
14	0.00	78.74	-6.32	12	149					-0.01	-5.07	-	-	-	-5.08	1.00						
15	0.00	78.74	-6.32	7	156					-0.06	-5.20	-	-	-	-5.26	1.00						
16	0.40	78.74	-6.32	10	166			0.50		0.00	-5.01	-	-	-	-5.01	1.00						
17	0.00	78.74	-6.32	14	180					-0.05	-5.16	-	-	-	-5.21	1.00						
18	0.00	78.74	-6.32	17	197					-0.11	-5.35	-	-	-	-5.46	1.00						
19	0.40	78.74	-6.32	13	209			0.50		0.00	-5.27	-	-	-	-5.27	1.00						
20	0.00	78.74	-6.32	15	225					0.00	-5.30	-	-	-	-5.30	1.00						
21	0.00	78.74	-6.32	16	240					-0.07	-5.51	-	-	-	-5.58	1.00						
22	0.40	78.74	-6.32	17	257			0.50		0.00	-5.44	-	-	-	-5.44	1.00						
23	0.00	78.74	-6.32	22	278					-0.06	-5.63	-	-	-	-5.69	1.00						
24	0.00	78.74	-6.32	23	302					-0.14	-5.84	-	-	-	-5.98	1.00						
25	0.40	78.74	-6.32	23	325			0.50		0.00	-5.82	-	-	-	-5.82	1.00						
26	0.00	78.74	-6.32	27	352					0.00	-5.94	-	-	-	-5.94	1.00						
27	0.00	78.74	-6.32	13	365					0.00	-6.14	-	-	-	-6.14	1.00						
28	0.40	78.74	-6.32	11	376			0.50		0.00	-6.01	-	-	-	-6.01	1.00						
29	0.00	78.74	-6.32	12	388					-0.06	-6.18	-	-	-	-6.23	1.00						
30	0.00	78.74	-6.32	18	406					-0.13	-6.39	-	-	-	-6.53	0.97						

Figure IV.2.C: Observed Soil Moisture, Ks, and Water Budget Check columns

D. Crop

The crop shown here is the crop that was selected on the ‘CoAgMet and Farm Information’ form. Changing the crop here will not change the crop parameters that are used by the CIS. The control depth can be changed on the ‘Cut 1’ sheet. For information on how to change GDD cutoffs, Kcr levels, MAD levels, temperature cutoffs, or emergence date see Section V.1 Water Chart Reference.

E. Treatment

The treatment is the irrigation method used. A few standard irrigation treatments are listed in a drop down menu when cell “B2:C2” is clicked. Selecting one of these default irrigation treatments will automatically update the Ea for the selected Irrigation treatment and recalculate the Soil Layer Deficits.

F. Location

The Location field is for reference only making it easier to differentiate between fields if irrigation scheduling is performed for several fields. The location will not be filled out by the CoAgMet and Farm Information form, but can be entered on the ‘Cut 1’ sheet if desired.

G. Weather Station

The CoAgMet station that was selected on the ‘CoAgMet and Farm Information’ form is shown here. The comment in cell “F3” shows the information for the selected station.

Cell “F3” contains a drop down menu with all of the available CoAgMet weather stations allowing the user to change weather stations as necessary. If a station is selected that has a last observed date before the green-up date an error message will be displayed. The weather data will be updated to a newly selected station when the ‘Refresh Data’ button is clicked.

H. Control Depth, in

The control depth is used for calculated and observed total soil water deficits, also known as the rooting depth. The root zone for forage crops is assumed to be constant. When the control depth is changed on the ‘Cut 1’ sheet, the soil layer deficits will automatically be recalculated.

I. Ea

The irrigation application efficiency (Ea) is the ratio of the Net Irrigation to the Gross Irrigation. In other words, Ea is the fraction of the gross applied irrigation that gets stored in the root zone. Applied irrigation that is not stored in the root zone is assumed to be lost via surface runoff and/or deep percolation. When the Ea is changed on the ‘Cut 1’ sheet the Soil Layer Deficits will automatically be recalculated.

J. Total Percolation + Runoff

The CIS assumes that any net irrigation or precipitation that is greater than the current total soil deficit will either runoff or percolate. The total percolation + runoff is the sum of these daily runoff or percolation values over the course of the growing season to date. Percolation and runoff are usually caused by over irrigation, but can also be caused by large precipitation events.

K. Total Gross Irrigation

The total gross irrigation applied over the growing season to date is recorded in cell “O3” for reference.

3. Kcr

The ‘Kcr’ sheet contains a graph of the crop coefficient for the selected cutting cycle. The selected cutting cycle can be changed with a drop-down menu similar to the drop-down menu on the ‘Water Chart’ sheet. An example of the crop coefficient sheet is shown below in Figure IV.3

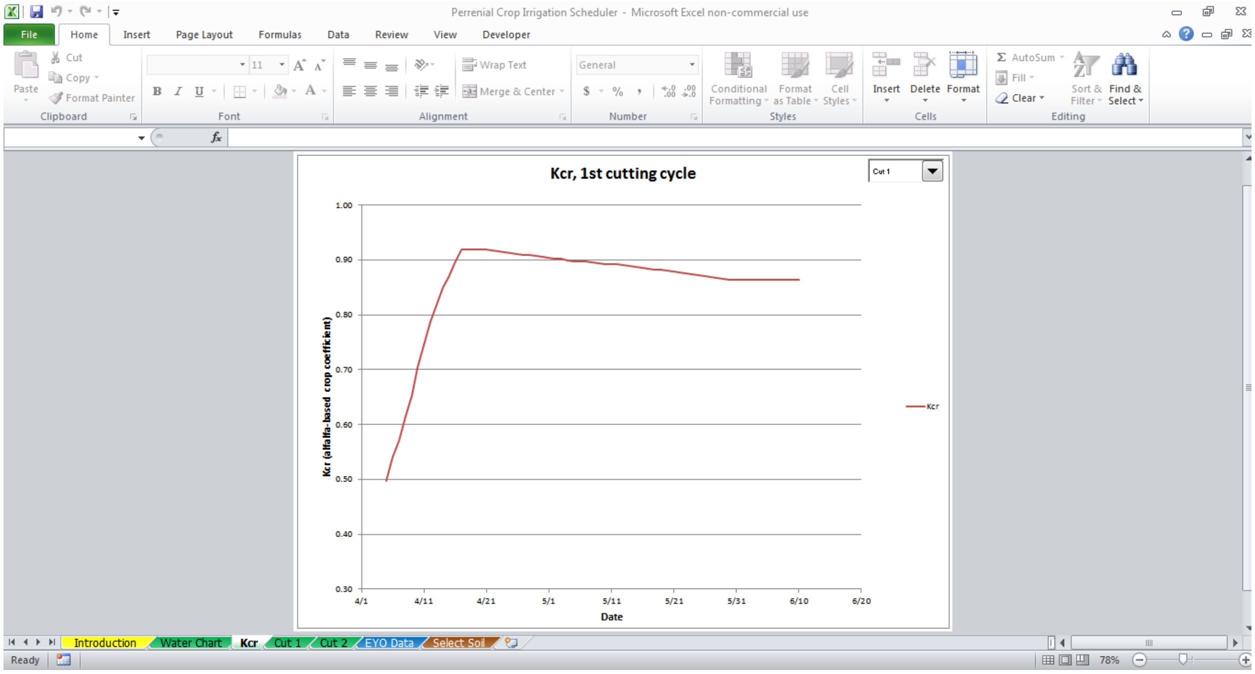


Figure IV.3: The Kcr sheet

V. Analysis Pages

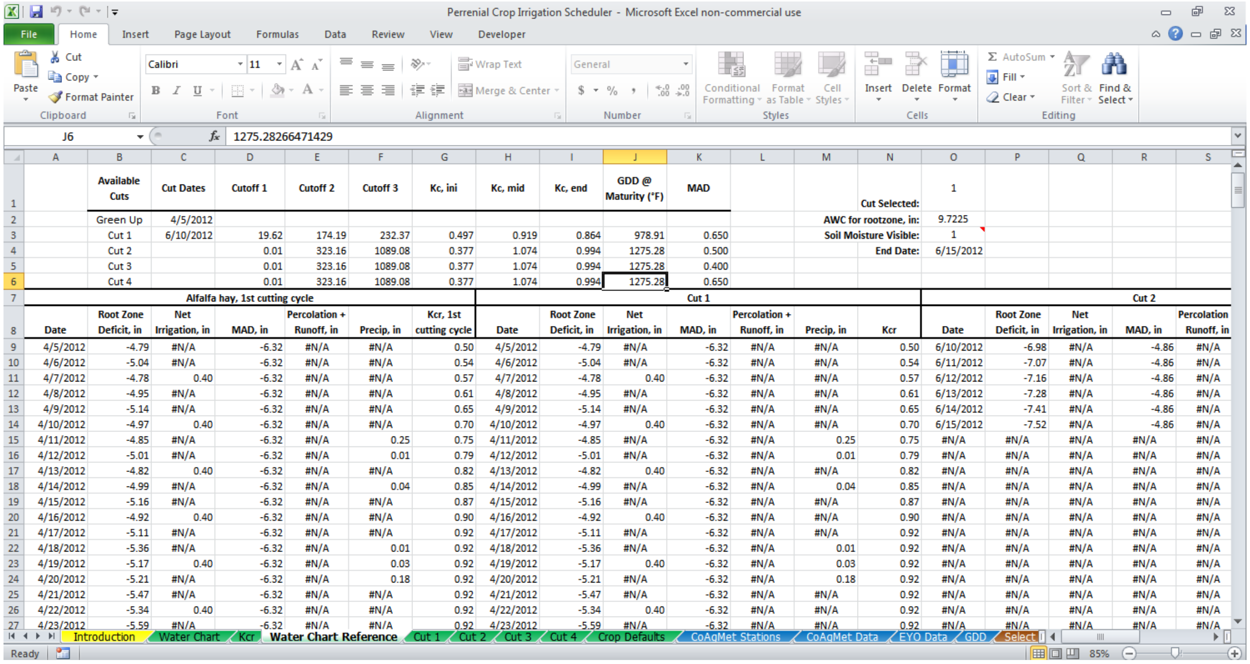
The Colorado Irrigation Scheduler uses several background analysis pages to store information that is queried from the NRCS Web Soil Survey and from CoAgMet and to perform calculations. The user should not need to use these sheets, but they are described below for completeness.

These pages can be made visible with the ‘Show/Hide Analysis’ option buttons on the ‘Introduction’ sheet or the option buttons on the ‘Select Soil’ sheet. These sheets are described below.

1. Water Chart Reference

The ‘Water Chart Reference’ sheet, shown in Figure V.1, contains the crop coefficient cutoff information for each of the cutting cycles, cut dates, as well as some other references. This sheet also allows the ‘Water Chart’ sheet and the ‘Kcr’ sheet to show data for one cut at a time via the drop down menu on each of these sheets. If it is necessary to edit crop coefficient data, the ‘Water Chart Reference’ sheet can be Unprotected via the ‘Review’ ribbon. Once the necessary changes are made, click the ‘Refresh Weather’ button on one of the cut sheets or on the ‘Water Chart’ sheet.

WARNING: Making changes to the ‘Water Chart Reference’ sheet could cause the CIS to become corrupted and stop working properly. See Appendix A: Protection for more information about sheet protection in the CIS.



J6 1275.28266471429

Available Cuts	Cut Dates	Cutoff 1	Cutoff 2	Cutoff 3	Kc, ini	Kc, mid	Kc, end	GDD @ Maturity (°F)	MAD	Cut Selected:	1
Green Up	4/5/2012									AWC for rootzone, in:	9.7225
Cut 1	6/10/2012	19.62	174.19	232.37	0.497	0.919	0.864	978.91	0.650	Soil Moisture Visible:	1
Cut 2		0.01	323.16	1089.08	0.377	1.074	0.994	1275.28	0.500	End Date:	6/15/2012
Cut 3		0.01	323.16	1089.08	0.377	1.074	0.994	1275.28	0.400		
Cut 4		0.01	323.16	1089.08	0.377	1.074	0.994	1275.28	0.650		

Alfalfa hay, 1st cutting cycle							Cut 1							Cut 2				
Date	Root Zone Deficit, in	Net Irrigation, in	MAD, in	Percolation + Runoff, in	Precip, in	Kcr, 1st cutting cycle	Date	Root Zone Deficit, in	Net Irrigation, in	MAD, in	Percolation + Runoff, in	Precip, in	Kcr	Date	Root Zone Deficit, in	Net Irrigation, in	MAD, in	Percolation Runoff, in
4/5/2012	-4.79	#N/A	-6.32	#N/A	#N/A	0.50	4/5/2012	-4.79	#N/A	-6.32	#N/A	#N/A	0.50	6/10/2012	-6.98	#N/A	-4.86	#N/A
4/6/2012	-5.04	#N/A	-6.32	#N/A	#N/A	0.54	4/6/2012	-5.04	#N/A	-6.32	#N/A	#N/A	0.54	6/11/2012	-7.07	#N/A	-4.86	#N/A
4/7/2012	-4.78	0.40	-6.32	#N/A	#N/A	0.57	4/7/2012	-4.78	0.40	-6.32	#N/A	#N/A	0.57	6/12/2012	-7.16	#N/A	-4.86	#N/A
4/8/2012	-4.95	#N/A	-6.32	#N/A	#N/A	0.61	4/8/2012	-4.95	#N/A	-6.32	#N/A	#N/A	0.61	6/13/2012	-7.28	#N/A	-4.86	#N/A
4/9/2012	-5.14	#N/A	-6.32	#N/A	#N/A	0.65	4/9/2012	-5.14	#N/A	-6.32	#N/A	#N/A	0.65	6/14/2012	-7.41	#N/A	-4.86	#N/A
4/10/2012	-4.97	0.40	-6.32	#N/A	#N/A	0.70	4/10/2012	-4.97	0.40	-6.32	#N/A	#N/A	0.70	6/15/2012	-7.52	#N/A	-4.86	#N/A
4/11/2012	-4.85	#N/A	-6.32	#N/A	0.25	0.75	4/11/2012	-4.85	#N/A	-6.32	#N/A	0.25	0.75	#N/A	#N/A	#N/A	#N/A	#N/A
4/12/2012	-5.01	#N/A	-6.32	#N/A	0.01	0.79	4/12/2012	-5.01	#N/A	-6.32	#N/A	0.01	0.79	#N/A	#N/A	#N/A	#N/A	#N/A
4/13/2012	-4.82	0.40	-6.32	#N/A	#N/A	0.82	4/13/2012	-4.82	0.40	-6.32	#N/A	#N/A	0.82	#N/A	#N/A	#N/A	#N/A	#N/A
4/14/2012	-4.99	#N/A	-6.32	#N/A	0.04	0.85	4/14/2012	-4.99	#N/A	-6.32	#N/A	0.04	0.85	#N/A	#N/A	#N/A	#N/A	#N/A
4/15/2012	-5.16	#N/A	-6.32	#N/A	#N/A	0.87	4/15/2012	-5.16	#N/A	-6.32	#N/A	#N/A	0.87	#N/A	#N/A	#N/A	#N/A	#N/A
4/16/2012	-4.92	0.40	-6.32	#N/A	#N/A	0.90	4/16/2012	-4.92	0.40	-6.32	#N/A	#N/A	0.90	#N/A	#N/A	#N/A	#N/A	#N/A
4/17/2012	-5.11	#N/A	-6.32	#N/A	#N/A	0.92	4/17/2012	-5.11	#N/A	-6.32	#N/A	#N/A	0.92	#N/A	#N/A	#N/A	#N/A	#N/A
4/18/2012	-5.36	#N/A	-6.32	#N/A	0.01	0.92	4/18/2012	-5.36	#N/A	-6.32	#N/A	0.01	0.92	#N/A	#N/A	#N/A	#N/A	#N/A
4/19/2012	-5.17	0.40	-6.32	#N/A	0.03	0.92	4/19/2012	-5.17	0.40	-6.32	#N/A	0.03	0.92	#N/A	#N/A	#N/A	#N/A	#N/A
4/20/2012	-5.21	#N/A	-6.32	#N/A	0.18	0.92	4/20/2012	-5.21	#N/A	-6.32	#N/A	0.18	0.92	#N/A	#N/A	#N/A	#N/A	#N/A
4/21/2012	-5.47	#N/A	-6.32	#N/A	#N/A	0.92	4/21/2012	-5.47	#N/A	-6.32	#N/A	#N/A	0.92	#N/A	#N/A	#N/A	#N/A	#N/A
4/22/2012	-5.34	0.40	-6.32	#N/A	#N/A	0.92	4/22/2012	-5.34	0.40	-6.32	#N/A	#N/A	0.92	#N/A	#N/A	#N/A	#N/A	#N/A
4/23/2012	-5.59	#N/A	-6.32	#N/A	#N/A	0.92	4/23/2012	-5.59	#N/A	-6.32	#N/A	#N/A	0.92	#N/A	#N/A	#N/A	#N/A	#N/A

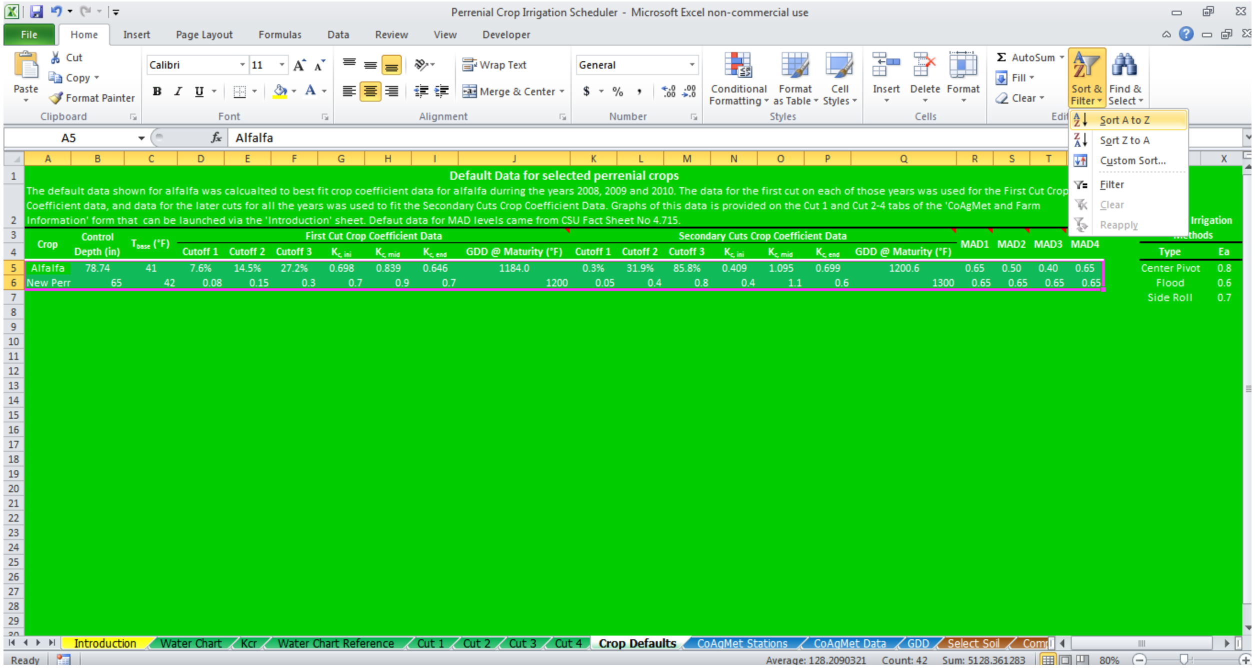
Figure V.1 Irrigation Sheet analysis columns

2. Cut Sheets

Each of the cut sheets (Cut 1-4) is only displayed if the previous cut date has been entered. For example the ‘Cut 4’ sheet will not be displayed until the cut date is entered for ‘Cut 3’. However these sheets will all be visible when the ‘Show Analysis’ button is pressed on the ‘Introduction’ or the ‘Select Soil’ sheet.

3. Crop Defaults

The Crop Defaults sheet contains some default values for specified crops (in columns A:U) and default irrigation methods and efficiencies (in columns W and X) . Additional crops can be added by unprotecting the sheet (there is no password) and adding the new crop to the list with all of the required information do not skip a row when entering a new crop. To re-alphabetize the default crop list, highlight all of the crops and their parameters. Select the ‘Home’ ribbon and click on the ‘Sort & Filter’ then ‘Sort A to Z’ (see Figure V.3). New irrigation methods can be added in a similar way.



A5 Alfalfa

Default Data for selected perrenial crops

The default data shown for alfalfa was calcualted to best fit crop coefficient data for alfalfa durring the years 2008, 2009 and 2010. The data for the first cut on each of those years was used for the First Cut Crop Coefficient data, and data for the later cuts for all the years was used to fit the Secondary Cuts Crop Coefficient Data. Graphs of this data is provided on the Cut 1 and Cut 2-4 tabs of the 'CoAgMet and Farm Information' form that can be launched via the 'Introduction' sheet. Defaut data for MAD levels came from CSU Fact Sheet No 4.715.

Crop	Control Depth (in)	T_{base} (°F)	First Cut Crop Coefficient Data							Secondary Cuts Crop Coefficient Data							MAD1	MAD2	MAD3	MAD4
			Cutoff 1	Cutoff 2	Cutoff 3	$K_{c,\ ini}$	$K_{c,\ mid}$	$K_{c,\ end}$	GDD @ Maturity (°F)	Cutoff 1	Cutoff 2	Cutoff 3	$K_{c,\ ini}$	$K_{c,\ mid}$	$K_{c,\ end}$	GDD @ Maturity (°F)				
Alfalfa	78.74	41	7.6%	14.5%	27.2%	0.698	0.839	0.646	1184.0	0.3%	31.9%	85.8%	0.409	1.095	0.699	1200.6	0.65	0.50	0.40	0.65
New Perr	65	42	0.08	0.15	0.3	0.7	0.9	0.7	1200	0.05	0.4	0.8	0.4	1.1	0.6	1300	0.65	0.65	0.65	0.65

Irrigation

Type	Ea
Center Pivot	0.8
Flood	0.6
Side Roll	0.7

Figure V.3 Adding new default crops, and re-alphabetizing the crop default crop list

Once a new default crop is added it can be selected on the ‘CoAgMet and Farm Information’ form as described in Chapter III.

4. CoAgMet Stations

The ‘CoAgMet Stations’ sheet contains a list of all of the available CoAgMet stations and their location, latitude, longitude, elevation, first observed and last observed data. This list is updated when the ‘CoAgMet and Farm Information’ form is launched (by pressing the ‘Set Up Farm Using data from CoAgMet’ button on the ‘Introduction’ sheet).

6. CoAgMet Data

The ‘CoAgMet Data’ sheet contains the data that was most recently queried from CoAgMet in columns “A:G”. The etr_asce and the pp is in millimeters, columns “I:K” converts these values into inches and the date into the format used by the CIS.

7. GDD

The ‘GDD’ sheet calculates the daily growing degree day from maximum and minimum temperature data taken from CoAgMet. A maximum temperature cutoff is not used for forage crops. The daily GDD is copied to column “J” of the cut sheets, where it is used to calculate the GDD from the previous cut or green up. The daily GDD contribution for any day that does not have a maximum temperature and a minimum temperature recorded is neglected. If the base temperature is changed on the GDD sheet, the change will not come into effect until the weather data is refreshed.

7. Soil hydraulic properties

The ‘Soil hydraulic properties’ sheet contains a spreadsheet model (Ahuja et al., 1989; Brooks and Corey, 1964) that estimates the field capacity as well as other soil parameters from the percentage of sand and clay in the soil and the soil bulk density. This sheet is used to estimate the field capacity of different soils, from the information queried from the NRCS Web Soil Survey (the available water content given by the WSS is used instead of the AWC predicted by this spreadsheet model).

This model could also be used to estimate Available Water (in/in) (shown as **Q**AW) and Field Capacity (in/in) (shown as **Q**FC) on the ‘Select Soil’ sheet if the NRCS WSS will not be used.

8. Compiled Soils

The Compiled Soils sheet contains all of the soil properties that are used to calculate the soil available water capacity (AWC) and the Field Capacity (FC) for each of the soil types provided by the NRCS WSS. The soil survey provides the soil layer depths, available water content, percentage of sand, silt and clay in each layer, moist bulk density and several other soil parameters. The soil layer depths and an average of the available water content are used directly from the NRCS Web Soil Survey. Then the field capacity is estimated with a spreadsheet model developed by Allan Andales that uses the sand and clay percentage and the moist bulk density of each layer (Brooks and Corey, 1964; Ahuja et al., 1989). For more information see Chapter V.7 Soil hydraulic properties.

9. NRCS Soil Report

The ‘NRCS Soil Report’ sheet contains the WSS report as it was copied into Excel. This data was used to compile the ‘Compiled Soils’ sheet.

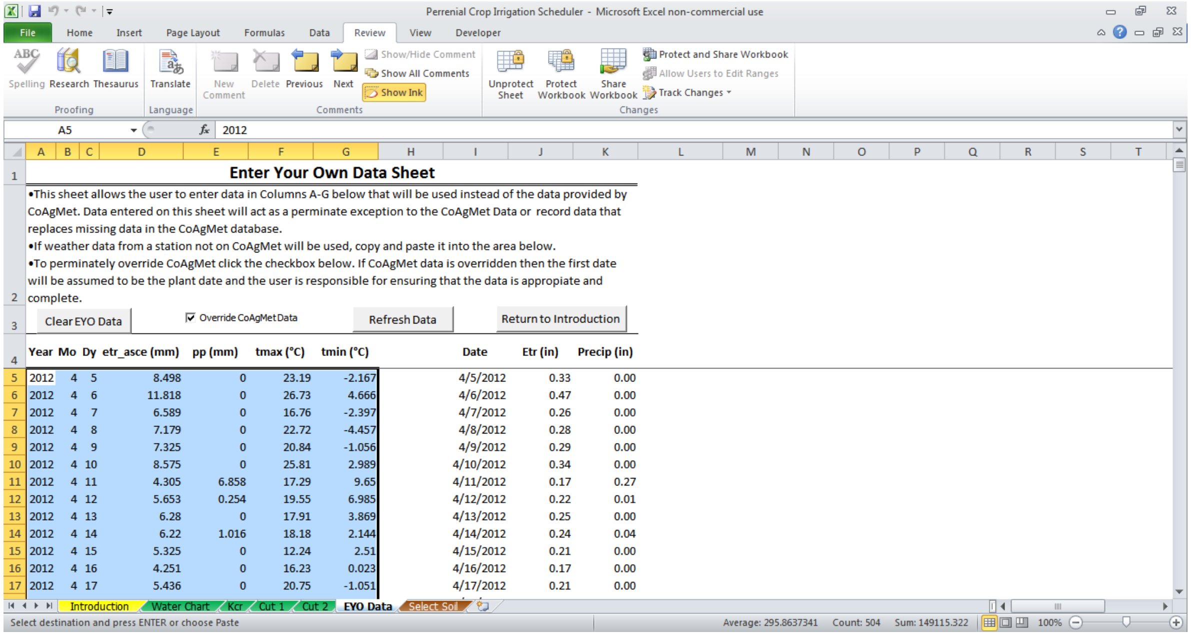
10. Map Data

The Map Data sheet shows the breakdown of the soil types, their acreage and their percent of the field. This data was copied from the NRCS Web Soil Survey. Sometimes the WSS contains two soil layers under the same heading, when this occurs a row is added to the 'Map Data' sheet. The added row will have "Added" in the "Map Unit Symbol" column. The drop down menu on the 'Select Soil' sheet references this page.

11. EYO Data

The EYO Data sheet allows the user to manually enter weather data that will be used for irrigation scheduling. This sheet will also record permanent replacements to gaps or inaccurate data in the CoAgMet weather data where they may occur.

If data is available from a different source it can be copied into columns A through G and the 'Override CoAgMet Data' check-box should be clicked. *If the Override check-box is checked then the user is responsible for ensuring that the weather data on the EYO Data page is accurate and complete.* An example is shown below in Figure V.11.A.



Enter Your Own Data Sheet

- This sheet allows the user to enter data in Columns A-G below that will be used instead of the data provided by CoAgMet. Data entered on this sheet will act as a perminate exception to the CoAgMet Data or record data that replaces missing data in the CoAgMet database.
- If weather data from a station not on CoAgMet will be used, copy and paste it into the area below.
- To perminately override CoAgMet click the checkbox below. If CoAgMet data is overridden then the first date will be assumed to be the plant date and the user is responsible for ensuring that the data is appropiate and complete.

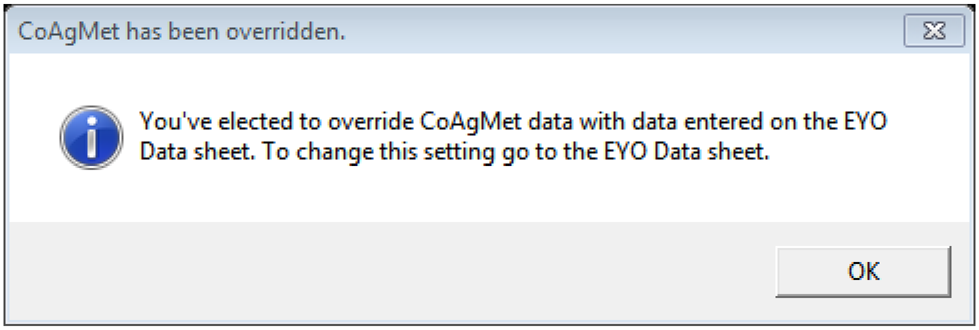
Clear EYO Data ☑ Override CoAgMet Data Refresh Data Return to Introduction

Year	Mo	Dy	etr_asce (mm)	pp (mm)	tmax (°C)	tmin (°C)	Date	Etr (in)	Precip (in)
2012	4	5	8.498	0	23.19	-2.167	4/5/2012	0.33	0.00
2012	4	6	11.818	0	26.73	4.666	4/6/2012	0.47	0.00
2012	4	7	6.589	0	16.76	-2.397	4/7/2012	0.26	0.00
2012	4	8	7.179	0	22.72	-4.457	4/8/2012	0.28	0.00
2012	4	9	7.325	0	20.84	-1.056	4/9/2012	0.29	0.00
2012	4	10	8.575	0	25.81	2.989	4/10/2012	0.34	0.00
2012	4	11	4.305	6.858	17.29	9.65	4/11/2012	0.17	0.27
2012	4	12	5.653	0.254	19.55	6.985	4/12/2012	0.22	0.01
2012	4	13	6.28	0	17.91	3.869	4/13/2012	0.25	0.00
2012	4	14	6.22	1.016	18.18	2.144	4/14/2012	0.24	0.04
2012	4	15	5.325	0	12.24	2.51	4/15/2012	0.21	0.00
2012	4	16	4.251	0	16.23	0.023	4/16/2012	0.17	0.00
2012	4	17	5.436	0	20.75	-1.051	4/17/2012	0.21	0.00

Figure V.11.A Enter Your Own Data Sheet

Columns I through K will automatically convert data into English Units from the Metric units that are typically reported by most data logging software. *The data that is entered must have the units prescribed with evapotranspiration of reference alfalfa (etr_asce) and precipitation (pp) in millimeters and maximum daily temperature (tmax) and minimum daily temperature (tmin) in degrees Celsius.*

Once the user has finished updating data click the “Refresh Data” button. This will display a message box reminding the user that the CoAgMet weather override is in effect as shown below in Figure V.11.B. This warning will be displayed whenever the “Refresh Data” button is clicked.



CoAgMet has been overridden.

You've elected to override CoAgMet data with data entered on the EYO Data sheet. To change this setting go to the EYO Data sheet.

Figure V.11.B CoAgMet Override warning

Index

Works Cited

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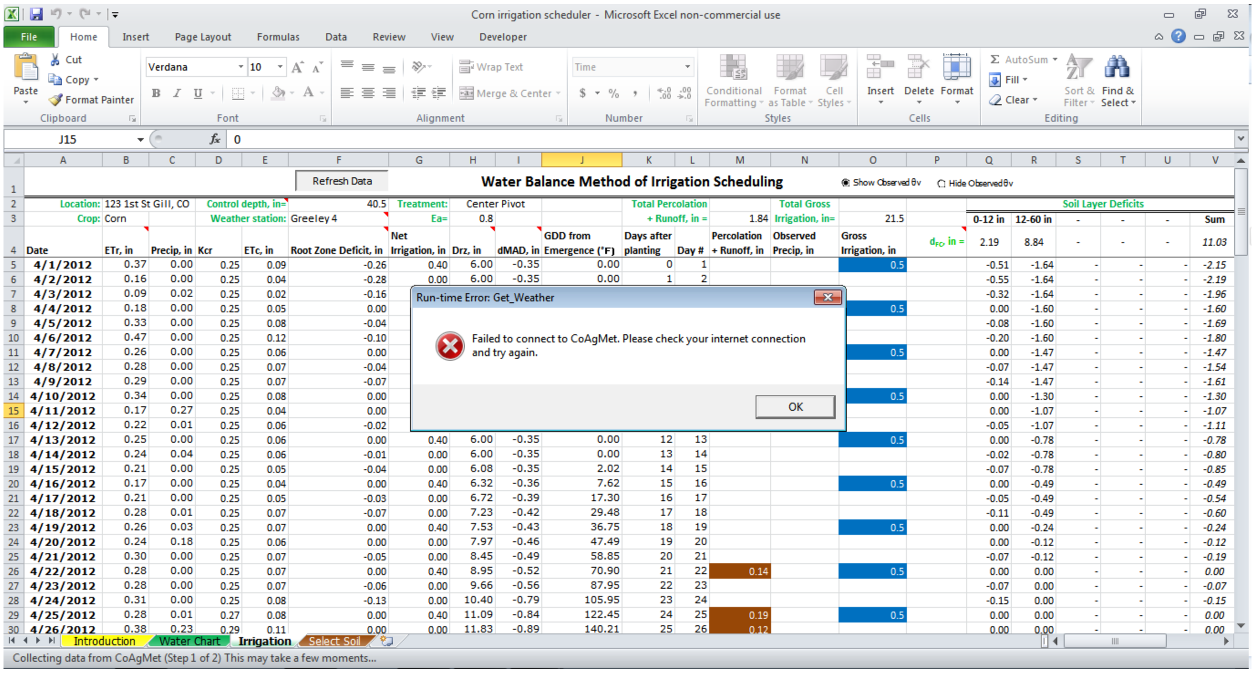
Barta, R., Broner, I., Schneekloth, J. & Waskom, R. (2004). Colorado High Plains Irrigation Practices Guide. Special Report No. 14. Colorado Water Resources Research Institute, Fort Collins, CO. (http://www.cwi.colostate.edu/publications/SR/14.pdf)

Brooks, R. H., & Corey, A. T. (1964). Hydraulic properties of porous media. *Colorado State Univ. Hydrol. Paper No. 3*, 27.

Appendix A: Common Errors

1. Internet Connection Problems

The most common errors that occur are related to internet connection problems. If the ‘Refresh Data’ button or the ‘ Set Up Farm Using data from CoAgMet‘ button is pressed without an internet connection an error similar to Figure App A.1 will likely appear.



J15 f_x 0

Water Balance Method of Irrigation Scheduling

● Show Observed θv ○ Hide Observed θv

Location: 123 1st St Gill, CO | Control depth, in= 40.5 | Treatment: Center Pivot | Total Percolation + Runoff, in = 1.84 | Total Gross Irrigation, in= 21.5

Crop: Corn | Weather station: Greeley 4 | Ea= 0.8

Soil Layer Deficits

Date	ETr, in	Precip, in	Kcr	ETc, in	Root Zone Deficit, in	Net Irrigation, in	Drz, in	dMAD, in	GDD from Emergence (°F)	Days after planting	Day #	Percolation + Runoff, in	Observed Precip, in	Gross Irrigation, in	d_{FC}, in =	0-12 in	12-60 in	-	-	-	Sum
																2.19	8.84	-	-	-	11.03
4/1/2012	0.37	0.00	0.25	0.09	-0.26	0.40	6.00	-0.35	0.00	0	1			0.5		-0.51	-1.64	-	-	-	-2.15
4/2/2012	0.16	0.00	0.25	0.04	-0.28	0.00	6.00	-0.35	0.00	1	2					-0.55	-1.64	-	-	-	-2.19
4/3/2012	0.09	0.02	0.25	0.02	-0.16											-0.32	-1.64	-	-	-	-1.96
4/4/2012	0.18	0.00	0.25	0.05	0.00									0.5		0.00	-1.60	-	-	-	-1.60
4/5/2012	0.33	0.00	0.25	0.08	-0.04											-0.08	-1.60	-	-	-	-1.69
4/6/2012	0.47	0.00	0.25	0.12	-0.10											-0.20	-1.60	-	-	-	-1.80
4/7/2012	0.26	0.00	0.25	0.06	0.00									0.5		0.00	-1.47	-	-	-	-1.47
4/8/2012	0.28	0.00	0.25	0.07	-0.04											-0.07	-1.47	-	-	-	-1.54
4/9/2012	0.29	0.00	0.25	0.07	-0.07											-0.14	-1.47	-	-	-	-1.61
4/10/2012	0.34	0.00	0.25	0.08	0.00									0.5		0.00	-1.30	-	-	-	-1.30
4/11/2012	0.17	0.27	0.25	0.04	0.00											0.00	-1.07	-	-	-	-1.07
4/12/2012	0.22	0.01	0.25	0.06	-0.02											-0.05	-1.07	-	-	-	-1.11
4/13/2012	0.25	0.00	0.25	0.06	0.00	0.40	6.00	-0.35	0.00	12	13			0.5		0.00	-0.78	-	-	-	-0.78
4/14/2012	0.24	0.04	0.25	0.06	-0.01	0.00	6.00	-0.35	0.00	13	14					-0.02	-0.78	-	-	-	-0.80
4/15/2012	0.21	0.00	0.25	0.05	-0.04	0.00	6.08	-0.35	2.02	14	15					-0.07	-0.78	-	-	-	-0.85
4/16/2012	0.17	0.00	0.25	0.04	0.00	0.40	6.32	-0.36	7.62	15	16			0.5		0.00	-0.49	-	-	-	-0.49
4/17/2012	0.21	0.00	0.25	0.05	-0.03	0.00	6.72	-0.39	17.30	16	17					-0.05	-0.49	-	-	-	-0.54
4/18/2012	0.28	0.01	0.25	0.07	-0.07	0.00	7.23	-0.42	29.48	17	18					-0.11	-0.49	-	-	-	-0.60
4/19/2012	0.26	0.03	0.25	0.07	0.00	0.40	7.53	-0.43	36.75	18	19			0.5		0.00	-0.24	-	-	-	-0.24
4/20/2012	0.24	0.18	0.25	0.06	0.00	0.00	7.97	-0.46	47.49	19	20					0.00	-0.12	-	-	-	-0.12
4/21/2012	0.30	0.00	0.25	0.07	-0.05	0.00	8.45	-0.49	58.85	20	21					-0.07	-0.12	-	-	-	-0.19
4/22/2012	0.28	0.00	0.25	0.07	0.00	0.40	8.95	-0.52	70.90	21	22	0.14		0.5		0.00	0.00	-	-	-	0.00
4/23/2012	0.28	0.00	0.25	0.07	-0.06	0.00	9.66	-0.56	87.95	22	23					-0.07	0.00	-	-	-	-0.07
4/24/2012	0.31	0.00	0.25	0.08	-0.13	0.00	10.40	-0.79	105.95	23	24					-0.15	0.00	-	-	-	-0.15
4/25/2012	0.28	0.01	0.27	0.08	0.00	0.40	11.09	-0.84	122.45	24	25	0.19		0.5		0.00	0.00	-	-	-	0.00
4/26/2012	0.38	0.23	0.29	0.11	0.00	0.00	11.83	-0.89	140.21	25	26	0.12				0.00	0.00	-	-	-	0.00

Run-time Error: Get_Weather

Failed to connect to CoAgMet. Please check your internet connection and try again.

OK

Collecting data from CoAgMet (Step 1 of 2) This may take a few moments...

Figure App A.1 Internet Connection Error

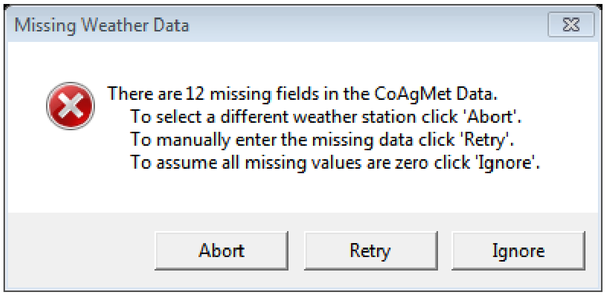
If this occurs, open your default internet browser check that a website will load, close the browser and try again.

If no website will load try the following

4. Ensure that your computer has an active internet connection
5. Reset your internet modem and/or wireless router
6. Contact your internet provider

2. Missing Data

Sometimes CoAgMet stations go down and weather data is missing. If this occurs you will be prompted with an error message like the one shown in Figure A.2i below.



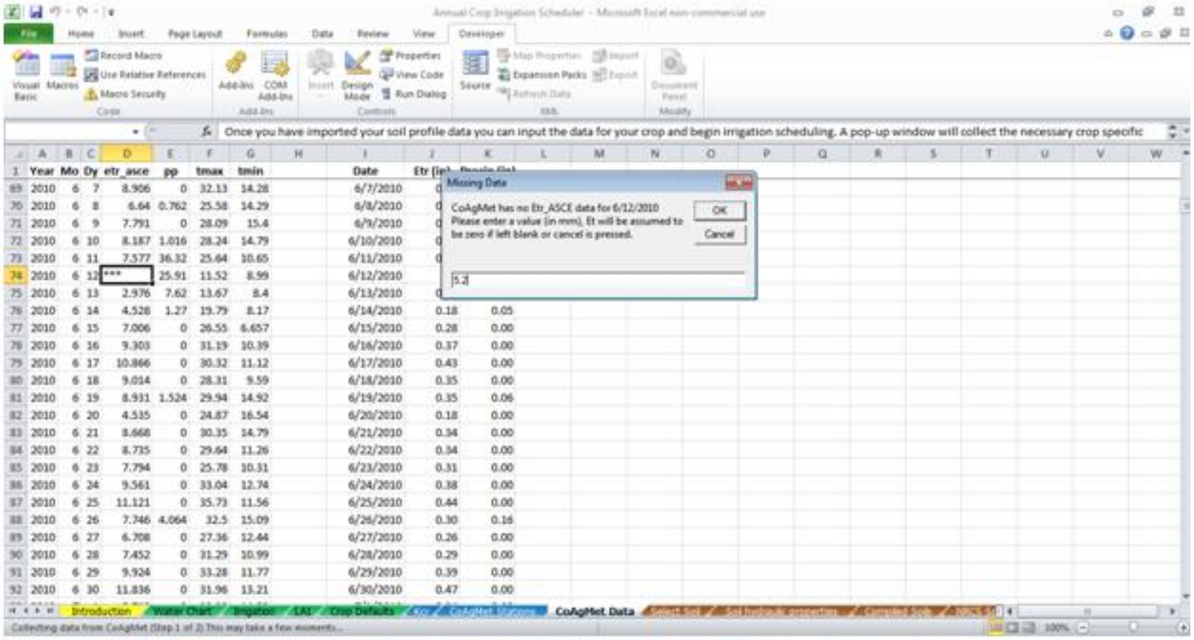
There are 12 missing fields in the CoAgMet Data.
To select a different weather station click 'Abort'.
To manually enter the missing data click 'Retry'.
To assume all missing values are zero click 'Ignore'.

Figure App A.2i: Missing Weather Data error message

Clicking ‘Abort’ will stop Excel from running analysis on the current weather data and return the user to the ‘CoAgMet and Farm Information’ form or the ‘Irrigation’ sheet (depending on what prompted the error).

Clicking ‘Retry’ allows the user to enter a value for each of the missing fields manually. This will select the ‘CoAgMet Data’ sheet and provide an input box for each missing field. An alternative is to fill missing data using the ‘EYO Data’ sheet. *Notice that Etr and precip values need to be entered in millimeters and maximum and minimum temperatures need to be entered in degrees Celsius.* See Figure A.2ii below for an example. Once all the missing values are entered the weather data will finish compiling.

Clicking ‘Ignore’ will replace all missing data value with zero. This neglects any Et or precip that occurred and any GDDs that may have accumulated, respectively, on the day with missing data.



Once you have imported your soil profile data you can input the data for your crop and begin irrigation scheduling. A pop-up window will collect the necessary crop specific

	Year	Mo	Dy	etr_asce	pp	tmax	tmin	Date	Etr (in)	Precip (in)
69	2010	6	7	8.906	0	32.13	14.28	6/7/2010		
70	2010	6	8	6.64	0.762	25.58	14.29	6/8/2010		
71	2010	6	9	7.791	0	28.09	15.4	6/9/2010		
72	2010	6	10	8.187	1.016	28.24	14.79	6/10/2010		
73	2010	6	11	7.577	36.32	25.64	10.65	6/11/2010		
74	2010	6	12	***	25.91	11.52	8.99	6/12/2010		
75	2010	6	13	2.976	7.62	13.67	8.4	6/13/2010		
76	2010	6	14	4.528	1.27	19.79	8.17	6/14/2010	0.18	0.05
77	2010	6	15	7.006	0	26.55	6.657	6/15/2010	0.28	0.00
78	2010	6	16	9.303	0	31.19	10.39	6/16/2010	0.37	0.00
79	2010	6	17	10.866	0	30.32	11.12	6/17/2010	0.43	0.00
80	2010	6	18	9.014	0	28.31	9.59	6/18/2010	0.35	0.00
81	2010	6	19	8.931	1.524	29.94	14.92	6/19/2010	0.35	0.06
82	2010	6	20	4.535	0	24.87	16.54	6/20/2010	0.18	0.00
83	2010	6	21	8.668	0	30.35	14.79	6/21/2010	0.34	0.00
84	2010	6	22	8.735	0	29.64	11.26	6/22/2010	0.34	0.00
85	2010	6	23	7.794	0	25.78	10.31	6/23/2010	0.31	0.00
86	2010	6	24	9.561	0	33.04	12.74	6/24/2010	0.38	0.00
87	2010	6	25	11.121	0	35.73	11.56	6/25/2010	0.44	0.00
88	2010	6	26	7.746	4.064	32.5	15.09	6/26/2010	0.30	0.16
89	2010	6	27	6.708	0	27.36	12.44	6/27/2010	0.26	0.00
90	2010	6	28	7.452	0	31.29	10.99	6/28/2010	0.29	0.00
91	2010	6	29	9.924	0	33.28	11.77	6/29/2010	0.39	0.00
92	2010	6	30	11.836	0	31.96	13.21	6/30/2010	0.47	0.00

CoAgMet has no Etr_ASCE data for 6/12/2010
Please enter a value (in mm). Et will be assumed to be zero if left blank or cancel is pressed.

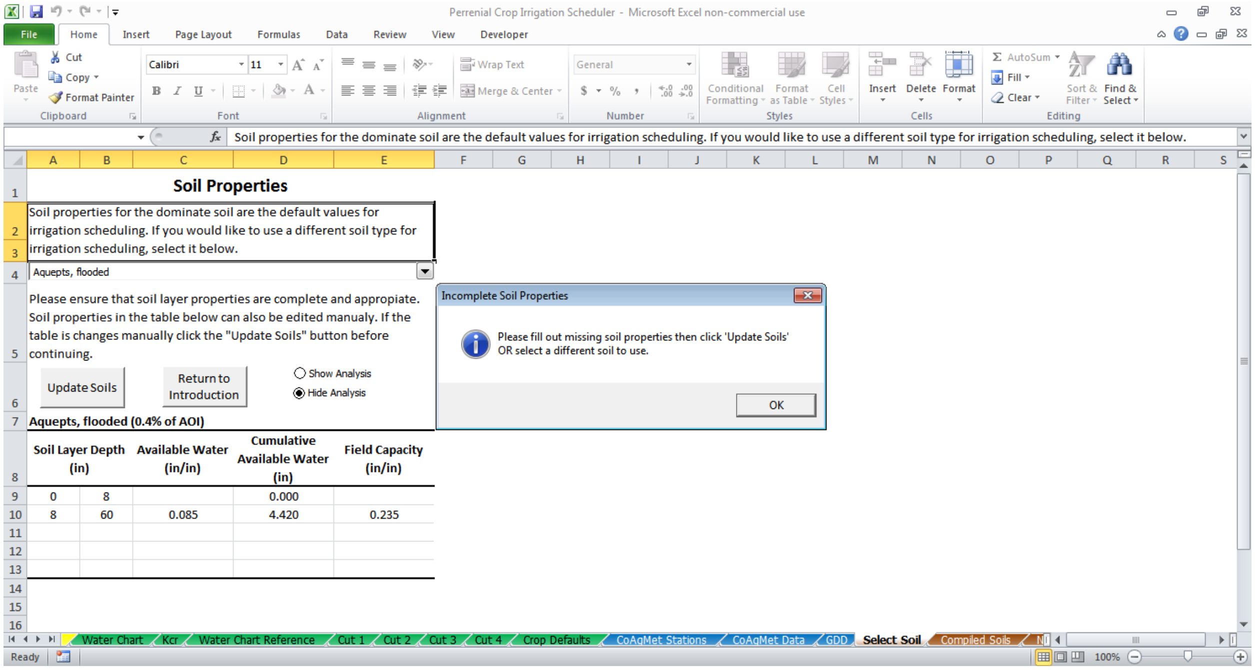
5.2

Collecting data from CoAgMet (Step 1 of 2) This may take a few moments...

Figure App A.2ii: An example of the input box used to enter missing weather data

3. Incomplete Soil Properties

Sometimes the NRCS WSS does not have soil properties for all soil layers for a specific soil type. If a soil type is selected that has missing soil properties and error message will be displayed as shown below in Figure App A.3. If this occurs fill in the missing fields for select a different soil type to use for irrigation scheduling.



Soil properties for the dominate soil are the default values for irrigation scheduling. If you would like to use a different soil type for irrigation scheduling, select it below.

Soil Properties

Soil properties for the dominate soil are the default values for irrigation scheduling. If you would like to use a different soil type for irrigation scheduling, select it below.

Aquepts, flooded

Please ensure that soil layer properties are complete and appropiate. Soil properties in the table below can also be edited manualy. If the table is changes manually click the "Update Soils" button before continuing.

○ Show Analysis
● Hide Analysis

Aquepts, flooded (0.4% of AOI)

Soil Layer Depth (in)		Available Water (in/in)	Cumulative Available Water (in)	Field Capacity (in/in)
0	8		0.000	
8	60	0.085	4.420	0.235

Incomplete Soil Properties

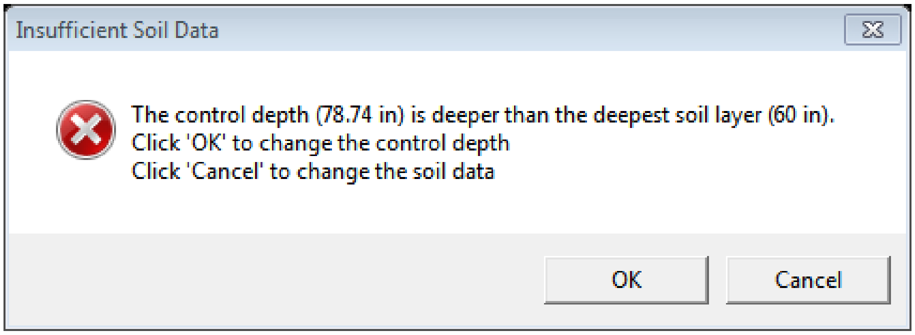
Please fill out missing soil properties then click 'Update Soils' OR select a different soil to use.

OK

Figure App A.3: Incomplete Soil Properties Error Message, for this soil type there is no AWC or FC for the soil layer 0-8 in

4. Insufficient soil data

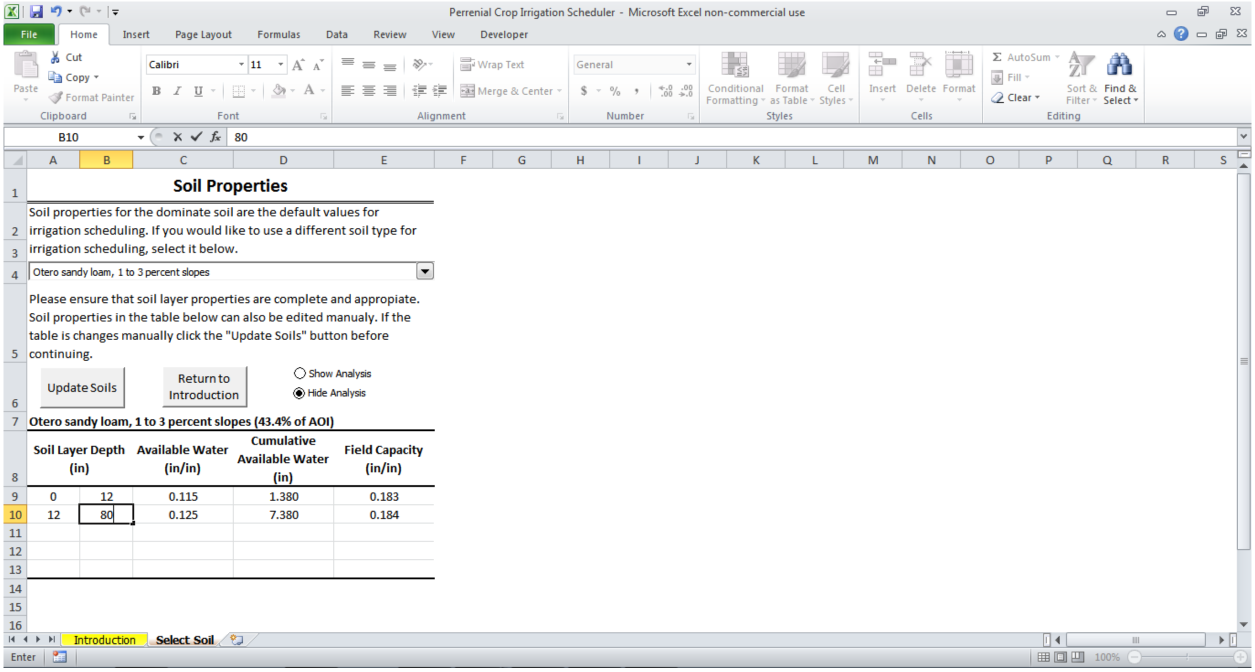
For soil layer scheduling purposes the control depth needs to be less than the deepest soil layer. If a control depth is entered that is deeper than the deepest soil layer an error message will be displayed as below in Figure App A.4. This error is most likely to occur while using the 'CoAgMet and Farm Information' form. Clicking 'OK' will return you to the 'CoAgMet and Farm Information' form to change the Control Depth. Clicking 'Cancel' will close the 'CoAgMet and Farm Information' form and select the 'Select Soil' sheet so that the user can update the soil layers so that there is enough soil data for calculations, once the soils data is entered click the 'Update Soils' button.



The control depth (78.74 in) is deeper than the deepest soil layer (60 in).
Click 'OK' to change the control depth
Click 'Cancel' to change the soil data

Figure App A.4i: Insufficient Soil Data error message

For the example shown in Figure App A.4, we will assume that the soil properties at 60 in below the surface are the same from 60 in to 80 in below the surface. To do so, click 'Cancel'. This will close the 'CoAgMet and Farm Information' form and select the 'Select Soil' sheets as shown below. The lower bound of the second soil layer was changed to 80 from 60. After this the 'Update Soils' button was clicked, and this allowed the data to finish compiling.



B10 = 80

Soil Properties

Soil properties for the dominate soil are the default values for irrigation scheduling. If you would like to use a different soil type for irrigation scheduling, select it below.

Otero sandy loam, 1 to 3 percent slopes

Please ensure that soil layer properties are complete and appropiate. Soil properties in the table below can also be edited manualy. If the table is changes manually click the "Update Soils" button before continuing.

○ Show Analysis
● Hide Analysis

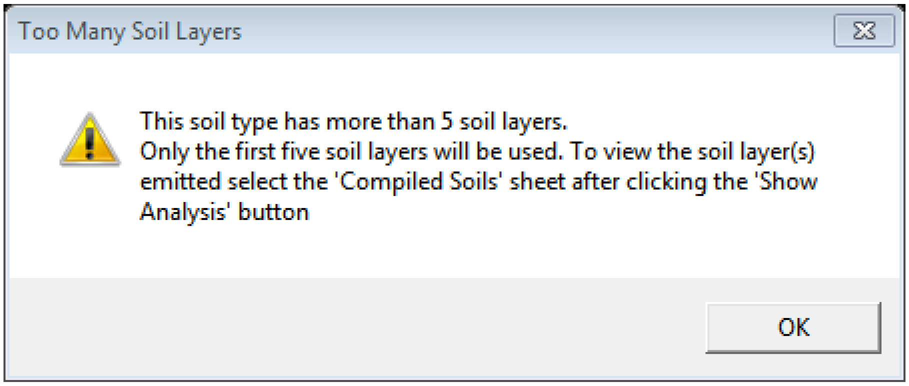
Otero sandy loam, 1 to 3 percent slopes (43.4% of AOI)

Soil Layer Depth (in)		Available Water (in/in)	Cumulative Available Water (in)	Field Capacity (in/in)
0	12	0.115	1.380	0.183
12	80	0.125	7.380	0.184

Figure App A.4ii: Updating the soil layers so that the maximum soil depth exceeds the control depth

5. Too Many Soil Layers

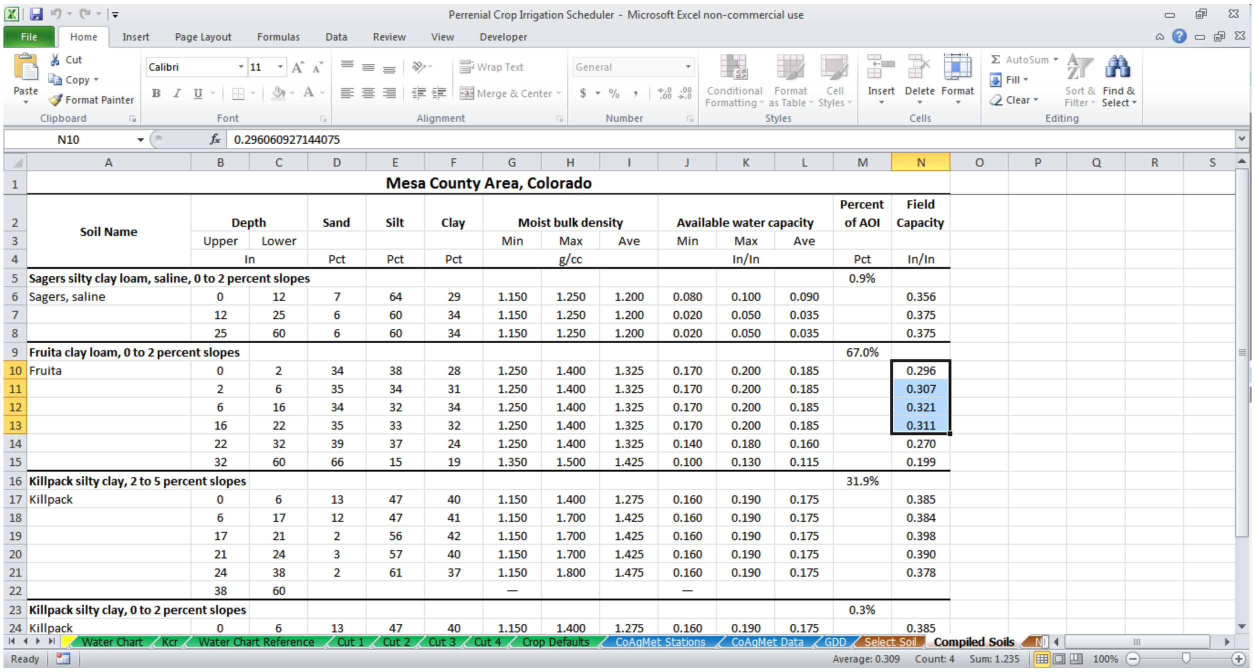
The CIS is limited to calculate soil layer deficits for five or less layers. Sometimes the WSS has more than five layers. If this occurs the user will be prompted with an error message similar to Figure App A.5i below. There are several suggestions on how to deal with this error are shown below.



This soil type has more than 5 soil layers.
Only the first five soil layers will be used. To view the soil layer(s) emitted select the 'Compiled Soils' sheet after clicking the 'Show Analysis' button

Figure App A.5i: Too Many Soil Layers error message

4. If the first five layers are sufficient to cover the root-zone then only use the first five layers.
5. Choose a different soil type
6. Combine soil layers by
    a. Click the ‘Show Analysis’ button
    b. Select the ‘Compiled Soils’ sheet.
    c. Using the data on this sheet as a reference, combine soil layers with similar AWC and FC so that there are five or less total layers.
    d. Enter these new layers manually on the ‘Select Soil’ sheet, it may be helpful to write down the soil properties. In the example shown in Figure App A.5ii, the first four layers have the same AWC so an average of their FC was used (0.309 in/in).
    e. Click the ‘Hide Analysis’ button
    f. Click the ‘Update Soils’ button
    g. An example of the new soil properties table is shown in Figure App A.5iii

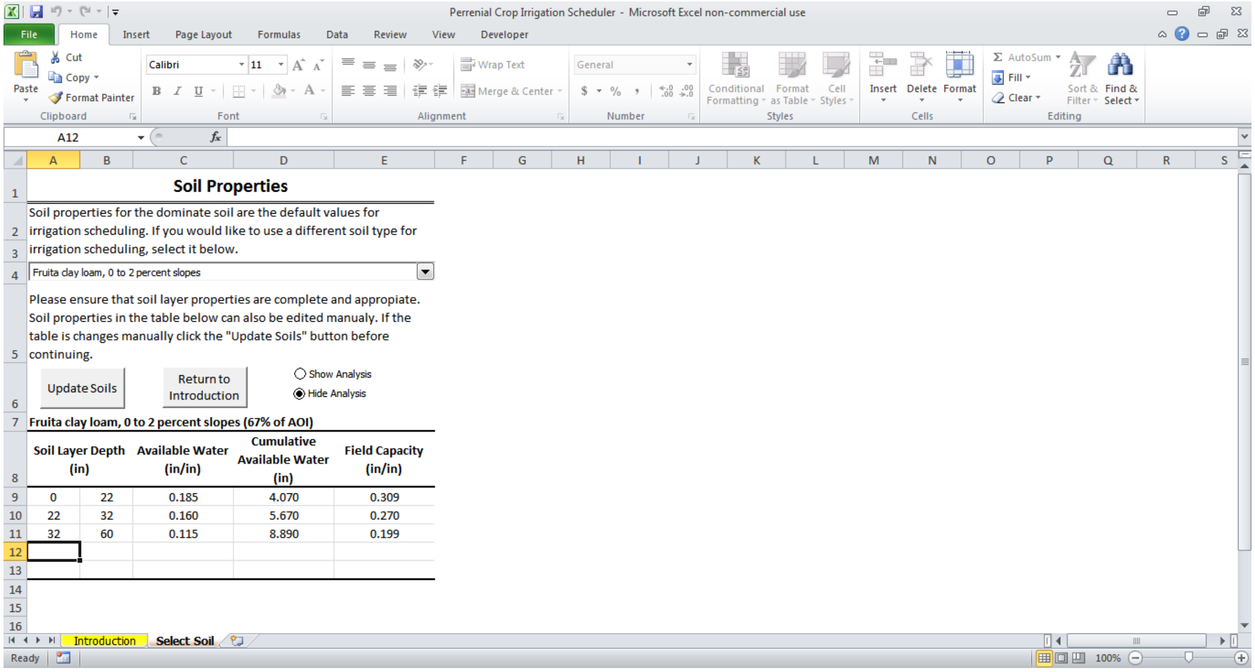


N10 0.296060927144075

Mesa County Area, Colorado

Soil Name	Depth		Sand	Silt	Clay	Moist bulk density			Available water capacity			Percent of AOI	Field Capacity
	Upper	Lower				Min	Max	Ave	Min	Max	Ave		
	In		Pct	Pct	Pct	g/cc			In/In			Pct	In/In
Sagers silty clay loam, saline, 0 to 2 percent slopes												0.9%	
Sagers, saline	0	12	7	64	29	1.150	1.250	1.200	0.080	0.100	0.090		0.356
	12	25	6	60	34	1.150	1.250	1.200	0.020	0.050	0.035		0.375
	25	60	6	60	34	1.150	1.250	1.200	0.020	0.050	0.035		0.375
Fruita clay loam, 0 to 2 percent slopes												67.0%	
Fruita	0	2	34	38	28	1.250	1.400	1.325	0.170	0.200	0.185		0.296
	2	6	35	34	31	1.250	1.400	1.325	0.170	0.200	0.185		0.307
	6	16	34	32	34	1.250	1.400	1.325	0.170	0.200	0.185		0.321
	16	22	35	33	32	1.250	1.400	1.325	0.170	0.200	0.185		0.311
	22	32	39	37	24	1.250	1.400	1.325	0.140	0.180	0.160		0.270
	32	60	66	15	19	1.350	1.500	1.425	0.100	0.130	0.115		0.199
Killpack silty clay, 2 to 5 percent slopes												31.9%	
Killpack	0	6	13	47	40	1.150	1.400	1.275	0.160	0.190	0.175		0.385
	6	17	12	47	41	1.150	1.700	1.425	0.160	0.190	0.175		0.384
	17	21	2	56	42	1.150	1.700	1.425	0.160	0.190	0.175		0.398
	21	24	3	57	40	1.150	1.700	1.425	0.160	0.190	0.175		0.390
	24	38	2	61	37	1.150	1.800	1.475	0.160	0.190	0.175		0.378
	38	60				—			—				
Killpack silty clay, 0 to 2 percent slopes												0.3%	
Killpack	0	6	13	47	40	1.150	1.400	1.275	0.160	0.190	0.175		0.385

Figure App A.5ii: Compiled Soils sheet showing all of the soil layers



Soil Properties

Soil properties for the dominate soil are the default values for irrigation scheduling. If you would like to use a different soil type for irrigation scheduling, select it below.

Fruita clay loam, 0 to 2 percent slopes

Please ensure that soil layer properties are complete and appropiate. Soil properties in the table below can also be edited manually. If the table is changes manually click the "Update Soils" button before continuing.

○ Show Analysis
● Hide Analysis

Fruita clay loam, 0 to 2 percent slopes (67% of AOI)

Soil Layer Depth (in)		Available Water (in/in)	Cumulative Available Water (in)	Field Capacity (in/in)
0	22	0.185	4.070	0.309
22	32	0.160	5.670	0.270
32	60	0.115	8.890	0.199

Figure App A.5iii: Updated soil properties table

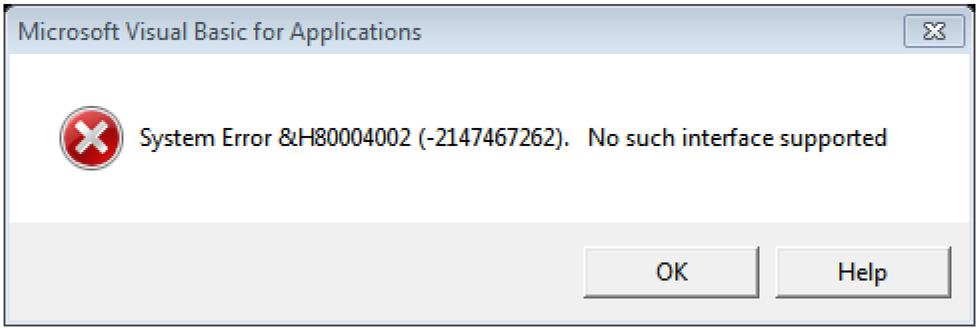
6. Protection

The CIS does not require a password to unprotect sheets and make changes; however doing so may cause errors.

IF A PASSWORD IS ASSIGNED TO ANY SHEET THE CIS WILL NO LONGER FUNCTION PROPERLY. To password protect the CIS see the 'Workbook_Macros' module in the VBA editor.

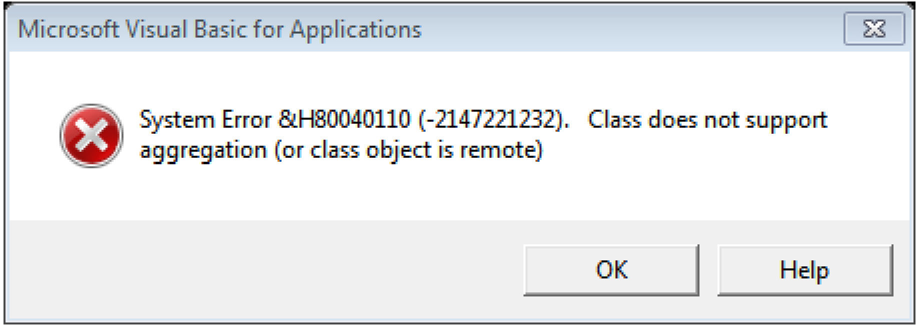
7. System Errors

If several irrigation scheduler or similar Excel files are open at once, the following (or similar) dialogue boxes may be displayed. A fix is to press 'Ok' until messages stop appearing, then close all open Excel files and reopen only the necessary Excel files.



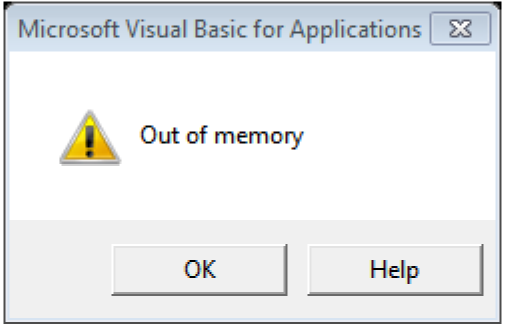
Microsoft Visual Basic for Applications

System Error &H80004002 (-2147467262). No such interface supported



Microsoft Visual Basic for Applications

System Error &H80040110 (-2147221232). Class does not support aggregation (or class object is remote)



Microsoft Visual Basic for Applications

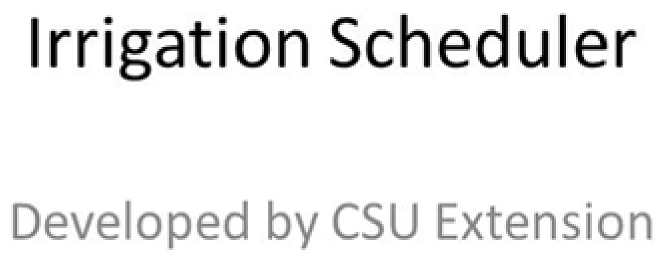
Out of memory

8. Other Problems

If any of the parameters on the ‘Irrigation’ sheet, the ‘Kcr’ sheet or the ‘Select Soil’ sheet are deleted the CIS will stop functioning properly.

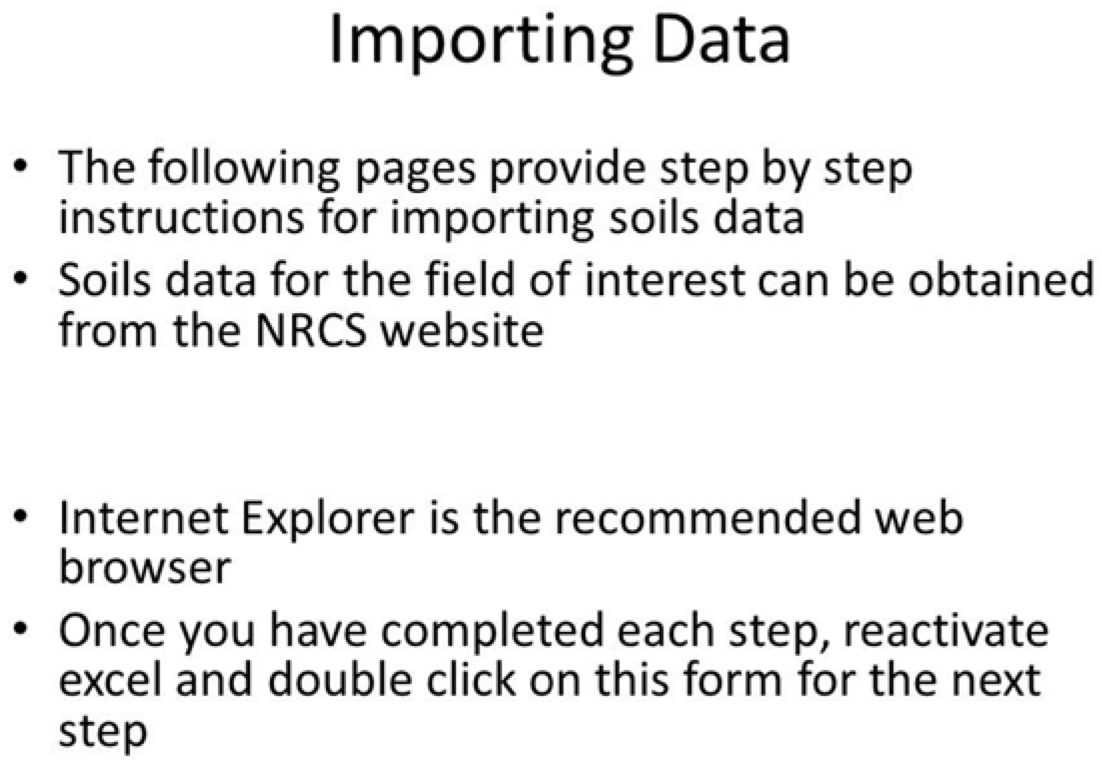
3. Check that all fields are entered (See the respective section in this manual for more information.)
4. Use either the ‘Reset All’ or ‘Reset Crop’ button on the ‘Introduction’ sheet and re-setup the farm

Appendix B: Web Soil Survey Slides



Irrigation Scheduler

Developed by CSU Extension



Importing Data

- The following pages provide step by step instructions for importing soils data
- Soils data for the field of interest can be obtained from the NRCS website

- Internet Explorer is the recommended web browser
- Once you have completed each step, reactivate excel and double click on this form for the next step

Step 1: Click “Start WSS” to begin Web Soil Survey

Welcome to Web Soil Survey (WSS)

Web Soil Survey (WSS) provides soil data and information produced by the National Cooperative Soil Survey. It is operated by the USDA Natural Resources Conservation Service (NRCS) and provides access to the largest natural resource information system in the world. NRCS has soil maps and data available online for more than 95 percent of the nation's counties and anticipates having 100 percent in the near future. The site is updated and maintained online as the single authoritative source of soil survey information.

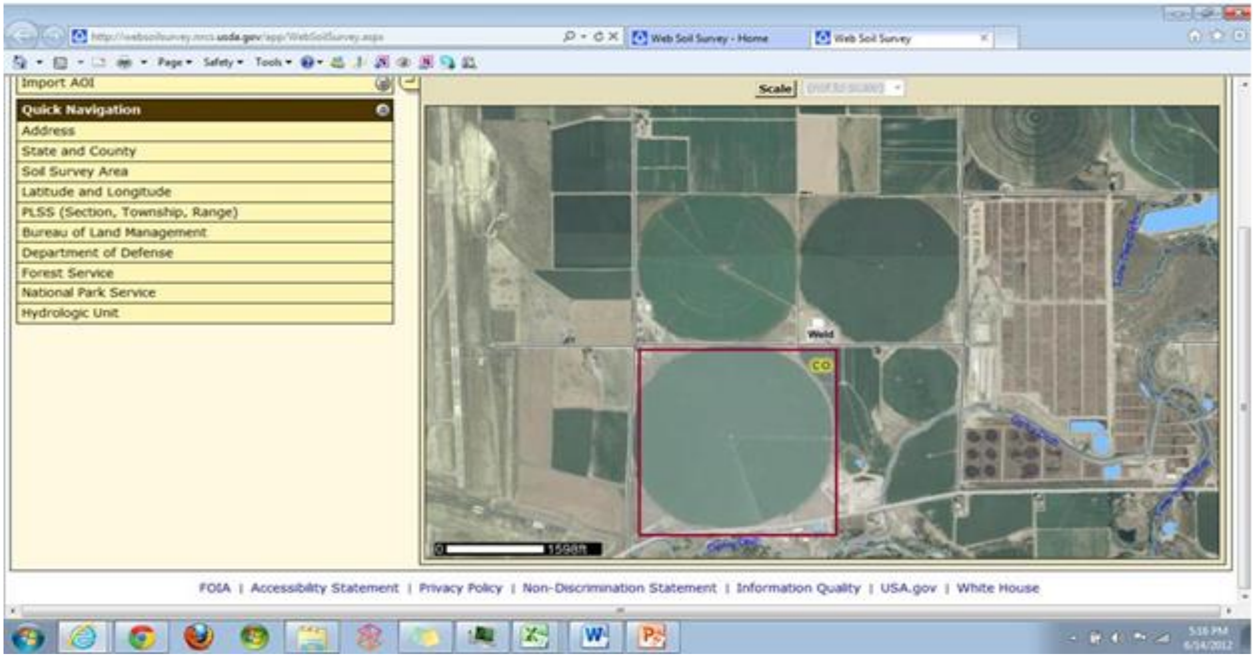
Four Basic Steps

1 Define..

Area of Interest (AOI)

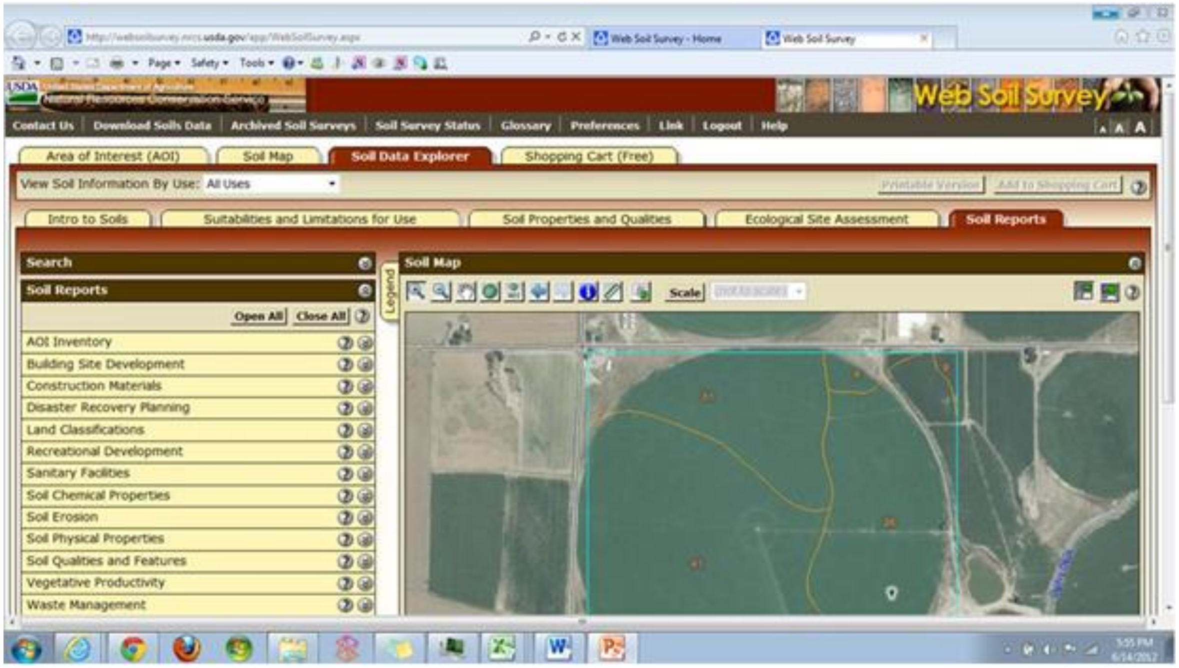
Use the Area of Interest tab to define your area of interest.

Step 2: Select an Area of Interest (AOI) using the website’s interface

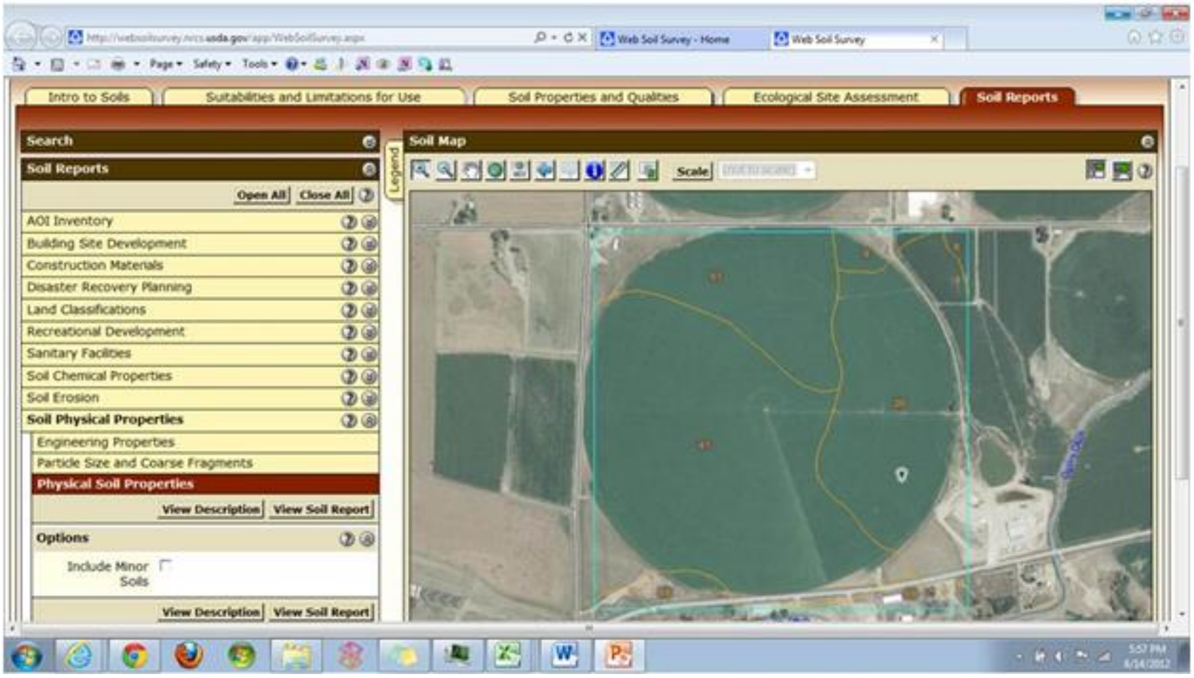


Step 3: Select the Soil Map Tab and Copy the Map Unit Legend

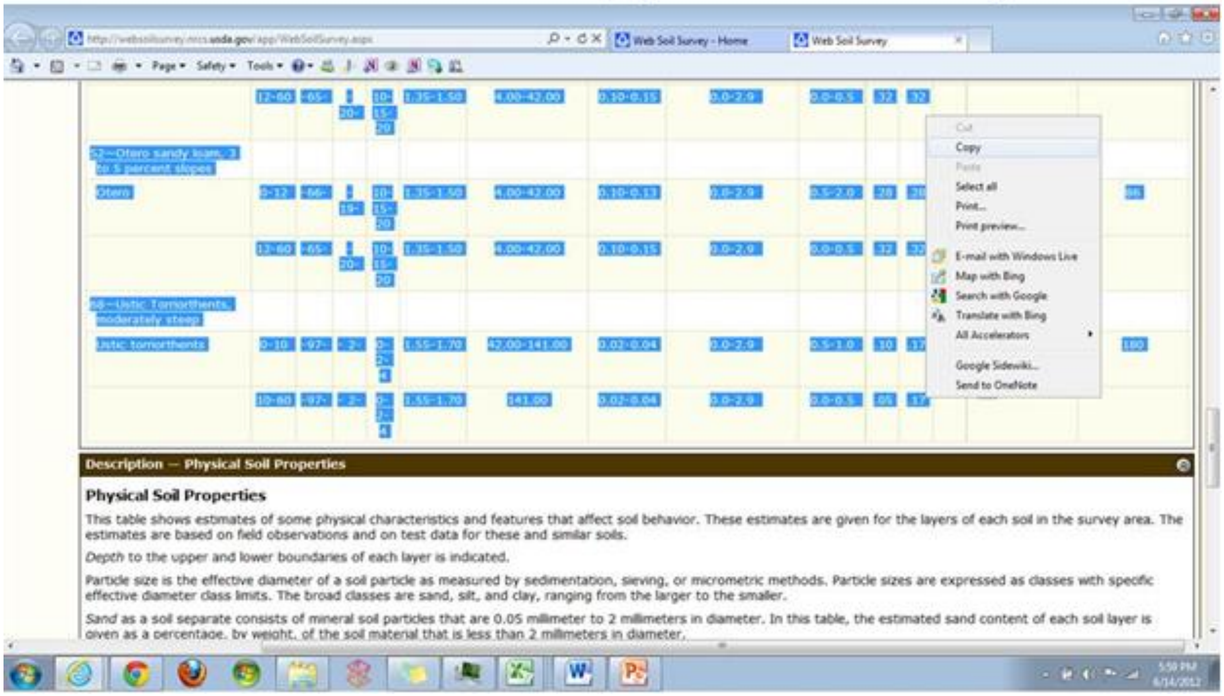
Step 4: Select the "Soil Data Explorer" Tab Then Select the "Soils Report" Secondary Tab



Step 5: Select "Soil Physical Properties" Then Select "Physical Soil Properties"



Step 6: Click "View Soil Report" Scroll Down and Copy the Entire Report



	12-60	-65-	20-	10-15-20	1.35-1.50	4.00-42.00	0.10-0.15	0.0-2.9	0.0-0.5	.32	.32	
52—Otero sandy loam, 3 to 5 percent slopes												
Otero	0-12	-66-	19-	10-15-20	1.35-1.50	4.00-42.00	0.10-0.13	0.0-2.9	0.5-2.0	.28	.28	86
	13-60	-65-	20-	10-15-20	1.35-1.50	4.00-42.00	0.10-0.15	0.0-2.9	0.0-0.5	.32	.32	
58—Ustic Torriorthents, moderately steep												
Ustic torriorthents	0-10	-97-	-2-	0-2-4	1.55-1.70	42.00-141.00	0.02-0.04	0.0-2.9	0.5-1.0	.10	.17	180
	10-60	-97-	-2-	0-2-4	1.55-1.70	141.00	0.02-0.04	0.0-2.9	0.0-0.5	.05	.17	

Description — Physical Soil Properties

Physical Soil Properties

This table shows estimates of some physical characteristics and features that affect soil behavior. These estimates are given for the layers of each soil in the survey area. The estimates are based on field observations and on test data for these and similar soils.

Depth to the upper and lower boundaries of each layer is indicated.

Particle size is the effective diameter of a soil particle as measured by sedimentation, sieving, or micrometric methods. Particle sizes are expressed as classes with specific effective diameter class limits. The broad classes are sand, silt, and clay, ranging from the larger to the smaller.

Sand as a soil separate consists of mineral soil particles that are 0.05 millimeter to 2 millimeters in diameter. In this table, the estimated sand content of each soil layer is given as a percentage, by weight, of the soil material that is less than 2 millimeters in diameter.

APPENDIX III: VISUAL BASIC SOURCE CODE FOR DAILY WATER BALANCE USED IN BOTH VERSIONS OF THE COLORADO IRRIGATION SCHEDULER (CIS)

```
Sub Soil_Layer_Deficit()
'Written by Caleb Erkman 6/19/12
'This macro performs a daily water budget for the crop taking into account
'the decifit in each layer, precip, ET, and irrigation

If Sheets("Irrigation").Range("A5").value = "" Then
   Exit Sub
End If

Application.ScreenUpdating = False
If Sheets("Irrigation").Range("A5").value = "" Then
   Exit Sub
End If
OldStatusBar = Application.DisplayStatusBar
Application.DisplayStatusBar = True

Dim cursheet, cursel As String
cursheet = ActiveSheet.Name
If cursheet = "Irrigation" Then
   cursel = ActiveWindow.ActiveCell.Address
End If

Sheets("Irrigation").Select
Call Analysis_Visible(True)
Call UnProtect_All
'This sub manages the water budget for a soil profile with five layers as set up on
'the irrigation sheet.

'Definition of variables:
'water_in is the sum of the inputs to the net water buget,
   'commonly water_in = Precip + Net Irrigation
'ET is the net evapo-transpiration. This model assumes this is the only way that
   'water leaves the system when the soil layer deficit is non-zero
'drz is a decimal number that is the depth of the rootzone for the given day
   '(in inches)
```

```
't(i) is an array containing the thickness of the soil layers
'cumt(i) is an array containing the cumulative depth of the soil layers

'The soil layer depths are assumed to be constant, shown below
Dim i, j, rctr, size, layers, MADi As Integer
Dim t(5), cumt(5), ET, drz, water_in, MAD(3), TAW, AWC(5), GDD(4), Ks, dMAD, D As
Double

dMAD = 0
'The GDD array contains the GDD cutoffs for the end of the seedling, rapid development,
'full canopy and senescence phases and GDD at maturity, respectively.

Sheets("Kcr").Select
'Assign MAD levels
For MADi = 0 To 3
   MAD(MADi) = Cells(MADi + 1, 13).value
Next
For Each i In Range("B4, E4, H4, I2") 'Ensure that all of the crop data is entered
   If i = "" Or IsNumeric(i) = False Then
      MsgBox "Please enter crop development data via the 'Set up Farm Using data from
CoAgMet' button" & _
         "or the Kcr page (visible if the 'Show Analysis' button is selected)", vbCritical +
vbOKOnly, _
         "Missing Crop Data"
      If Sheets("Introduction").Range("S1").value = 2 Then
         Sheets("Kcr").Visible = False
      End If
      Sheets(cursheet).Select
      Exit Sub
   End If
Next
'Record GDD cutoffs
GDD(0) = 0
GDD(1) = Range("B4").value * Range("I2").value
GDD(2) = Range("E4").value * Range("I2").value
GDD(3) = Range("H4").value * Range("I2").value
GDD(4) = Range("I2").value

Sheets("Select Soil").Select
j = 1
```

```
t(0) = 0
cumt(0) = 0
layers = 0
'Record soil layer depths and AWC
Do Until Cells(j + 8, 1).value = ""
   t(j) = Cells(j + 8, 2).value - Cells(j + 8, 1).value
   cumt(j) = Cells(j + 8, 2).value
   AWC(j) = Cells(j + 8, 3).value
   layers = layers + 1
   j = j + 1
Loop
Sheets("Irrigation").Select

'These variables are for the root distribution model
Dim roots(5) As Double
'A universial root distribution model is used for all crops
'roots(5) is an array that contains the fraction of the roots in each layer

Range("P5:W5").Select
Range(Selection, Selection.End(xlDown)).ClearContents
Range(Selection, Selection.End(xlDown)).ClearComments

Range("F5").Select
Range(Selection, Selection.End(xlDown)).ClearContents

Range("A5").Select
size = Range(Selection, Selection.End(xlDown)).Count + 4
Range(Range("M5"), Cells(size, 13)).ClearContents

rctr = 5
Do Until Cells(rctr, 1).value = ""

   ET = Cells(rctr, 5).value 'ETc is in collumn E
   drz = Cells(rctr, 8).value 'Drz is in collumn H
   If Cells(rctr, 14).value = "" Then 'Precip + Net Irrigation
      water_in = Cells(rctr, 3).value + Cells(rctr, 7).value
   Else 'Use the user's value for precip if available
      water_in = Cells(rctr, 14).value + Cells(rctr, 7).value
   End If
   For i = 1 To 5
```

```
        'If there is no information for the selected layer we don't need to do calculations
        If Cells(3, i + 16).value = "-" Then
            Cells(rctr, i + 16).value = "-"
        'If Observed moisture content was known for a day use that to calculate the deficit
        ElseIf Not Cells(rctr, i + 24).value = "" And IsNumeric(Cells(rctr, i + 24).value) Then
            Cells(rctr, i + 16).value = Cells(4, i + 16).value - Cells(rctr, i + 24).value * t(i)
            If cumt(i) < drz Then
                TAW = TAW + AWC(i) * t(i)
            ElseIf drz > cumt(i - 1) Then
                TAW = TAW + AWC(i) * (drz - cumt(i - 1))
            End If

            If Cells(rctr, i + 16).value > 0 Then
                Cells(rctr, i + 16).value = Cells(rctr, i + 16).value * -1
            Else
                Cells(rctr, i + 16).value = 0
            End If
        'In the case that no initial soil moisture content is entered the deficit is assumed to be 0
        ElseIf rctr = 5 Then
            Cells(rctr, i + 16).value = 0
            Ks = 1
        Else
        'If the ET is non-zero than we assume that water is removed in relation to
        'the root density using the root zone density algorithm

            If cumt(i - 1) > drz Then
                roots(i) = 0
            ElseIf cumt(i) < drz Then
                roots(i) = 1.8 * (cumt(i) / drz) - 0.8 * (cumt(i) / drz) ^ 2 - (1.8 * (cumt(i - 1) / drz) - 0.8
* (cumt(i - 1) / drz) ^ 2)
            Else
                roots(i) = 1 - (1.8 * (cumt(i - 1) / drz) - 0.8 * (cumt(i - 1) / drz) ^ 2)
            End If

            Ks = Cells(rctr - 1, 23).value

            Cells(rctr, i + 16).value = Cells(rctr - 1, i + 16).value - ET * Ks * roots(i)

        'For water_in we assume that water, from net irrigation (column G) or precipitation (column
C),
```

```
        'fills the soil profile top down. So layer 1 is filled first and then layer 2 and so on.
        'It is assumed that all precip and irrigation data are positive values

            If Not water_in = 0 Then
                If Not Cells(rctr, i + 16).value = 0 Then
                    If water_in > Abs(Cells(rctr, i + 16).value) Then
                        water_in = water_in + Cells(rctr, i + 16).value
                        Cells(rctr, i + 16).value = 0
                    Else
                        Cells(rctr, i + 16).value = Cells(rctr, i + 16).value + water_in
                        water_in = 0

                    End If
                End If
        'If there is excess water after the root zone is fully filled it is reported as Runoff+Percolation
in Column M
                If (Cells(3, i + 16 + 1).value = "-" Or i = 5) And water_in > 0 Then
                    Cells(rctr, 13).value = water_in
                    water_in = 0
                End If
            End If

        'Determine parameters needed to calculate Ks
            If cumt(i) < drz Then
                TAW = TAW + AWC(i) * t(i)
            ElseIf drz > cumt(i - 1) Then
                TAW = TAW + AWC(i) * (drz - cumt(i - 1))
            End If
        'Limit the defict in a layer to the the AWC * thickness (available water in inches)
        'The logic is that the plant will remove the ET from the easiest accessable layer.
        'If one layers is completely depleted (-AWC*t=D) then the ET is removed from the next
        'lower layer. Because of the exponential root weight used it is safe to assume
        'that shallower soil layers will be depleted before the deeper soil layers.

            If Abs(Cells(rctr, i + 15).value) > (AWC(i - 1) * t(i - 1)) And i > 1 Then
                Cells(rctr, i + 16).value = Cells(rctr, i + 16).value + (Cells(rctr, i + 15).value + AWC(i
- 1) * t(i - 1))
                Cells(rctr, i + 15).value = -1 * AWC(i - 1) * t(i - 1)
            End If
```

```
            If Abs(Cells(rctr, i + 16).value) > (AWC(i) * t(i)) And (i = 5 Or Cells(3, i + 17).value =
"-") Then
                Cells(rctr, i + 16).value = -1 * AWC(i) * t(i)
            End If
        End If

    Next

    'Once the deficts are determined for each layer we need to determine a root zone
    'deficit. The root zone deficit is the sum of the deficit in all the soil layers that
    'the root zone fill completely, plus the fraction of the defict in a layer that is not
    'entirely spanned proportional to the factional coverage.
    If drz <= cumt(1) Then
        Cells(rctr, 6).value = drz / cumt(1) * Cells(rctr, 17).value
    ElseIf drz <= cumt(2) Then
        Cells(rctr, 6).value = Cells(rctr, 17).value + (drz - cumt(1)) / _
            (t(2)) * Cells(rctr, 18).value
    ElseIf drz <= cumt(3) Then
        Cells(rctr, 6).value = WorksheetFunction.Sum(Cells(rctr, 17), Cells(rctr, 18)) + _
            (drz - cumt(2)) / (t(3)) * Cells(rctr, 19).value
    ElseIf drz <= cumt(4) Then
        Cells(rctr, 6).value = WorksheetFunction.Sum(Range(Cells(rctr, 17), Cells(rctr, 19))) + _
            (drz - cumt(3)) / (t(4)) * Cells(rctr, 20).value
    ElseIf drz <= cumt(5) Then
        Cells(rctr, 6).value = WorksheetFunction.Sum(Range(Cells(rctr, 17), Cells(rctr, 20))) + _
            (drz - cumt(4)) / (t(5)) * Cells(rctr, 21).value
    Else
        Cells(rctr, 6).value = WorksheetFunction.Sum(Range(Cells(rctr, 17), Cells(rctr, 21)))
    End If
    '[OPTIONAL] Check if all ET was used, uncomenting the line below will display a sum of the
weighted
    'root densities for all soil layers in Column P. This should always equal 1.
    'Cells(rctr, 16).value = roots(0) + roots(1) + roots(2) + roots(3) + roots(4) + roots(5)

    'We can now determine the Ks value for the previous day
        If Cells(rctr - 1, 10).value < GDD(1) Then
            j = 0
        ElseIf Cells(rctr - 1, 10).value > GDD(2) Then
            j = 1
        ElseIf Cells(rctr - 1, 10).value < GDD(3) Then
```

```
            j = 2
        Else
            j = 3
        End If
        D = Cells(rctr, 6).value
        dMAD = Cells(rctr, 9).value
        If Abs(D) < Abs(dMAD) Then
            Ks = 1
        Else
            Ks = (TAW + D) / ((1 - MAD(j)) * TAW)
        End If
        Cells(rctr, 23).value = Ks
        dMAD = 0
        TAW = 0

    If Round(rctr / size * 100, 0) Mod 10 = 0 Then
        Application.StatusBar = "Updating Soil Layer Deficits " & Round(rctr / size * 100, 0) & "% complete"
    End If
    rctr = rctr + 1
Loop
Range("V4").Select
Selection.AutoFill Destination:=Range(Cells(4, 22), Cells(size, 22)), Type:=xlFillValues

Application.StatusBar = False
Application.DisplayStatusBar = OldStatusBar
Call Protect_All
Call Analysis_Visible

Sheets(cursheet).Select
If cursheet = "Irrigation" Then
    Range(cursel).Activate
End If

End Sub
```

APPENDIX IV: VISUAL BASIC SOURCE CODE FOR ROOT GROWTH ALGORITHM USED IN THE COLORADO IRRIGATION SCHEDULER (CIS): ANNUALS

D_{rz} = IF(J10=0,6,IF(J10>=Kcr!$I$2*Kcr!$E$4,$F$2,(Irrigation!$F$2-6)/(Kcr!$I$2*Kcr!$E$4)* J10+6))

If GDD = 0

$$Drz = 0$$

Elseif J10>=GDD @ $K_{c,ini}$

$$Drz = D_{max}$$

Else

$$Drz = \frac{D_{max} - 6}{GDD\ @\ K_{c,ini}} * GDD + 6$$

APPENDIX V: SAMPLE SUBSET OF COAGMET DATA USED TO CALCULATE REFERENCE EVAPOTRANSPIRATION USED IN THE COLORADO IRRIGATION SCHEDULERS

Table A1 – Sample of weather variables obtained from CoAgMet station GLY-04 used to calculate reference evapotranspiration using the hourly version of the ASCE (2005) Standardized Reference ET Equation during 2010 in the perennial crop field. All weather variables used in the evaluation of the Colorado Irrigation Schedulers can be obtained through the CoAgMet website (http://climate.colostate.edu/~coagmet/).

Year	Month	Day	Hour	Mean Temp (°C)	RH (fraction)	Vapor Pressure (kPa)	Solar Radiation (kJ/m^2 * min)	Mean Wind Speed (m/s)
2010	5	11	0	4.226	0.768	0.634	0	0.55
2010	5	11	1	4.05	0.771	0.629	0	0.294
2010	5	11	2	4.082	0.788	0.644	0	0.387
2010	5	11	3	4.537	0.799	0.674	0	0.88
2010	5	11	4	5.194	0.763	0.674	0	0.666
2010	5	11	5	5.332	0.74	0.66	0.023	2.178
2010	5	11	6	5.272	0.724	0.643	0.972	2.249
2010	5	11	7	5.787	0.706	0.65	4.102	2.758
2010	5	11	8	6.387	0.714	0.685	5.575	3.745
2010	5	11	9	6.332	0.736	0.704	5.203	4.851
2010	5	11	10	6.259	0.751	0.714	5.023	5.767
2010	5	11	11	5.939	0.75	0.698	5.667	5.218
2010	5	11	12	6.76	0.695	0.684	8.85	5.018
2010	5	11	13	8.51	0.613	0.68	15.47	5.754
2010	5	11	14	8.58	0.619	0.69	6.288	6.99
2010	5	11	15	8.09	0.655	0.706	5.28	7.526
2010	5	11	16	7.571	0.711	0.74	1.959	7.395
2010	5	11	17	6.039	0.869	0.814	1.798	7.022
2010	5	11	18	5.604	0.911	0.828	0.604	5.698
2010	5	11	19	5.522	0.92	0.832	0.091	2.852

Year	Month	Day	Hour	Mean Temp (°C)	RH (fraction)	Vapor Pressure (kPa)	Solar Radiation (kJ/m^2 * min)	Mean Wind Speed (m/s)
2010	5	11	20	5.22	0.908	0.804	0	3.95
2010	5	11	21	3.866	0.905	0.729	0	5.415
2010	5	11	22	1.369	0.937	0.632	0	5.438
2010	5	11	23	0.466	0.953	0.602	0	3.594
2010	5	12	0	-0.098	0.965	0.585	0	2.2
2010	5	12	1	-0.174	0.971	0.586	0	1.935
2010	5	12	2	-0.019	0.973	0.593	0	1.973
2010	5	12	3	0.123	0.965	0.595	0	2.283
2010	5	12	4	0.1	0.962	0.592	0	1.953
2010	5	12	5	0.193	0.946	0.586	0.03	1.982
2010	5	12	6	0.066	0.949	0.582	1.402	2.326
2010	5	12	7	0.279	0.94	0.586	5.433	2.82
2010	5	12	8	0.528	0.922	0.585	6.909	3.846
2010	5	12	9	0.854	0.929	0.604	10.41	3.688
2010	5	12	10	1.422	0.911	0.617	12.95	3.255
2010	5	12	11	1.665	0.906	0.624	11.27	2.81
2010	5	12	12	2.746	0.835	0.621	18.28	2.571
2010	5	12	13	3.654	0.797	0.632	21.49	2.895
2010	5	12	14	4.137	0.781	0.641	15	3.613
2010	5	12	15	4.34	0.743	0.619	12.94	3.457
2010	5	12	16	4.618	0.705	0.599	16.5	4.452
2010	5	12	17	4.422	0.701	0.587	15.43	5.448
2010	5	12	18	3.783	0.725	0.58	4.634	4.196
2010	5	12	19	3.484	0.712	0.558	0.85	2.58
2010	5	12	20	3.121	0.752	0.575	0.024	1.574
2010	5	12	21	2.358	0.818	0.592	0	0.288
2010	5	12	22	2.415	0.811	0.589	0	0.695
2010	5	12	23	2.193	0.847	0.606	0	0.624

APPENDIX VI: ATMOMETER MEASURED EVAPOTRANSPIRATION DATA

Table A2 – Atmometer measured evapotranspiration (ET, mm d^{-1}) data from the Arkansas Valley Research Center used in the evaluation of atmometer performance. Atmometer measured ET was obtained using an ETgage Model E (ETgage Company, Loveland, CO, USA (http://www.etgage.com) and a HOBO Pendant Event Data Logger UA-003-64 (Onset Computer Corporation, Bourne, MA, USA).

Date	ET (mm d^{-1})	Date	ET (mm d^{-1})	Date	ET (mm d^{-1})	Date	ET (mm d^{-1})
5/22/2008	7.37	5/15/2009	5.59	4/24/2010	2.54	6/23/2011	1.27
5/23/2008	6.10	5/16/2009	4.57	4/25/2010	2.54	6/24/2011	6.60
5/24/2008	8.89	5/17/2009	6.35	4/26/2010	2.79	6/25/2011	7.62
5/25/2008	8.38	5/18/2009	8.38	4/27/2010	2.54	6/26/2011	6.86
5/26/2008	4.06	5/19/2009	10.41	4/28/2010	2.79	6/27/2011	10.92
5/27/2008	3.30	5/20/2009	10.16	4/29/2010	3.05	6/28/2011	8.13
5/28/2008	5.59	5/21/2009	4.57	4/30/2010	2.29	6/29/2011	8.64
5/29/2008	11.18	5/22/2009	4.57	5/1/2010	1.78	6/30/2011	8.38
5/30/2008	8.64	5/23/2009	5.33	5/2/2010	2.03	7/1/2011	12.45
5/31/2008	8.38	5/24/2009	3.81	5/3/2010	2.03	7/2/2011	8.13
6/1/2008	7.37	5/25/2009	3.30	5/4/2010	3.05	7/3/2011	6.86
6/2/2008	9.91	5/26/2009	1.78	5/5/2010	5.08	7/4/2011	7.37
6/3/2008	7.62	5/27/2009	5.08	5/6/2010	7.87	7/5/2011	8.13
6/4/2008	5.84	5/28/2009	6.10	5/7/2010	4.06	7/6/2011	8.64
6/5/2008	2.03	5/29/2009	7.62	5/8/2010	5.59	7/7/2011	6.60
6/6/2008	7.62	5/30/2009	8.13	5/9/2010	8.13	7/8/2011	5.08
6/7/2008	8.13	5/31/2009	7.11	5/10/2010	6.86	7/9/2011	5.59
6/8/2008	6.35	6/1/2009	4.83	5/11/2010	3.30	7/10/2011	6.60
6/9/2008	6.86	6/2/2009	0.51	5/12/2010	2.29	7/11/2011	5.59
6/10/2008	12.19	6/3/2009	2.54	5/13/2010	2.79	7/12/2011	6.35
6/11/2008	9.91	6/4/2009	4.83	5/14/2010	1.78	7/13/2011	7.11
6/12/2008	8.89	6/5/2009	6.86	5/15/2010	2.54	7/14/2011	7.37
6/13/2008	8.64	6/6/2009	10.41	5/16/2010	5.08	7/15/2011	7.37
6/14/2008	11.18	6/7/2009	8.89	5/17/2010	4.57	7/16/2011	8.38
6/15/2008	12.19	6/8/2009	7.37	5/18/2010	4.06	7/17/2011	10.92
6/16/2008	2.29	6/9/2009	8.13	5/19/2010	3.56	7/18/2011	11.94
6/17/2008	8.13	6/10/2009	3.30	5/20/2010	4.57	7/19/2011	11.18
6/18/2008	9.14	6/11/2009	3.05	5/21/2010	5.08	7/20/2011	11.94
6/19/2008	5.84	6/12/2009	5.84	5/22/2010	11.18	7/21/2011	8.64
6/20/2008	6.86	6/13/2009	4.32	5/23/2010	7.87	7/22/2011	4.32
6/21/2008	8.13	6/14/2009	3.81	5/24/2010	7.37	7/23/2011	6.86
6/22/2008	9.14	6/15/2009	5.84	5/25/2010	5.08	7/24/2011	8.13
6/23/2008	8.38	6/16/2009	8.13	5/26/2010	4.83	7/25/2011	7.62
6/24/2008	8.13	6/17/2009	8.64	5/27/2010	8.13	7/26/2011	7.87

Date	ET (mm d^{-1})	Date	ET (mm d^{-1})	Date	ET (mm d^{-1})	Date	ET (mm d^{-1})
6/25/2008	9.65	6/18/2009	8.89	5/28/2010	9.14	7/27/2011	8.38
6/26/2008	9.65	6/19/2009	8.13	5/29/2010	9.65	7/28/2011	6.60
6/27/2008	10.16	6/20/2009	2.79	5/30/2010	6.10	7/29/2011	5.59
6/28/2008	6.35	6/21/2009	8.89	5/31/2010	6.86	7/30/2011	5.84
6/29/2008	8.38	6/22/2009	6.35	6/1/2010	7.87	7/31/2011	7.11
6/30/2008	8.64	6/23/2009	5.84	6/2/2010	6.35	8/1/2011	7.87
7/1/2008	9.91	6/24/2009	8.13	6/3/2010	7.87	8/2/2011	8.89
7/2/2008	9.40	6/25/2009	8.38	6/4/2010	10.41	8/3/2011	5.84
7/3/2008	5.84	6/26/2009	7.62	6/5/2010	10.41	8/4/2011	3.56
7/4/2008	8.38	6/27/2009	8.38	6/6/2010	9.40	8/5/2011	5.84
7/5/2008	9.91	6/28/2009	7.62	6/7/2010	10.16	8/6/2011	6.35
7/6/2008	7.87	6/29/2009	8.13	6/8/2010	7.37	8/7/2011	7.62
7/7/2008	4.83	6/30/2009	8.38	6/9/2010	6.35	8/8/2011	7.37
7/8/2008	5.84	7/1/2009	8.64	6/10/2010	10.67	8/9/2011	7.62
7/9/2008	5.59	7/2/2009	8.13	6/11/2010	5.59	8/10/2011	7.11
7/10/2008	8.38	7/3/2009	5.33	6/12/2010	1.27	8/11/2011	4.83
7/11/2008	9.91	7/4/2009	4.83	6/13/2010	2.54	8/12/2011	6.10
7/12/2008	6.10	7/5/2009	3.56	6/14/2010	3.81	8/13/2011	6.35
7/13/2008	7.37	7/6/2009	4.57	6/15/2010	5.59	8/14/2011	4.57
7/14/2008	8.13	7/7/2009	8.13	6/16/2010	7.87	8/15/2011	6.10
7/15/2008	8.13	7/8/2009	7.87	6/17/2010	9.65	8/16/2011	7.11
7/16/2008	8.38	7/9/2009	8.89	6/18/2010	8.64	8/17/2011	7.11
7/17/2008	7.87	7/10/2009	7.87	6/19/2010	6.35	8/18/2011	5.33
7/18/2008	4.83	7/11/2009	7.87	6/20/2010	7.87	8/19/2011	6.10
7/19/2008	9.40	7/12/2009	7.87	6/21/2010	6.60	8/20/2011	6.10
7/20/2008	10.41	7/13/2009	7.11	6/22/2010	7.87	8/21/2011	5.59
7/21/2008	10.92	7/14/2009	9.14	6/23/2010	7.87	8/22/2011	5.59
7/22/2008	10.16	7/15/2009	7.87	6/24/2010	7.62	8/23/2011	6.60
7/23/2008	11.68	7/16/2009	9.40	6/25/2010	9.40	8/24/2011	7.62
7/24/2008	9.91	7/17/2009	8.13	6/26/2010	9.14	8/25/2011	7.87
7/25/2008	7.37	7/18/2009	7.62	6/27/2010	5.59	8/26/2011	6.86
7/26/2008	37.08	7/19/2009	8.13	6/28/2010	7.11	8/27/2011	8.89
7/27/2008	7.11	8/20/2009	5.08	6/29/2010	8.13	8/28/2011	8.13
7/28/2008	7.11	8/21/2009	6.10	6/30/2010	8.13	8/29/2011	8.38
7/29/2008	6.35	8/22/2009	7.37	7/1/2010	8.64	8/30/2011	4.83
7/30/2008	8.64	8/23/2009	9.14	7/2/2010	8.89	8/31/2011	8.13
7/31/2008	10.41	8/24/2009	6.86	7/3/2010	8.13	9/1/2011	8.38
8/1/2008	10.41	8/25/2009	4.83	7/4/2010	4.57	9/2/2011	9.14
8/2/2008	12.45	8/26/2009	4.83	7/5/2010	6.10	9/3/2011	6.35
8/3/2008	10.67	8/27/2009	6.35	7/6/2010	5.84	9/4/2011	5.84
8/4/2008	8.64	8/28/2009	6.86	7/7/2010	3.56	9/5/2011	4.57

Date	ET (mm d^{-1})	Date	ET (mm d^{-1})	Date	ET (mm d^{-1})	Date	ET (mm d^{-1})
8/5/2008	5.08	8/29/2009	5.33	7/8/2010	3.56	9/6/2011	5.59
8/6/2008	7.37	8/30/2009	4.83	7/9/2010	5.08	9/7/2011	5.59
8/7/2008	1.52	8/31/2009	5.59	7/10/2010	6.86	9/8/2011	3.81
8/8/2008	4.57	9/1/2009	6.35	7/11/2010	8.13	9/9/2011	4.06
8/9/2008	6.86	9/2/2009	5.84	7/12/2010	7.37	9/10/2011	4.32
8/10/2008	3.81	9/3/2009	5.59	7/13/2010	10.67	9/11/2011	4.57
8/11/2008	5.84	9/4/2009	2.29	7/14/2010	10.67	9/12/2011	5.08
8/12/2008	6.86	9/5/2009	4.06	7/15/2010	7.11	9/13/2011	5.33
8/13/2008	5.59	9/6/2009	4.83	7/16/2010	8.89	9/14/2011	3.05
8/14/2008	4.32	9/7/2009	6.10	7/17/2010	9.91	9/15/2011	1.52
8/15/2008	1.27	9/8/2009	6.10	7/18/2010	7.62	9/16/2011	2.29
8/16/2008	0.25	9/9/2009	5.08	7/19/2010	8.13	9/17/2011	3.05
8/17/2008	2.03	9/10/2009	4.57	7/20/2010	5.33	9/18/2011	4.57
8/18/2008	3.30	9/11/2009	4.32	7/21/2010	5.08	9/19/2011	4.06
8/19/2008	4.32	9/12/2009	1.78	7/22/2010	6.60	9/20/2011	4.57
8/20/2008	4.32	9/13/2009	4.06	7/23/2010	4.57	9/21/2011	4.83
8/21/2008	6.35	9/14/2009	4.57	7/24/2010	3.05	9/22/2011	3.81
8/22/2008	7.87	9/15/2009	4.57	7/25/2010	1.02	9/23/2011	3.56
8/23/2008	4.83	9/16/2009	3.30	7/26/2010	6.86	-	-
8/24/2008	6.10	9/17/2009	3.56	7/27/2010	6.60	-	-
8/25/2008	6.35	9/18/2009	4.32	7/28/2010	6.35	-	-
8/26/2008	6.35	9/19/2009	4.32	7/29/2010	6.86	-	-
8/27/2008	6.35	9/20/2009	5.59	7/30/2010	6.10	-	-
8/28/2008	6.10	9/21/2009	0.51	7/31/2010	2.29	-	-
8/29/2008	4.32	9/22/2009	2.29	8/1/2010	6.10	-	-
8/30/2008	6.10	9/23/2009	0.76	8/2/2010	6.86	-	-
8/31/2008	7.11	9/24/2009	2.54	8/3/2010	5.84	-	-
9/1/2008	8.64	9/25/2009	2.03	8/4/2010	4.57	-	-
9/2/2008	5.84	9/26/2009	4.32	8/5/2010	3.81	-	-
9/3/2008	5.33	9/27/2009	6.10	8/6/2010	4.32	-	-
9/4/2008	5.33	9/28/2009	4.06	8/7/2010	5.84	-	-
9/5/2008	3.30	-	-	8/8/2010	5.84	-	-
9/6/2008	4.06	-	-	8/9/2010	3.81	-	-
9/7/2008	5.59	-	-	8/10/2010	5.33	-	-
9/8/2008	1.02	-	-	8/11/2010	6.60	-	-
9/9/2008	4.32	-	-	8/12/2010	6.10	-	-
9/10/2008	6.60	-	-	8/13/2010	6.60	-	-
9/11/2008	4.32	-	-	8/14/2010	6.86	-	-
9/12/2008	2.29	-	-	8/15/2010	3.05	-	-
9/13/2008	5.59	-	-	8/16/2010	3.30	-	-
9/14/2008	3.81	-	-	8/17/2010	4.83	-	-

Date	ET (mm d^{-1})	Date	ET (mm d^{-1})	Date	ET (mm d^{-1})	Date	ET (mm d^{-1})
9/15/2008	4.57	-	-	8/18/2010	6.60	-	-
9/16/2008	5.59	-	-	8/19/2010	6.86	-	-
9/17/2008	5.08	-	-	8/20/2010	6.60	-	-
9/18/2008	5.08	-	-	8/21/2010	7.87	-	-
9/19/2008	5.33	-	-	8/22/2010	8.64	-	-
9/20/2008	5.33	-	-	8/23/2010	8.38	-	-
9/21/2008	5.08	-	-	8/24/2010	5.33	-	-
9/22/2008	7.87	-	-	8/25/2010	6.35	-	-
9/23/2008	5.59	-	-	8/26/2010	7.11	-	-
9/24/2008	5.08	-	-	8/27/2010	8.38	-	-
9/25/2008	6.60	-	-	8/28/2010	9.65	-	-
9/26/2008	6.60	-	-	8/29/2010	8.89	-	-
9/27/2008	5.08	-	-	8/30/2010	8.64	-	-
9/28/2008	6.35	-	-	8/31/2010	6.86	-	-
9/29/2008	4.06	-	-	9/1/2010	6.35	-	-
9/30/2008	4.57	-	-	9/2/2010	5.33	-	-
-	-	-	-	9/3/2010	5.33	-	-
-	-	-	-	9/4/2010	6.60	-	-
-	-	-	-	9/5/2010	8.64	-	-
-	-	-	-	9/6/2010	7.62	-	-
-	-	-	-	9/7/2010	5.08	-	-
-	-	-	-	9/8/2010	4.06	-	-
-	-	-	-	9/9/2010	7.37	-	-