ArcET
A GIS Package for Statewide Irrigation Water Use Estimation

Technical Description and User Guide

(draft)

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Division of Water Resources

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Preface

The US Geological Survey (USGS) is required by Federal mandate to estimate and report on water use for each state at five-year intervals. While the periodic GUGS estimates of statewide water use are valuable for planning and management, many states have recognized a need to generate water use estimates on an annual basis, which would be more valuable in identifying and analyzing present water use and forecasting future water use. This implies a need for efficiency and accuracy of generating water use estimation.
A water use estimation project undertaken by Utah Water Research Laboratory (UWRL) is intended to meet the above needs. The primary goal of this project is to develop GIS-based methodology for statewide water use consistent with USGS water use categories. As part of this research project, a software package (an ArcGIS extension) was developed for automation of statewide irrigation water use estimation primarily for the purpose of long-term planning and management of regional water resources. This document is intended to describe the technical design and implementation of the proposed GIS-based approach.

The software package including the installation package, sample inputs, and source code is electronically available through the Internet (http://moose.cee.usu.edu/ArcET/) or by contacting anyone of the following persons:

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Section 1. Technical Description

1.1 Introduction

Agricultural water use, particularly irrigation water use, is one of the most important components of regional water budget and plays an important role in the water resources planning and managements. The need for detailed and accurate agricultural water use data is becoming critical with increasing water demands and limited water supplies in many places of the United States. While agricultural water use estimate can be done with a traditional survey inventory based approach, one can also implement some more advanced hydrological approaches to do it. In common sense, the latter is more efficient and accurate. No matter what approach you use, the basis for water use estimate would usually be the water balance equation.

Theoretically, we can estimate water flow at any spatial location based on the following soil water balance equation (Eqn.1) in case we know those required parameters for this equation.

$$\Delta W = PPT_{eff} + G + NIR - ET_{crop} \quad (1)$$

where

ΔW [L] is the change of soil moisture between the beginning and the end of the time period (for our case, a month),
PPT_{eff} [L] is the effective precipitation during the time period,
G [L] is the groundwater contribution during the time period
NIR [L] is the net irrigation water requirement,
ET_{crop} [L] is the potential consumptive use or potential evapotranspiration

Station-based parameters for this equation are easily available, so use of such an equation at point scale would be no problems. However, agricultural water use should be considered as an event at regional scale, therefore, to make regional agricultural water use one needs to apply this equation in a spatially distributed manner because of the strong spatial variations in parameters involving in estimation procedure.

The difference between the point estimate and regional estimate is the latter needs parameters at non-gage location as well as gage location. So to use water balance equation in spatially distributed manner effectively, we must understand and acquit the spatial distribution of the parameters, such as land use, cropping patterns, crop coefficients, etc. Usually point gage data is inadequate to give necessary information. GIS is one good way to provide and process these kinds of spatial distribution information. So we are trying to develop a GIS-based methodology for statewide agricultural water use estimate.

Then, we define the scope of this study as following:

- Formulate one GIS-based framework for agricultural water use estimate.
- Develop procedures for acquiring spatially distributed parameters.
- Automate the estimate of regional crop water consumption with GIS procedures

1.2 GIS-based Approach

We will make the annual statewide agricultural water use estimate for user-specified region at a monthly resolution. In this case, we could make following assumptions and simplify the water balance equation (Eqn. 1).

1. The soil moisture change between the beginning and the end of the time period (for our case, one month) can be omitted ($\Delta W = 0$).
2. No groundwater contribution during the time period (G =0)

Under above assumptions, the total irrigation water use can be estimated by following formulas:

$$NIR = MAX(ET_{crop} - PPT_{eff}, 0) \quad (2)$$

$$GIR = (1 - k_s)\frac{NIR}{IREF} \quad (3)$$

where

GIR is the gross crop irrigation water use that should be supplied
NIR is the net crop irrigation water requirement,
k_s is the shortage faction
$IREF$ is the irrigation efficiency
ET_{crop} is the estimated actual crop ET
PPT_{eff} is effective precipitation , usually estimated as 0.8 times actual precipitation

So, the basic task of estimating regional agricultural water use will include:

(1) estimation of crop evapotranspiration, ET_{crop}
(2) estimation of effective regional precipitation, PPT_{eff}
(3) estimation of irrigation, IREF
(4) estimation of shortage fraction, k_s

All these individual components can be estimated and presented in GIS format as in the framework (figure 1-1.).

Within this framework, external electronic station-based climate data and existing geo-datasets can be used to generate a series of GIS layers represent the spatial distribution of parameters used for water balance calculation, then those individual components involved in regional water budget will be estimated based on these generated GIS layers via particular GIS procedures.

In this framework, the necessary input datasets are:

- land use/cover information
- meteorological measurements (e.g. temperature, precipitation)
- crop coefficients
- distribution of irrigation facilities
- sub-divisions of the region of interest

In the following sections, we will describe procedures for the acquisition of all individual components in GIS format.

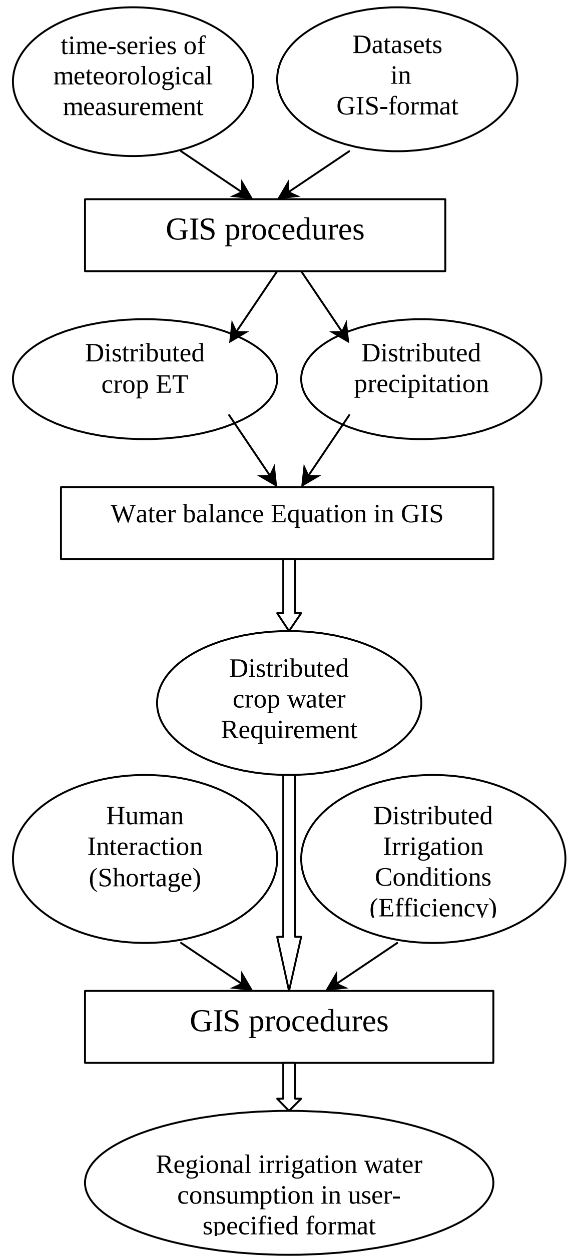


Figure 1-1. Framework of GIS-based Approach

1.3 Evapotranspiration estimation

While Evapotranspiration (ET) is an elementary component of regional water and energy balance, it is difficult to measure, and systematic measurements at regional scale are rare. In many cases, regional ET data needs to be estimated.

In the past years, some researchers explored the possibility of deriving regional ET from remotely sensed data(Price 1990, Sucksdorff and Ottle 1990, Bastiaanssen 2000). While remote- sensing approaches can provide high spatial resolution and coverage, they provide lower temporal resolution limited by the frequency of satellite overpasses and sky conditions. Furthermore almost all these methods are diagnostic rather than predictive. In other words, this category of approach can't furnish us with ET information under the possible future change of either individual climate factor or the land surface characteristics. However, in many cases like long- term water resources planning, the ET needs to be estimated under given scenarios with simulated or estimated climate and planned land use patterns. Taking into consideration the above facts, ET is commonly estimated from ground meteorological data with available land cover information through the conventional "reference ET - crop coefficients" approach. This approach also allows to use simulated meteorological data from meteorological models or statistical approaches as well as observed data to derive ET series.

The meteorological variables driving the physical process of ET are readily available through routine monitoring networks such as MesoWest and National Climatic Data Center (NCDC). Established methods (Jensen et al. 1990)exist to calculate point-specific reference ET from point meteorological data. With the support of GIS technology, it is possible to extend these methods to get spatially distributed ET over a region.

1.3.1 Conceptual Framework

The conceptual Framework of the GIS-based approach for regional ET modeling is given in figure 1-2. The goal is to calculate crop evapotranspiration for every grid cell within the domain of a given study area. Inputs consist of time series of point meteorological data, land cover/land use data and crop coefficient tables. The meteorological data is interpolated to grids using interpolation procedures appropriate for the quantity being interpolated. These are then used to compute a grid of reference ET. The crop coefficient tables are used to provide a crop coefficient at each grid cell based upon land cover/land use data. Combining the crop coefficient with reference ET provides the estimated ET at each grid cell.

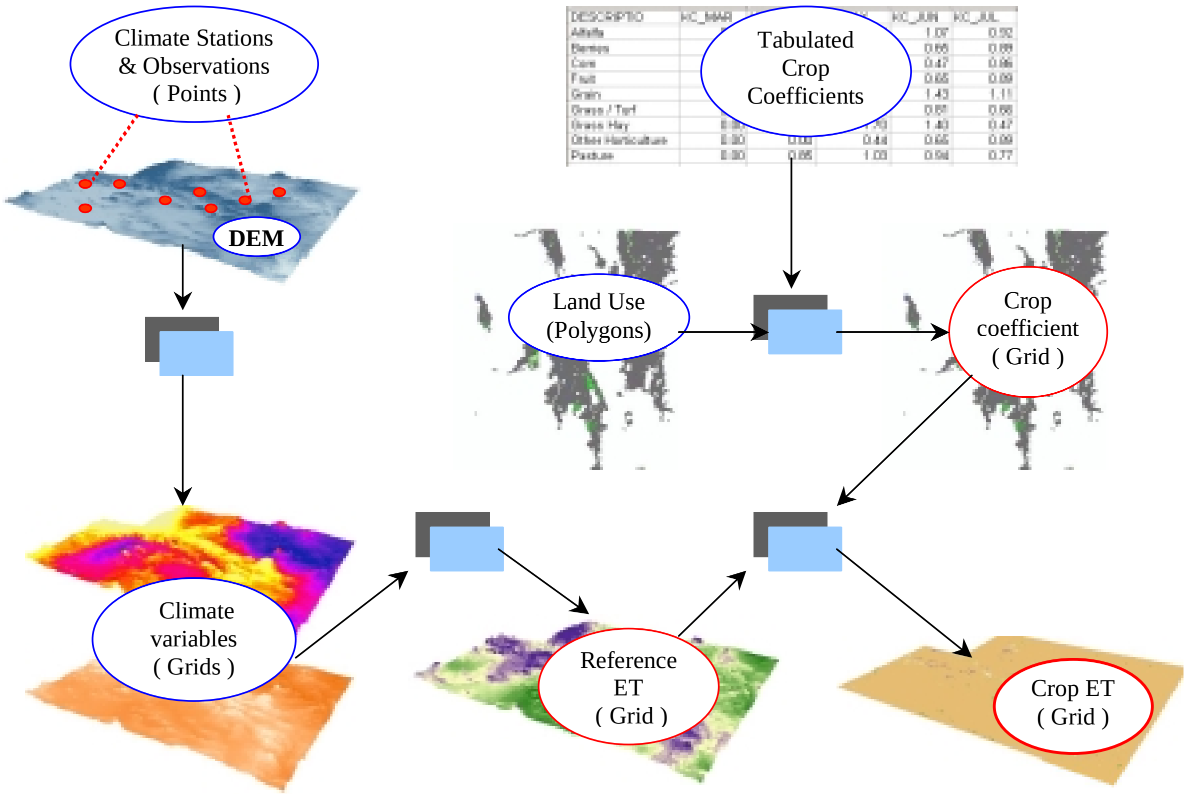


Figure 1-2. Illustration of the GIS-based approach for regional ET modeling

1.3.2 Functionality design

The ET calculation component consists of the following four modules shown in figure 1-3. The specific functionalities are as follows:

(1) Interpolating grids of spatially distributed meteorological parameters from point measurements
(2) Reference ET calculation at each grid cell
(3) Generating crop coefficient grids from land cover/use information
(4) Grid calculations to get crop ET

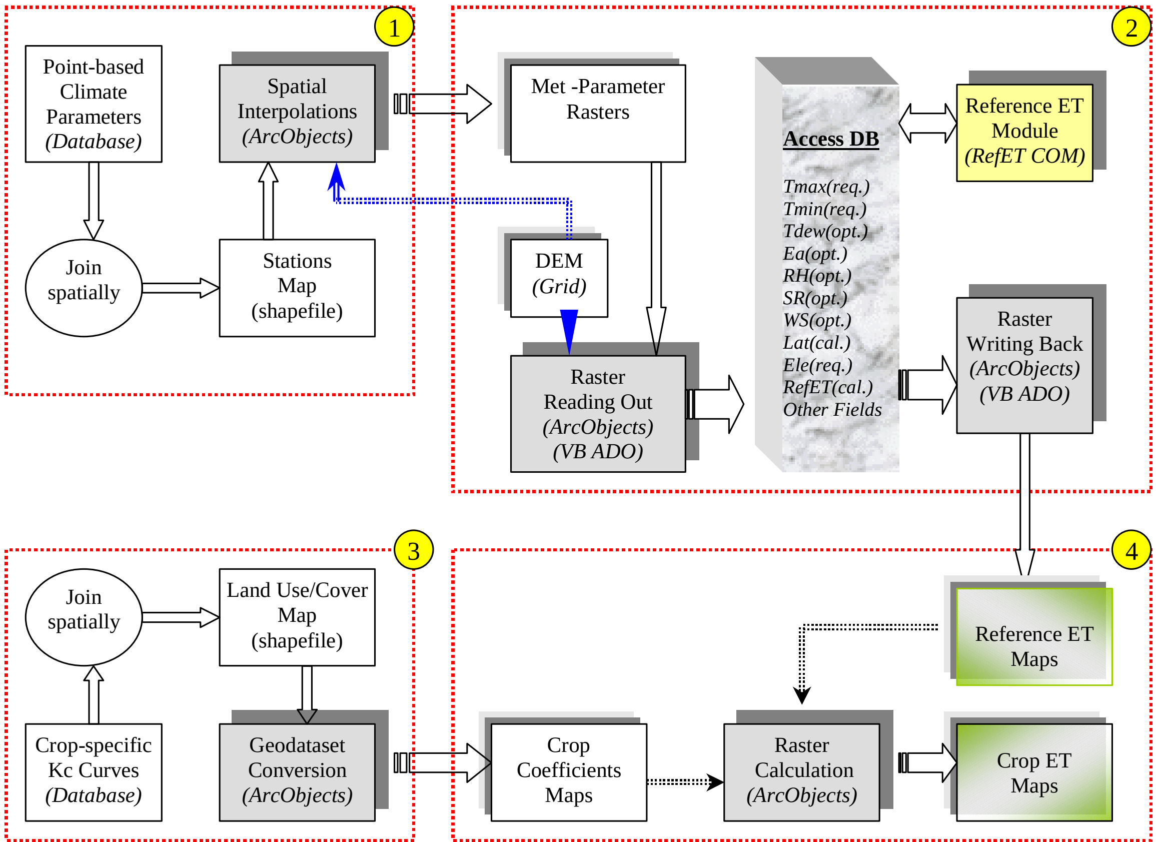


Figure 1-3. Functionality design of ET calculation component

The following sections discuss the functionality and design of each module.

Module 1: Interpolating grids of spatially distributed meteorological parameters from point measurements

ArcGIS provides a selection of two-dimensional spatial interpolation methods through ArcObjects. The specific interpolation scheme needs to recognize the physical attributes of the quantity being interpolated and the relationship to topography. ArcET implements particular interpolation schemes for near surface air temperature, air humidity, solar radiation and wind velocity.

1) Interpolation of Temperature

Temperature is fundamental to the calculation of ET. The dependence of temperature upon elevation represented in terms of a lapse rate lead us to implement an elevationally detrended approach for the interpolation of temperature.

In this scheme temperature at any location can be expressed as a combination of two components: a trend vertically varying with elevation and a horizontal random residual

$$T(u) = T_H(u) + T_V(u) \qquad (4)$$

where T_V is the vertical trend

T_H is the horizontal residual

The vertical trend at any location u within the study is assumed to be a function of elevation

$$T_V(u) = f(Z(u)) \qquad (5)$$

where $Z(u)$ is the elevation at location u

Taking a linear regression relationship, $f(Z(u)) = aZ(u) + b$ (6)

then, $T_V(u) = aZ(u) + b$ (7)

In above formula, *a* and *b* are regression coefficients obtained by developing a linear regression relationship between the measured temperature at each station and the station elevation over the whole set of stations at each calculation step.

The horizontal component at any on-gage location is interpolated from the residual difference between the measured temperature and the estimated trend value from the above linear regression at each station using ordinary Kriging(OK) or inverse distance weighted (IDW) depending on the spatial characteristics of the interpolated sets of point values.

$$T_H(u) = \sum_{i=1}^{n} w_i T_H(g_i) \qquad (8)$$

where $T_H(g_i) = T(g_i) - [aZ(g_i) + b]$ (9)

Then, the temperature at any location u within the study is estimated as

$$T(u) = aZ(u) + b + \sum_{i=1}^{n} w_i T_H(g_i) \qquad (10)$$

where

u represents any location within the study area

g_i represents the ith gage location among considered gages surrounding u

n is the total number of gages whose measurements are considered to be spatially correlated to the value at location u

w_i is the weight of the ith gage

$Z(u)$ is the elevation at location u

The operational procedure for temperature interpolation consists of the following steps:

(1) Establish a regional regression relationship between temperature and elevation from temperature observations and station elevations for each calculation time step

$\bar{T} = a_t Z + b_t$

(2) Remove the elevational trend ($\overline{T_i}$) from the measured values based on the above

regression, and get the residuals at gage locations, $T_i' = T_i - \overline{T}$
(3) Interpolate the residuals (T_i') with ArcGIS built-in ordinary Kriging or inverse distance weighted (IDW) to get the horizontal residual (T') of temperature at all other locations

(4) Use DEM and the regional regression relationship between temperature and elevation to get the vertical trend ($\overline{T}$) at all other locations
(5) Obtain the estimation of temperature (T) at any location by adding the above two terms, $T = \overline{T} + T'$

2) Interpolation of Humidity Data

Humidity information may be expressed in terms of dew point temperature, relative humidity or vapor pressure. We convert relative humidity and vapor pressure to dew point temperature, then apply the temperature interpolation scheme.

3) Interpolation of measured solar radiation

When point-based solar radiation data is available, ordinary Kriging (OK) or inverse distance weighted (IDW) is implemented depending on the spatial characteristics of the interpolated sets of point values. When there are no solar radiation measurements the empirical approach recommended in FAO56 (Allen et al. 1998) based upon the temperature range is adopted.

$$R_S = K_S \times \sqrt{(T_{max} - T_{min})} \times R_a \tag{11}$$

Where

T_{max} is maximum air temperature[^oC]

T_{min} is minimum air temperature[^oC]

R_a is extraterrestrial radiation []MJm^{-2}d^{-1}]

K_S is an empirical adjustment coefficient varying from 0.16 for interior locations to 0.19 for coastal regions.

4) Interpolation of measured wind speed

When wind data is available at some gage-locations, ordinary Kriging (OK) or inverse distance weighted (IDW) is implemented for this variable depending on the spatial characteristics of the interpolated sets of point values. In case that there is no wind data, an estimated value of wind speed is used over the entire area (Allen et al. 1998)

Module 2: Conduct reference ET calculation at cell level

Once the grids of individual meteorological variable are available, they are read into a personal database on a cell-by-cell basis. Then reference ET calculation with a particular method can be conducted over the database. The calculated values stored in the reference ET field of the personal database are used to generate reference ET grids.

To ensure that users from any region can apply this extension for their work, a selection of reference ET calculation methods are included in the extension as a method library. Users may select a particular method based on the data availability and regional climate & terrain conditions. The following methods are available:

1. FAO 56 Penman-Monteith (grass)
2. Standardized ASCE Penman-Monteith equation(s) (short / tall grass)
3. Hargreaves 1985
4. SCS modified Blaney-Criddle equation
5. Priestley-Taylor

Module3: Generating crop coefficient maps from land cover/use information

In order to obtain the corresponding distributed crop coefficient information, the following operations must be performed:

1. Look up existing crop types in the provided land use shapefile
2. Provide crop coefficients information corresponding to existing crop types
3. Join time series crop coefficients to specified land use polygons
4. Convert the joined crop coefficient attribute in the feature layer to a raster

This module implements procedures to perform these GIS operations automatically, and provide the modeler an interface to input or edit crop coefficient for available crop types.

Module 4: Grid calculations to get crop ET

The crop ET grids are obtained by multiplying crop coefficient grids with reference ET grids, using the *IMapAlgebraOp* raster calculator interface. The total ET within user provided zones is then summarized in an ET table.

1.4 Precipitation Estimation

Within a large region, especially a region with non-uniform topography, there must be considerable spatial variability in precipitation. Point precipitation data measured by precipitation station network provides high resolution in time, but typically sparse spatial coverage. In order to estimate precipitation at a non-gage location, usually some form of interpolation is carried out. In this GIS package, two schemes are provided for the spatial interpolation of precipitation.

Thinking of the dependence of precipitation upon elevation, the interpolation scheme used for temperature, the elevationally detrended approach as described in section 1.3.2, is also implemented for precipitation.

As an alternative way, one can also estimates precipitation at non-gage locations with supports from some additional datasets available to public.

One of these sources of spatial precipitation data is Oregon Climate Center, which provides PRISM (Parameter-elevation Regressions on Independent Slopes Model) generated gridded estimates of mean monthly precipitation maps at 2½ minute latitude/longitude (~4 km) spatial resolution. 1961-1990 mean monthly precipitation maps for the State of Utah can be found at http://www.ocs.orst.edu/prism/state_products/ut_maps.html. These generated datasets can be used as reference to make new precipitation interpolations at specific regions because of some special features. Some of such features that may benefit our water use estimate project are demonstrated as:

- Incorporates topographic effects on precipitation
- Captures rain shadows in great detail
- Accounts for the varying ability of terrain features to enhance precipitation
- Data format allows for easy use in GIS environment

To use the monthly PRISM dataset in interpolation process of monthly precipitation for specific time and location, we still need to develop a consistent interpolation scheme. For this purpose, we developed a normalization-interpolation-denormalization procedure as following.

First, known precipitation measurement values at a specific time (month), these local precipitation observations can be normalized by the following formula:

$$NP_i = \frac{P_i}{PP_i} \tag{12}$$

where,

P_i is the measured precipitation at station i

PP_i is the point value of PRISM surface at station i

NP_i is the normalized point value at station i

The second step of this specific procedure is to interpolate all the normalized values at gage stations and obtain a normalized surface at regional scale, providing normalized precipitation values at any location, $NP(x, y)$. Then one time-specific precipitation surface can be generated according to the following formula:

$$P(x, y) = NP(x, y) \times PP(x, y) \tag{13}$$

where

$PP(x, y)$ is PRISM surface value at any location with coordinates (x, y)

$NP(x, y)$ is the normalized surface value

$P(x, y)$ is the estimated precipitation at any location with coordinates (x, y)

Based on above procedure, we can get relatively accurate monthly precipitation distribution within the region of interest with reasonable considerations on spatial variability, topographic effects, etc. in any specific year.

1.5 Estimate of irrigation efficiency

Irrigation efficiency usually shows great geographical difference over regions. So the estimate the irrigation efficiency should be also done on a zone-by -zone basis.

Based on FAO's definition of irrigation efficiency, $E_e = E_c \times E_a$, irrigation efficiency (E_e) should include following two parts: (1) conveyance efficiency (E_c) or transmission efficiency, and (2) field application efficiency (E_a).

For a basic data unit, we assume that the conveyance efficiency, (E_c), or transmission efficiency is uniform for all kinds of irrigation scheme. So there will be only one overall conveyance efficiency value input for a basic data unit.

To have a better estimate of field application efficiency, the spatial distribution of irrigation methods within each basic data unit is required. But this kind of distributed data information is usually hard to obtain. So it is necessary to make some assumptions in order to make reasonable estimate on field application efficiency.

- No more than one type of crop grows in an elementary calculation unit (e.g. a grid cell or polygon).
- Crop irrigation water requirement is uniform in any point within this elementary calculation unit.
- Within a basic data unit, same type of crop at different lots apply same irrigation scheme, (same method distribution), therefore has same equivalent efficiency.

Based on above assumptions, it is reasonable to define an equivalent field application efficiency (EE) for calculation. Estimate of EE depends on the crop type and irrigation systems distribution at local point. So equivalent field application efficiency (EE) would be expected to vary from crop to crop and from zone to zone.

At any calculation unit, e.g. grid cell or polygon, field water use:

$$FU = \sum_{i=1}^{m} \left(\frac{IRR * A * PM_i}{EM_i} \right) \tag{14}$$

where

A area of the cell

IRR crop water requirement at this cell

PM_i area percentage of the crop irrigated by method (i)

EM_i field application efficiency of irrigation method (i)

Both IRR and A are constants for each calculation unit, so we have

$$FU = (IRR * A)\sum_{i=1}^{m}\left(\frac{PM_i}{EM_i}\right) \tag{15}$$

According to the definition of EE, the field water use can also be expressed as:

$$FU = \frac{IRR * A}{EE}$$ here, EE is equivalent field application efficiency.

Then, a value of equivalent field application efficiency could be obtained by:

$$\frac{1}{EE} = \sum_{i=1}^{m}\left(\frac{PM_i}{EM_i}\right) \quad \text{or} \quad EE = 1 \Big/ \sum_{i=1}^{m}\left(\frac{PM_i}{EM_i}\right) \tag{16}$$

Above method for EE estimation can be used for any basic data unit. Then, the estimate of field application efficiency for ***each crop*** in one ***data unit*** has a general form as

$$\begin{bmatrix} P_{1,1} & P_{1,2} & \cdots & \cdots & P_{1,m} \\ P_{2,1} & P_{2,2} & & & \vdots \\ \vdots & & \ddots & & \vdots \\ \vdots & & & \ddots & \\ P_{n,1} & \cdots & \cdots & & P_{n,m} \end{bmatrix} \times \begin{bmatrix} 1/EM_1 \\ 1/EM_2 \\ \vdots \\ \vdots \\ 1/EM_m \end{bmatrix} = \begin{bmatrix} 1/EE_1 \\ 1/EE_2 \\ \vdots \\ \vdots \\ 1/EE_n \end{bmatrix} \tag{17}$$

where

$P_{i,j}$ area percentage of the crop (i) irrigated by method (j)

EM_i field application efficiency of method (i)

EE_i equivalent field application efficiency of crop (i).

i: crop index i =1 to n
j irrigation method index j =1 to m

1.6 Conclusions

By implementing above methodology, the spatial patterns of the potential irrigation water consumptions can be estimated with acceptable accuracy. The strong uncertainty in shortage faction due to unpredictable human interfere makes it difficult to estimate the actual quantity of irrigation water. So the final production of this software package is the potentially applied water quantity at the field.

Section 2. Guide to using the extension

2.1 Running requirements & Installation

2.1.1 System Requirements

This tool package requires

- ESRI ArcGIS 8.0 or later version installed with a valid license at least for ArcView and Spatial Analyst

2.1.2 Installation and Start

ArcET is NOT a standalone executable application, it is actually a toolbar extension to ESRI ArcMap. The installation package provided by us will install the dynamic link library (DLL) file and resource functions used for database access on the user's computer.

Upon completion of the installation, users need to take the following steps to make it ready to use.

- Start ArcGIS:ArcMap, select ***Customize*** under ***Tools*** from the main menu

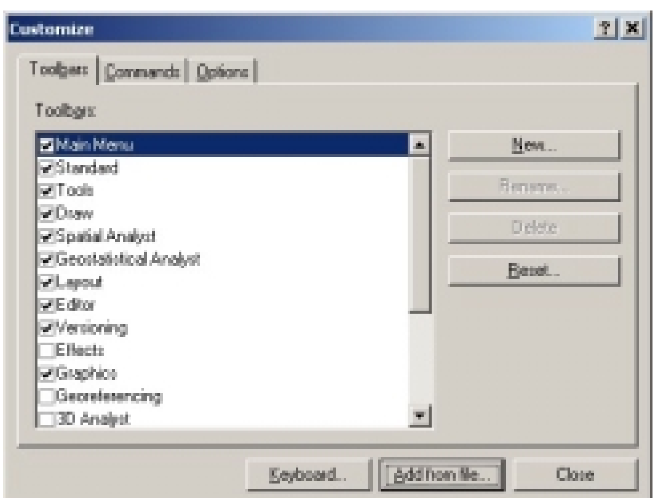


Figure 2-1. Interface for adding external DLLs into ArcMap

- Click the "***Add from file***" button as shown in above figure, and find the ***ArcET.dll*** in the specified folder, then click ***"Open"*** button.

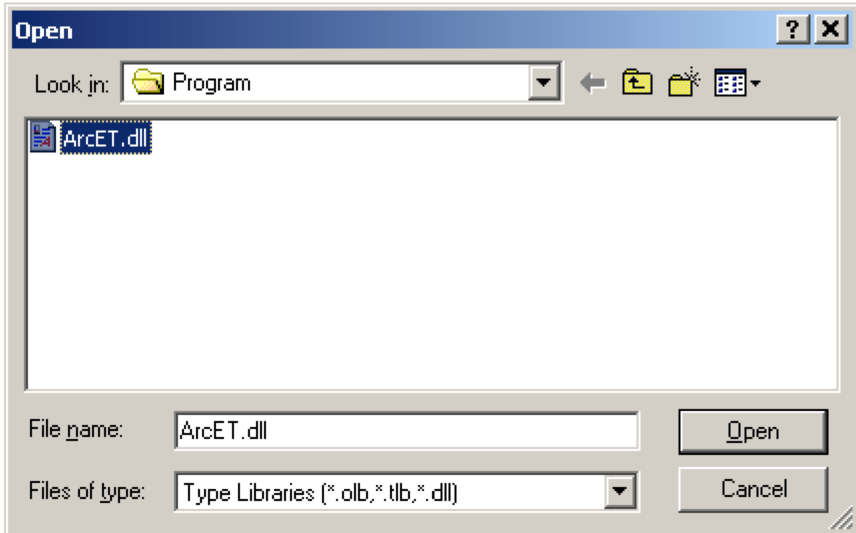


Figure 2-2. Dialog for finding external DLLs

- After the DLL file is loaded, an item "***ArcET: Water Use Estimation***" will appear in the Toolbars category (Figure 2-3), check it.

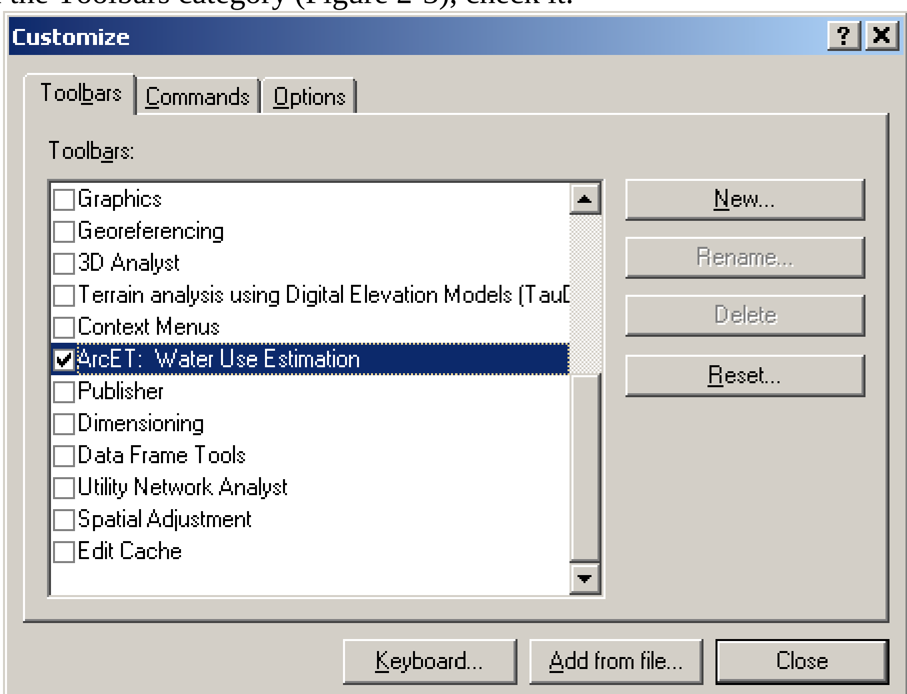


Figure 2-3. Interface for displaying extensions

- Then, a toolbar with one "***Irrigation Water Use Estimation***" menu will appear on the ArcMap interface frame as shown in Figure 2-4.

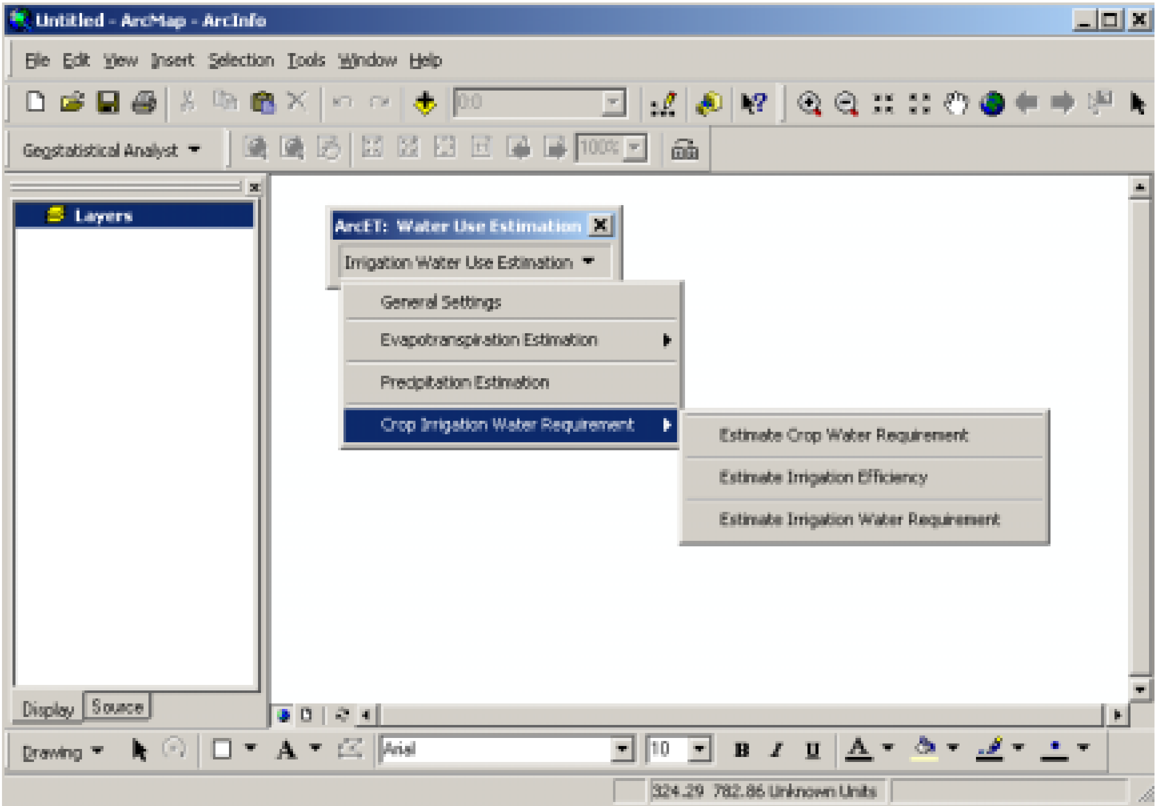


Figure 2-4. ArcMap Interface with ArcET toolbar

By now, ArcET is ready for use.

2.2 Data preparation

It is worth of noting here that all GIS datasets provided as inputs should be in the same coordinate system.

For calculation of potential crop ET only, users are required to input the following data:

(1) Weather Data Table: A data table providing time-series of meteorological variables
(2) Weather Stations: An ESRI shapefile that gives the location of climate stations
(3) Digital Elevation Model (DEM): DEM of the area of interest in ESRI GRID format
(4) Land Use/Cover Shapefile: An ESRI polygon shapefile for land use information
(5) Crop Coefficients Table: A DBF table with crop coefficients for each crop type
(6) Basic-Zone Shapefile: A polygon shapefile defining the areas where water use will be calculated. A key field that uniquely identifies water use polygons needs to be selected.

Additional inputs may be required as follows:

(7) PRISM monthly precipitation GRID (only required for some precipitation options and controlled on the "Precipitation Interpolation" tab)
(8) Information about the irrigation efficiency (only required for generating irrigation efficiency map)

2.3 Making Settings

Click the menu "Irrigation Water Use Estimation" in the "Water Use Estimation" toolbar, and select the "**General Settings**" menu item, this operation will load ***General Settings*** form, you will see tabs with different setting options on each of them (Figure 2-5).

- Basic Data
- Methods for Calculating Reference ET
- Precipitation Interpolation
- Output Options
- Performance Control

2.3.1 Locations of Input Datasets and Unit Information

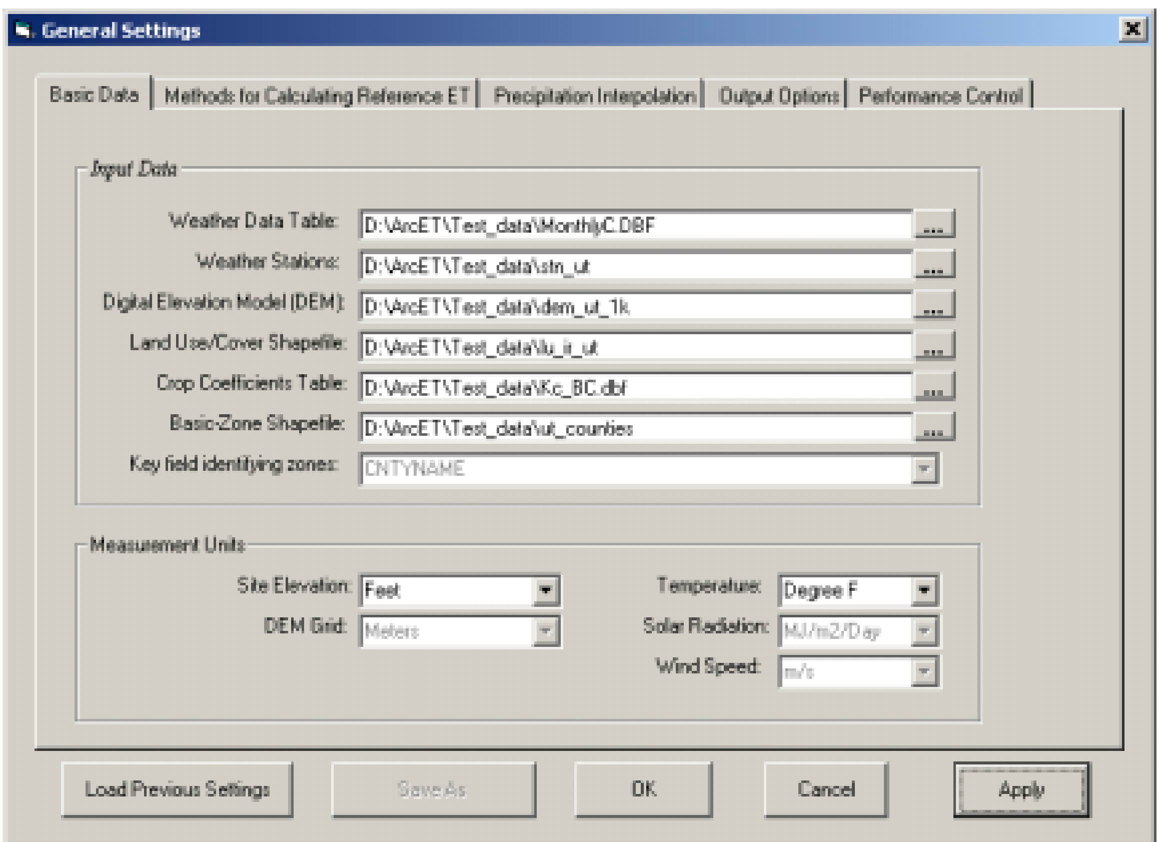


Figure 2-5. ArcET interface for input of basic datasets

Click the ***Basic Data*** tab, input or browse the dataset locations within the *Input Data* Category.

Another category on this tab is *Measurement Unit Information.* Select the appropriate units for each required item. The units required to be fixed for some inputs are displayed in gray as hints and can't be changed.

2.3.2 Select Reference ET Method and Corresponding Options

Before making a selection, the user can click the "**Get Info**" button in the "Met-Data Information" frame to see what kinds of meteorological data are available in the input database table based on field names (see appendix A). Available items will be checked.

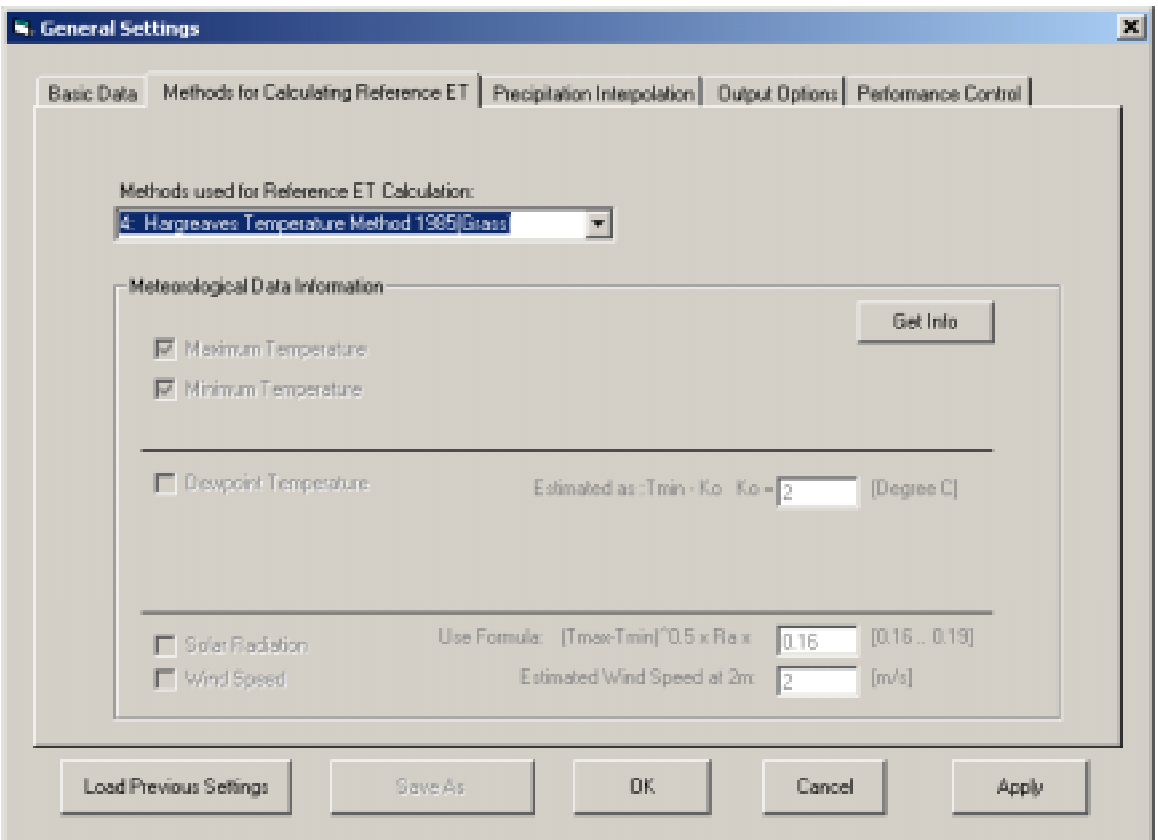


Figure 2-6. ArcET interface for selecting a reference ET method

Select one method from the combo box. Items required by the selected method will be enabled. In case the required meteorological data items are unchecked, the user must select corresponding options at the right of each item for those items as alternatives.

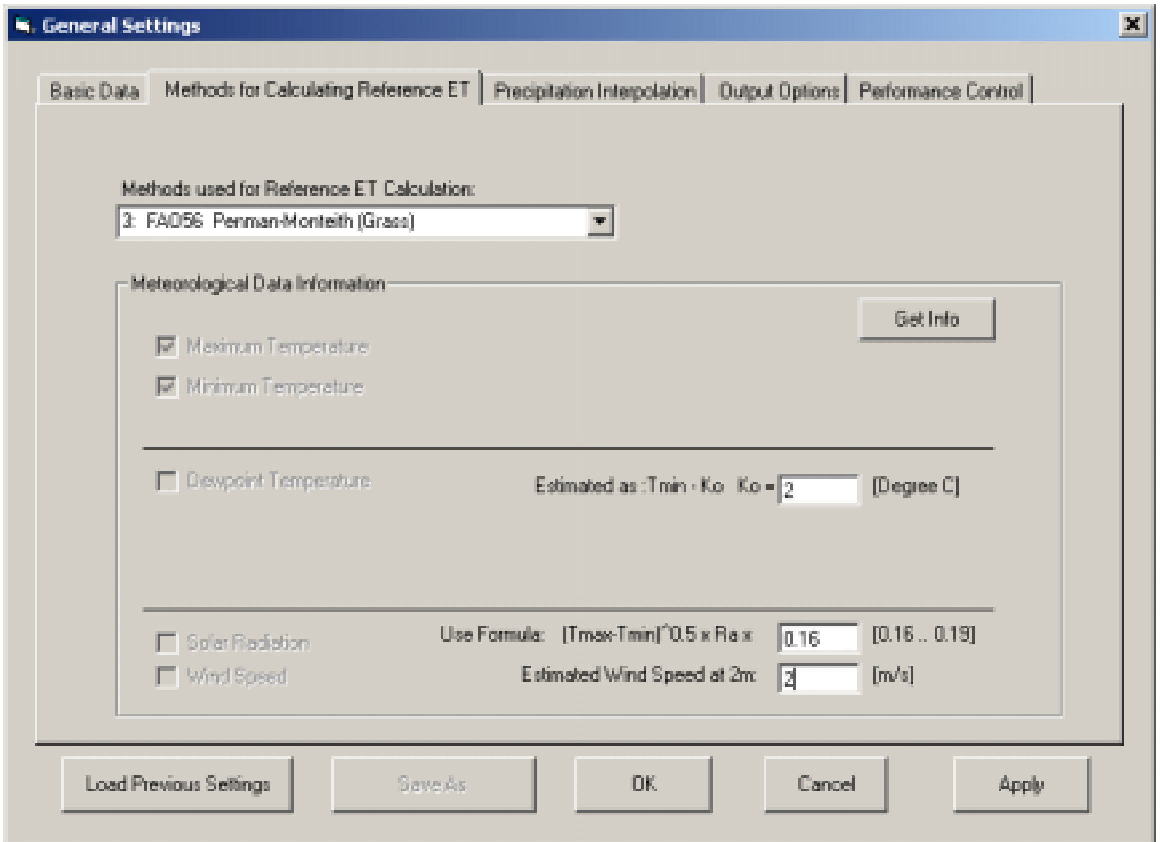


Figure 2-7. ArcET interface for making the settings for the selected reference ET method

2.3.3 Set interpolation scheme for precipitation

Two schemes (figure 2-8) are available for the precipitation interpolation as described in section 1.4. If the second option, "Use PRISM GRID as reference", is checked, users will be required to specify the location of one PRISM monthly GRID. For interpolation of multiple months, users should make sure that the last two letters of the specified GRID's name have to match the order of months.

2.3.4 Set the Output Options

Users need to do three things through this particular interface.

First, specify the workspace (a folder on your computer) for outputs. Then, tell ArcET the cell size you prefer and an ESRI shapefile that can specify extent of the domain modeled. In the present version, ArcET requires a polygon shapefile with a predefined projection. Finally, select beginning and end time of preferred period for modeling.

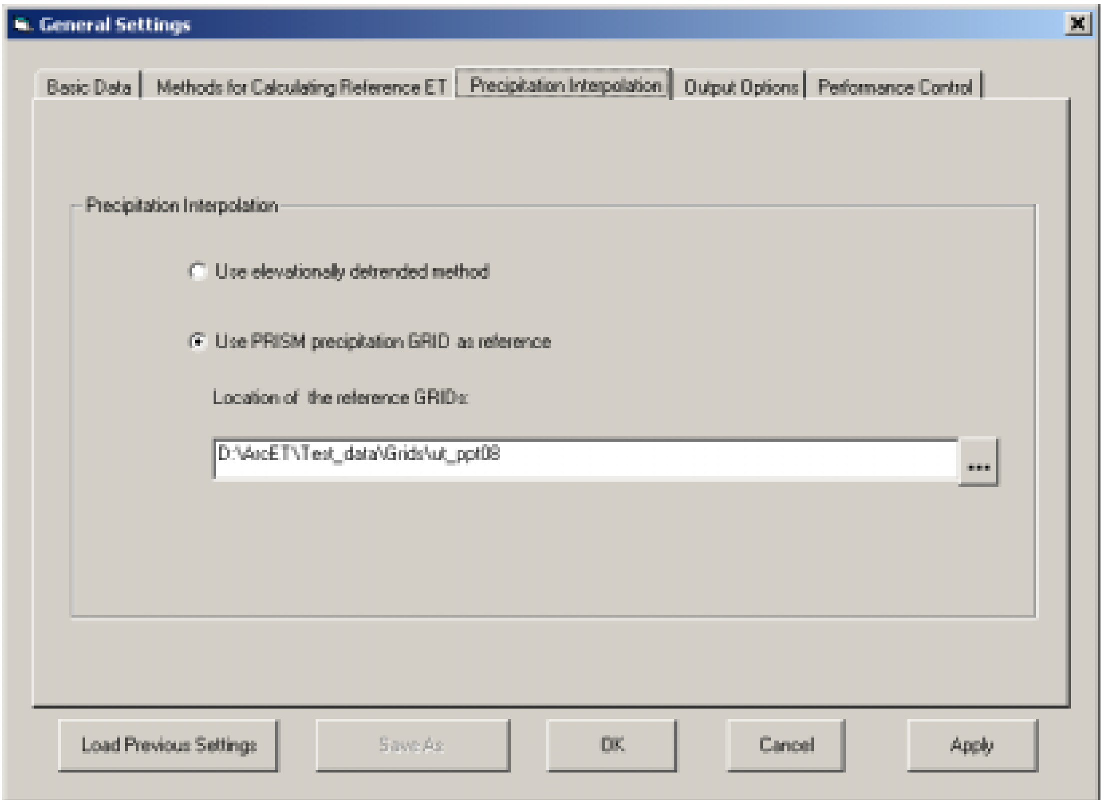


Figure 2-8. ArcET interface for setting precipitation interpolation

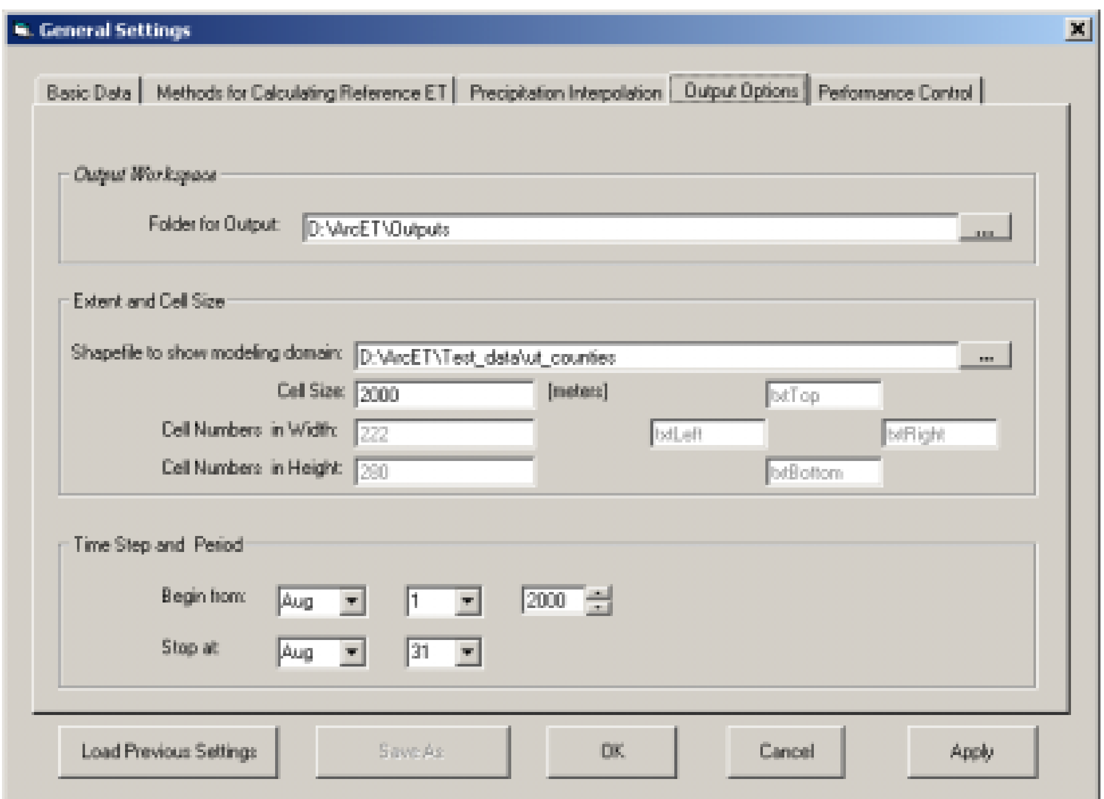


Figure 2-9. ArcET interface for setting output options

2.3.5 Saving and Loading of setting information

Once the all required information has been input through the "General Settings" interface, click "Apply" button at the bottom part of the interface, all specified information will be saved in default location. Then, users can click "Save As" button to save the above information in any place as one *.inf file. Next time for settings, users can just load specific settings directly from the *.inf file by clicking "Load Previous Settings".

2.4 Performing calculations

2.4.1 Evapotranspiration estimation

(1) To calculate reference ET

After finishing and saving all necessary settings, click the "Evapotranspiration Estimation" menu item from the "Irrigation Water Use Estimation" menu on the toolbar. From the sub-menu, click "Calculate Reference ET". Then the tool will start with the *Progress Monitor* window shown as figure 2-10. Once all scheduled tasks are done, the **Running Monitor** will show the end message as "Estimation of Reference ET is done …" and the total time for running in minutes. Now all reference ET maps can be saved in the output directory specified in the settings section.

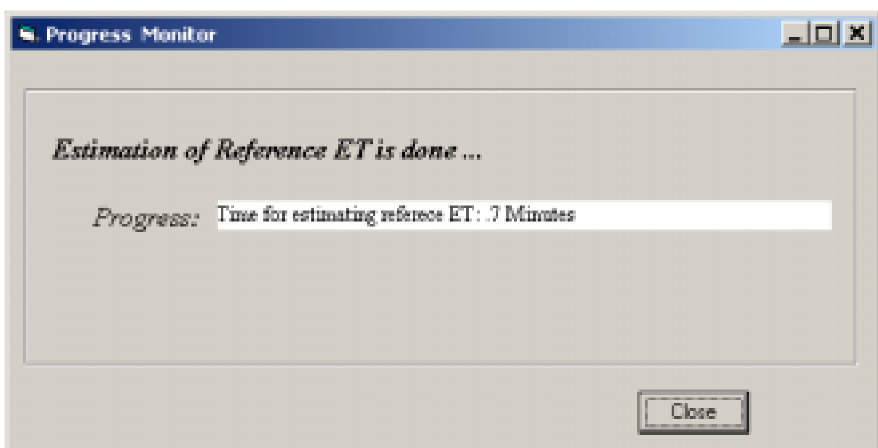


Figure 2-10. ArcET running interface

Note:

The calculation time depends on the spatial resolution (grid cell size), the selected reference ET equation, and computer speed.

(2) To generate crop coefficients maps

To get crop ET, crop coefficient distribution maps are necessary. To generate the crop coefficient maps, follow the following steps.

Click the "Evapotranspiration Estimation" menu item from the "Irrigation Water Use Estimation" menu on the toolbar. Then, select the menu item "Make Kc Maps". A window as Figure 2-11 will appear.

Within this interface are two frames with information for generating Kc maps. One is the land use / cover data source and the other is the available crop coefficients information in the specified external DBF table. The user can specify (input) this kind of information either in the "General Settings" section or at the time invoking the interface.

In the "Land Use/Cover" frame of the form, the user needs to specify the field name from which all available crop types are given by drop down the "Crop Type From" listbox, and then all available crop types will be listed in the "Crop Type" listbox. Depending on the field selected from the land use shapefile, the crop type may be listed in different formats (e.g. crop names or specific index codes).

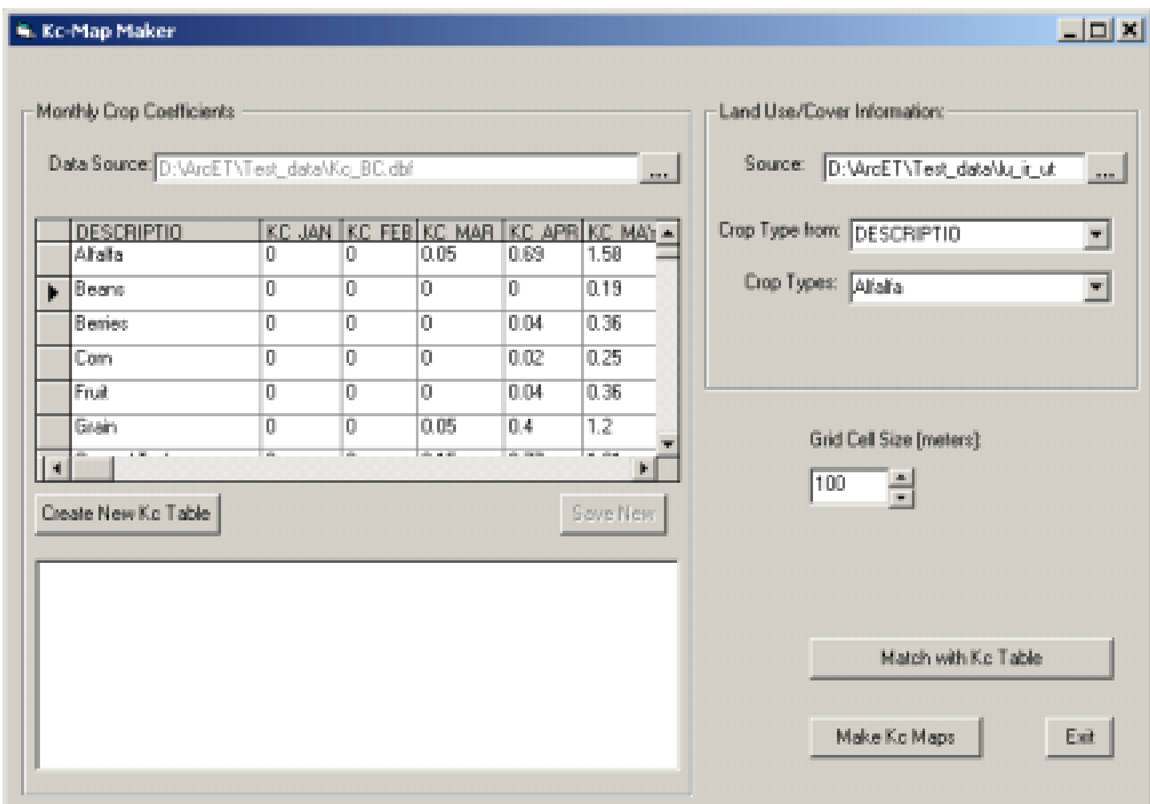


Figure 2-11. Initial interface for making Kc maps

The user can check the crop coefficients information in a graphic way by select any crop type in the displayed Kc table. Usually a Kc curve for the selected crop type will display in the bottom left area of the above interface (Figure 2-12).

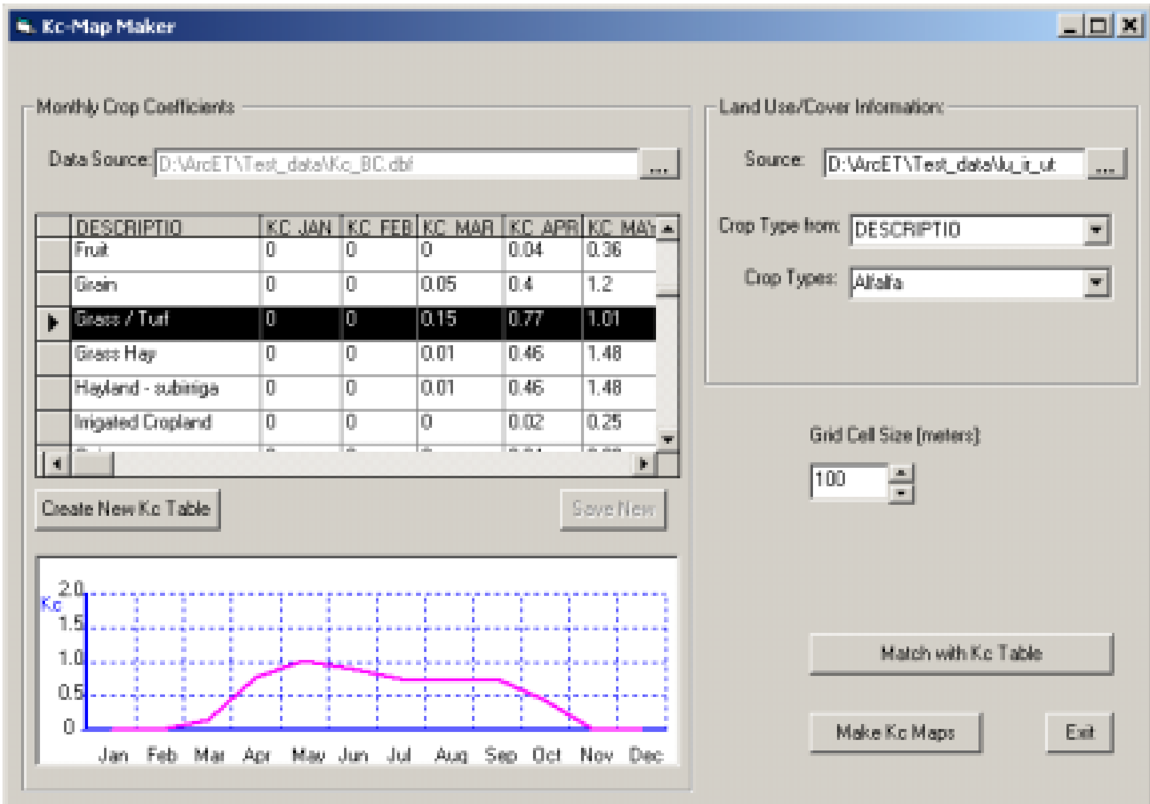


Figure 2-12. Interface for making Kc maps with drawn Kc curve

In case that the user DOES NOT have an existing external DBF table including Kc data, the user can create a new empty database table for use by clicking "Create New Kc Table" button. After doing this, the user can input Kc values for each crop type just within the displayed table. To make sure that Kc values for all crop types are input before making the map, it is better to click the "Match with Kc Table" button. By doing this step, the user can get the exact number of crop types and default values automatically into the database, and then the remaining work for the user is only to adjust (edit) those values in the table.

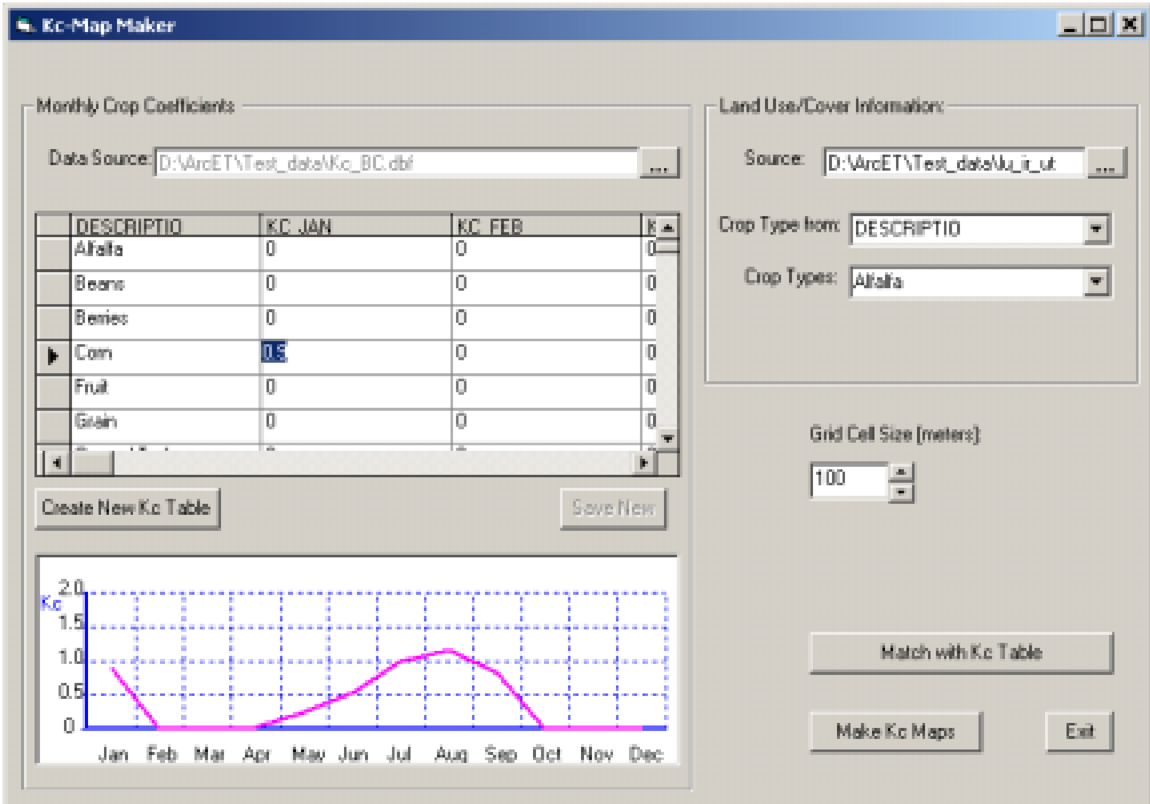


Figure 2-13. Interface for making Kc maps with editable Kc table

After crop coefficients are set, the user is close to the map generation. Now select an appropriate grid cell size (resolution of the map to be generated) and click the "Make Kc Maps" button.

Then, the generated Kc maps for corresponding period as for reference ET calculation will appear in the ArcMap.

(3) To estimate potential crop ET

Based on the conventional "Kc-Reference ET" approach, the crop ET maps can be obtained by overlaying the Kc Maps with corresponding reference layers at specific time interval. To do this, the only thing users need to do is to go click the "Evapotranspiration Estimation" menu item from the "Irrigation Water Use Estimation" menu on the toolbar. Then click "Estimate Crop ET" option. The monthly crop ET maps corresponding to specified time period will appear in ArcMap. Also, these maps will be saved in the output directory specified in the settings for future use.

2.4.2 Precipitation estimation

Go click the "Precipitation Estimation" menu item from the "Irrigation Water Use Estimation" menu on the toolbar. The tool will interpolate the point-measurements of precipitation for the whole area. Monthly precipitation maps corresponding to specified time period will appear in ArcMap as in Figure 2-14. Also, these maps will be saved in the output directory specified in the settings for future use.

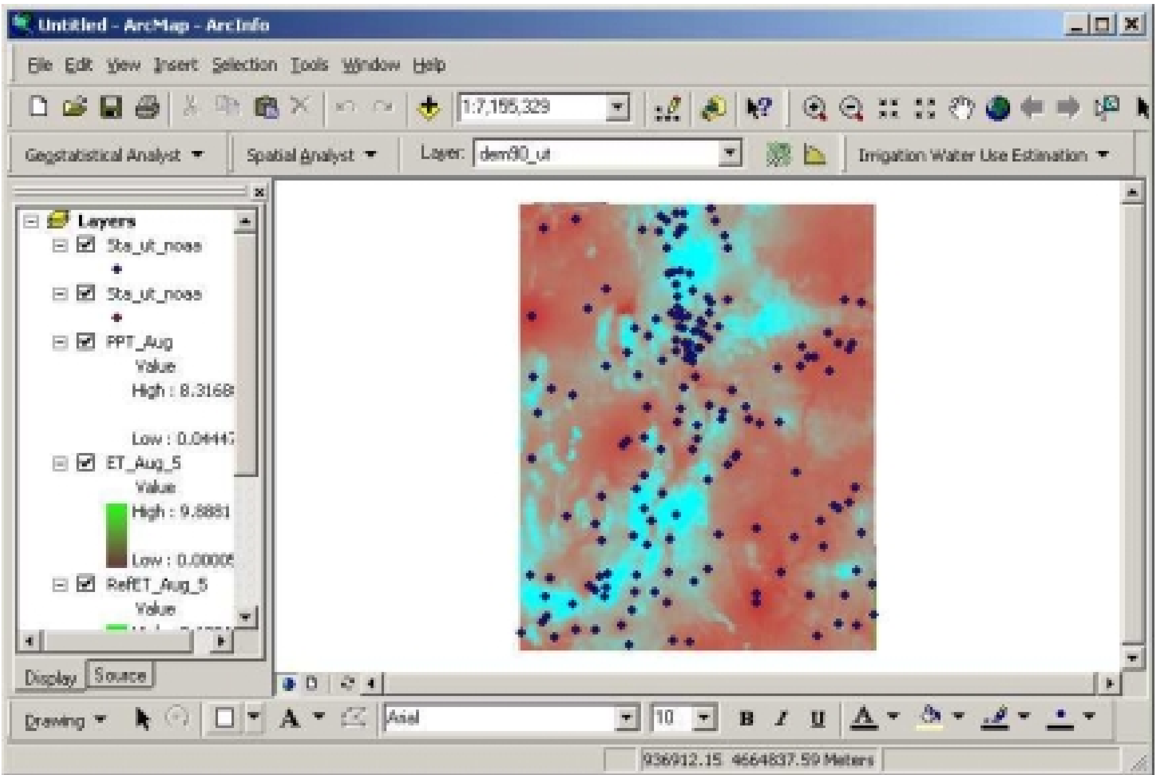


Figure 2-14. Precipitation maps resulted from interpolation

2.4.3 Estimation of crop irrigation water requirement

To estimate the potential irrigation water requirement for crop, users should do the following things according to the order.

1) Estimate crop water requirement
2) Estimate irrigation efficiency
3) Estimate irrigation water requirement

(1)Estimate crop water requirement

Go click the "Crop irrigation water requirement " menu item from the "Irrigation Water Use Estimation" menu on the toolbar. Then select "Estimate crop water requirement" option. Without any user interaction, monthly Crop irrigation water requirement maps corresponding to specified time period will appear in ArcMap as in Figure 2-15.

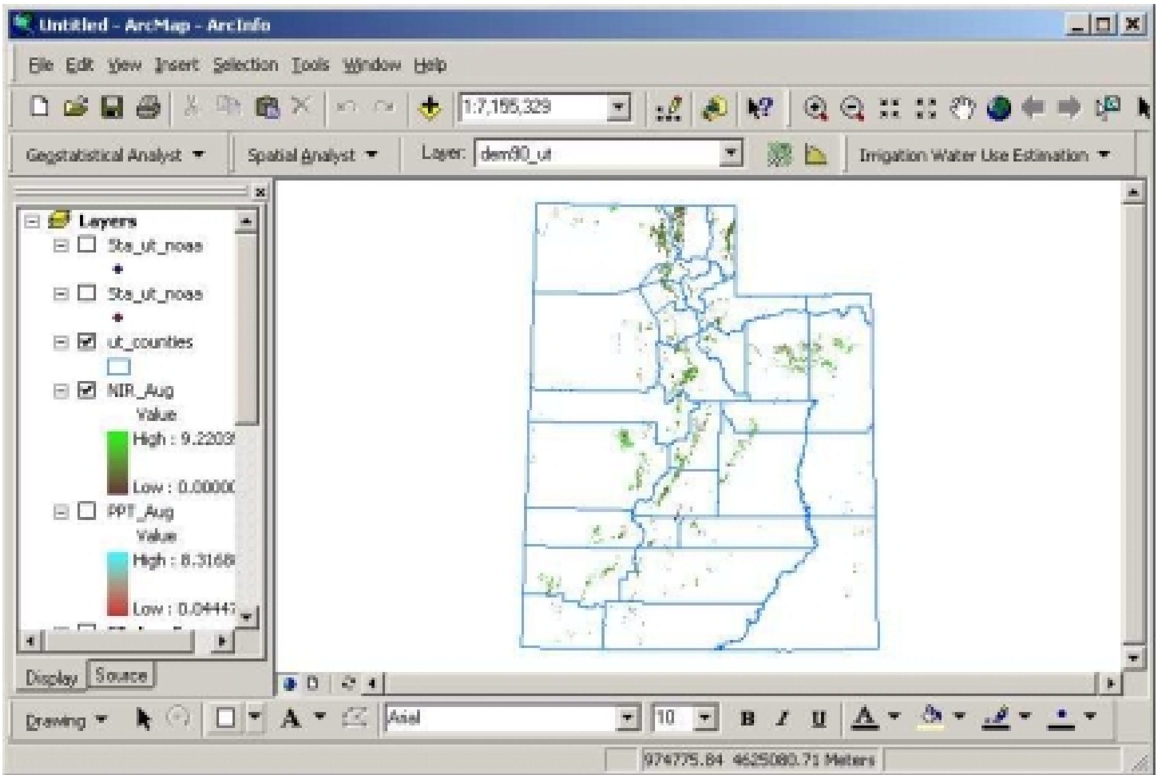


Figure 2-15. Calculated crop irrigation water requirement maps

(2) Estimate irrigation efficiency

This task is one-time work since the irrigation conditions at a particular region are relatively invariant. So users do not have to run this module every time they make water use estimation for different time periods. Click the "Crop irrigation water requirement " menu item from the "Irrigation Water Use Estimation" menu on the toolbar. Then select "Estimate Irrigation Efficiency" option. An interactive environment as figure 2-16 will appear.

At the very beginning, users are required to specify the Microsoft Access database file that includes a few tables corresponding to different irrigation information like default application efficiency of each irrigation type, the area percentage of each possible irrigation method applied to each crop. These tables have been predefined and provided in the ArcET distribution package. Users can double-click the textbox below the "Database providing irrigation information" label to browse the MDB file.

Once the right file is specified, click "Apply" button to connect to the database file. Then three frames displaying different information will appear as figure 2-17.

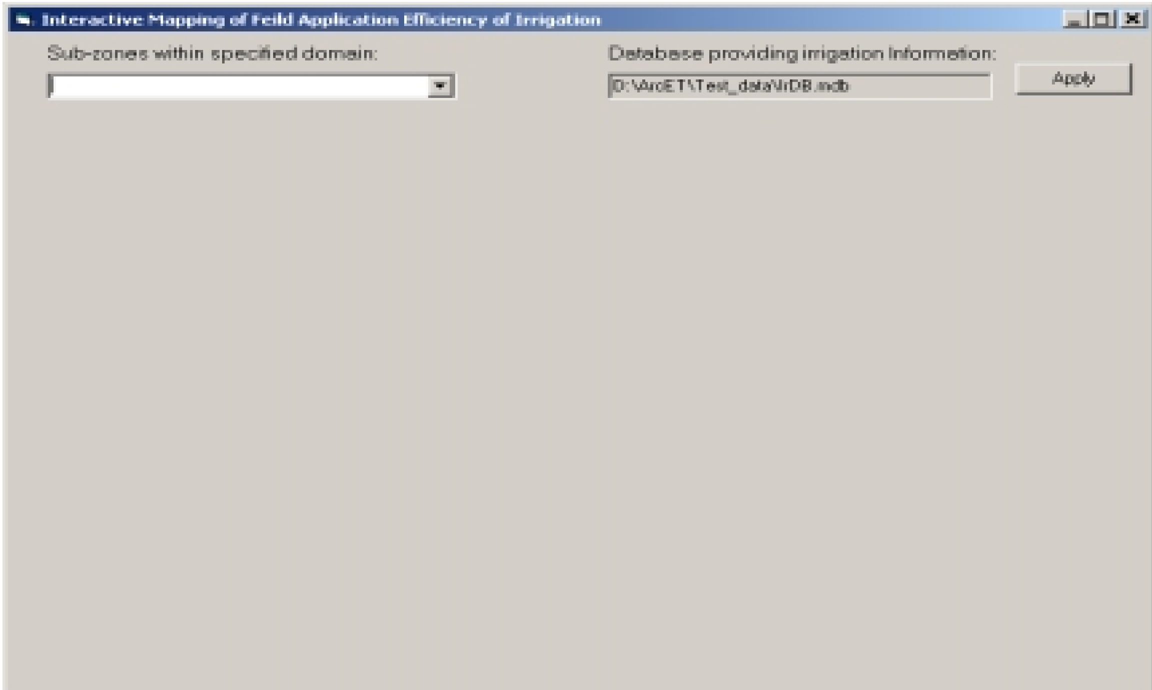


Figure 2-16. Interface for estimating region-specific irrigation efficiency

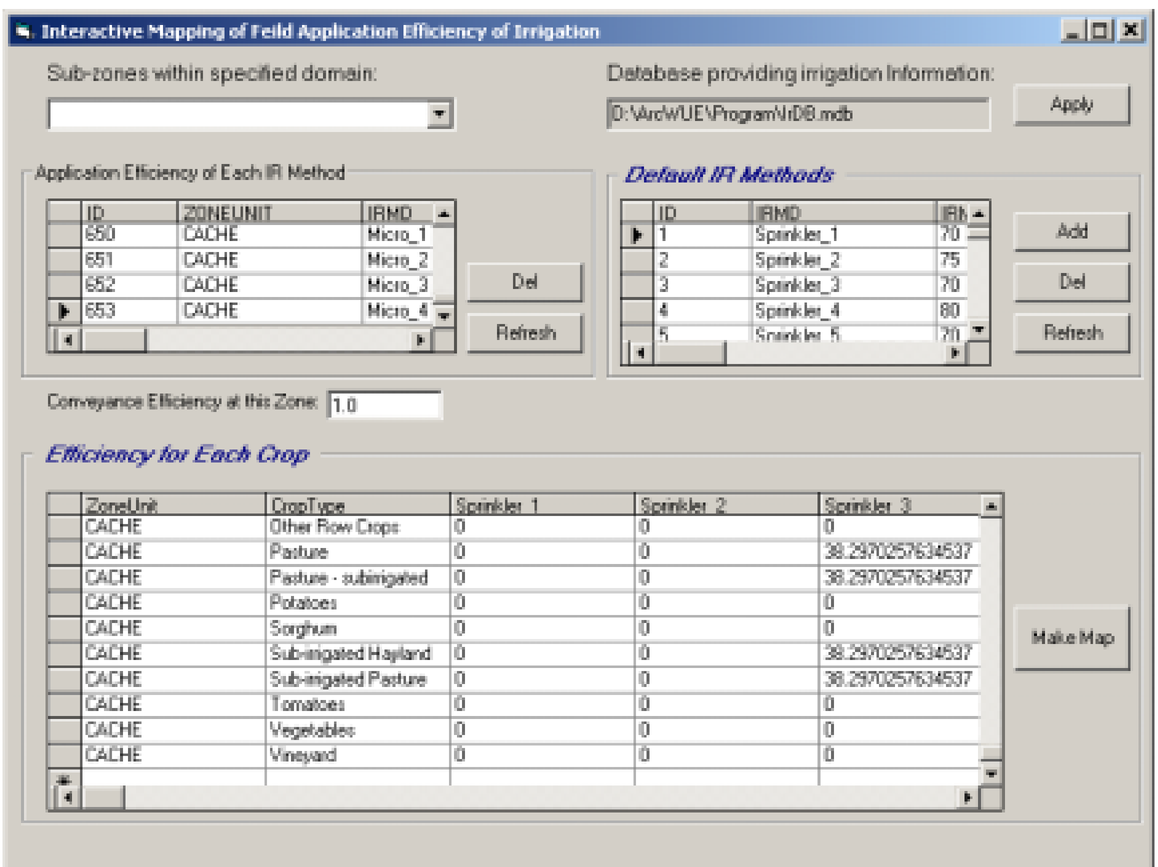


Figure 2-17. Interface for estimating region-specific irrigation efficiency (cont.)

At the very top of this interface, all sub-zones within the selected region are listed. The information in the three data tables will change automatically corresponding to each zone by default. In both top tables, the field name "IRMD" means irrigation method, the "IRMDEF" means the application efficiency corresponding to specific irrigation method. The top-right table gives default application efficiencies of possible irrigation methods within the region of interest. The top-left table gives the default application efficiencies of possible irrigation methods within the selected sub-zone based on the top-right table. Users have options to change the number of applicable irrigation methods and the application efficiency of any irrigation method within the selected sub-zone based on their experience. The bottom table shows the area percentage of different irrigation methods applied to a specific crop type at the selected sub-zone. Each crop is considered by default to be irrigated by all irrigation methods with equivalent area percentage unless users provide the practical estimation on the area percentage.

Above procedure is applied to all sub-zones by selecting the sub-zone one by one. This is to give users option to make change to any possible sub-zone.

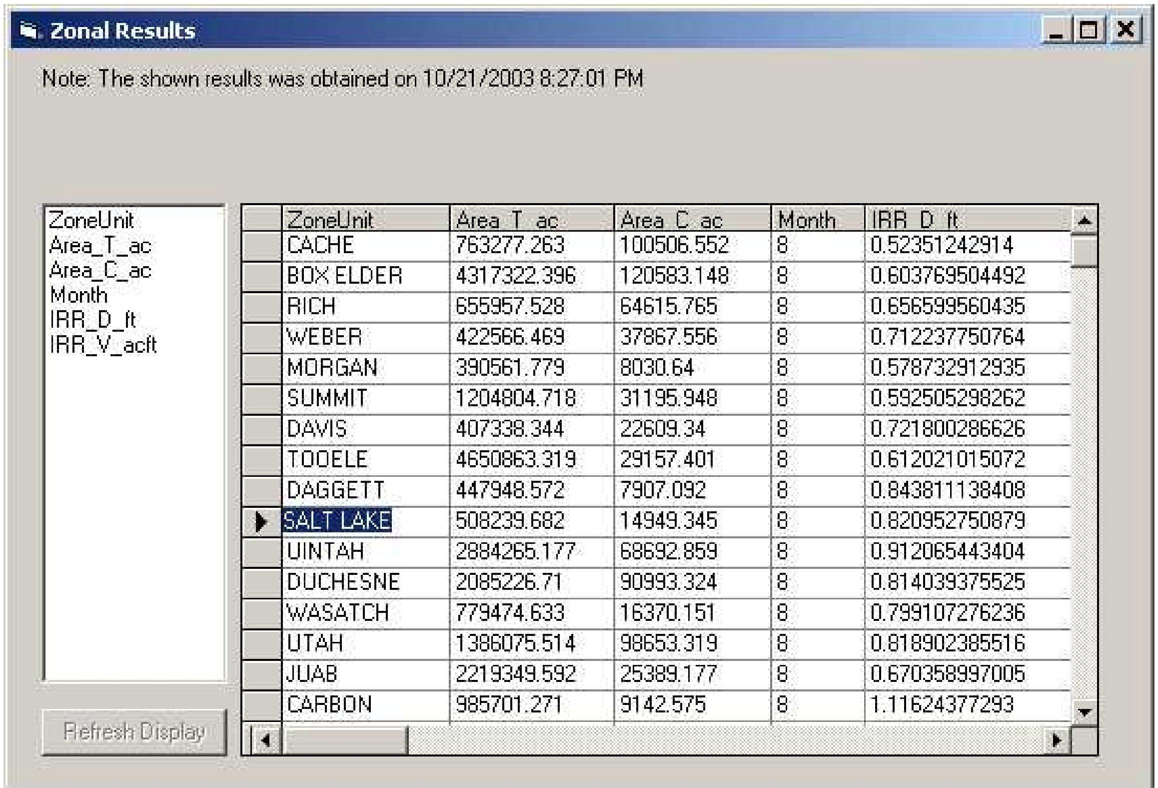
Once all sub-zones are selected (no sub-zones is left in the listbox), click "Make Map" button and a map to show distributed irrigation efficiency for the entire region will be generated and saved in the output folder.

(3) Estimate irrigation water requirement

Go click the "Crop Irrigation Water Requirement " menu item from the "Irrigation Water Use Estimation" menu on the toolbar. Then select "Estimate Irrigation Water Requirement" option. This step does NOT need any user interaction. After automatic calculations, monthly maps of crop irrigation water requirement corresponding to the specified time period will be added to ArcMap. As another format to provide the irrigation water use information, a table to show the estimation result at sub-zone level is generated as figure 2-18.

In this table users can obtained the following information.

ZoneUnit:	the sub-zone within the region of interest
Month:	month number specified previously
Area_T_ac:	the total area of the particular sub-zone in [acre.feet]
Area_C_ac:	the crop area of the particular sub-zone in [acre.feet]
IRR_D_ft:	the irrigation water requirement (depth in [feet]) at the sub-zone
IRR_V_acft:	the irrigation water requirement (volume in [ac.ft]) at the sub-zone



ZoneUnit	Area_T_ac	Area_C_ac	Month	IRR_D_ft
CACHE	763277.263	100506.552	8	0.52351242914
BOX ELDER	4317322.396	120583.148	8	0.603769504492
RICH	655957.528	64615.765	8	0.656599560435
WEBER	422566.469	37867.556	8	0.712237750764
MORGAN	390561.779	8030.64	8	0.578732912935
SUMMIT	1204804.718	31195.948	8	0.592505298262
DAVIS	407338.344	22609.34	8	0.721800286626
TOOELE	4650863.319	29157.401	8	0.612021015072
DAGGETT	447948.572	7907.092	8	0.843811138408
SALT LAKE	508239.682	14949.345	8	0.820952750879
UINTAH	2884265.177	68692.859	8	0.912065443404
DUCHESNE	2085226.71	90993.324	8	0.814039375525
WASATCH	779474.633	16370.151	8	0.799107276236
UTAH	1386075.514	98653.319	8	0.818902385516
JUAB	2219349.592	25389.177	8	0.670358997005
CARBON	985701.271	9142.575	8	1.11624377293

Figure 2-18. Tabulated irrigation water requirement at sub-zone level

The above table can be found as one DBF file at the output folder. All generated maps and tables are located in this folder for users' further processing.

Reference

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Brouwer, C., K. Prins and M. Heibloem, 1989. Irrigation Water Management: Irrigation Scheduling. FAO Training manual no. 4.

Jack Keller and Ron D. Bliesner, 1990. Sprinkler and trickle Irrigation. Thomson Publishing. pp. 45-60

Jensen, M. E., R. D. Burman, and R. G. Allen, editors. 1990. Evapotranspiration and Irrigation Water Requirements. American Society of Civil Engineers, New York.

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Price, J. C. 1990. Using Spatial Context in Satellite Data to Infer Region Scale Evapotranspiration. IEEE Transactions on Geoscience and Remote Sensing **25**:940-948.

Smajstrla, A.G. et al, 1991. Efficiencies of Florida Agricultural Irrigation Systems. (Online Document) Bulletin 247 of Agricultural Enginering, Institute of Food and Agricultural Science, University of Florida.***http://edis.ifas.ufl.edu/AE078***

Sucksdorff, Y., and C. Ottle. 1990. Application of satellite remote sensing to ertimate areal evapotranspiration over a watershed. Journal of Hydrology **121**:321-333.

Appendices

Appendix A Specification of inputs and outputs

1. Specification of inputs

Table A-1. Structure of weather data table

Field Name	Field Description
STN	Names of climate stations
VarName_Mon (e.g. **TM_Aug**)	Parameter(*VarName*) values at particular month(*Mon*)

VarName and *Mon* in above table are taken from the following two tables.

Table A-2. Representation of meteorological variable names

VarName	Description
TM	Maximum air temperature
TN	Minimum air temperature
TA	Average air temperature
TD	Dew-point temperature
P	Precipitation
SR	Incoming solar radiation
WS	Wind speed at 2m above ground

Table A-3. Representation of month name

Mon	Description
Jan	January
Feb	February
Mar	March
Apr	April
May	May
Jun	June
Jul	July
Aug	August
Sep	September
Oct	October
Nov	November
Dec	December

Table A-4. Units for meteorological inputs

Meteorological Variables	Unit
Temperature (TM, TN, TD,TA)	degree F or degree C
Precipitation (P)	inch
Solar radiation (SR)	$MJ.m^{-}2.Day^{-1}$
Wind speed (WS)	$m.s^{-1}$

Table A-5. Structure of the monthly crop coefficients table **(dBASE table)**

Field Name	Description
CropType	Crop types corresponding to those in the land use shapfile
Kc_Jan	Crop coefficient of particular crop type in January
Kc_Feb	Crop coefficient of particular crop type in February
Kc_Mar	Crop coefficient of particular crop type in March
Kc_Apr	Crop coefficient of particular crop type in April
Kc_May	Crop coefficient of particular crop type in May
Kc_Jun	Crop coefficient of particular crop type in June
Kc_Jul	Crop coefficient of particular crop type in July
Kc_Aug	Crop coefficient of particular crop type in August
Kc_Sep	Crop coefficient of particular crop type in September
Kc_Oct	Crop coefficient of particular crop type in October
Kc_Nov	Crop coefficient of particular crop type in November
Kc_Dec	Crop coefficient of particular crop type in December

2. Specification of outputs

Two kinds of outputs are provided by ArcET.

(1) Monthly maps

1) crop potential ET
2) precipitation
3) crop water requirement
4) irrigation water requirement

Units for these generated monthly maps are **[inch/month]**

(2) Tabulated estimation results are given in the following tables

1) StatCET.dbf for crop ET estimate
2) StatNIR.dbf for crop water requirement estimate
3) StatIRR.dbf for irrigation water requirement estimate

Table A-6. Structure of the summary tables

#	Field Name			Description
	StatCET	**StatNIR**	**StatIRR**	
1	ZoneUnit	ZoneUnit	ZoneUnit	Sub-divisions requiring water use estimation
2	Area_T_ac	Area_T_ac	Area_T_ac	Total area of this zone in [acre]
3	Area_C_ac	Area_C_ac	Area_C_ac	Total crop area of this zone in [acre]
4	Month	Month	Month	Number indicating the month
5	CET_D_ft	NIR_D_ft	IRR_D_ft	Estimated water depth in [feet]
6	CET_V_acft	NIR_V_acft	IRR_V_acft	Estimated water volume in [ac.ft]

Appendix B Structure & content of irrigation database

As described in section 2.4.3, one Microsoft Access database file is required for generating irrigation efficiency map. Within this database file, four tables have been predefined.

(1) IRMDDEF table

It gives default application efficiency of a particular irrigation method.

Table B-1. Structure of IRMDDEF table

Field Name	Field Description
ID	order number
IRMD	default names for possible methods
IRMDEF	application efficiency of each method in percentage
IRMDDES	detailed description of each IRMD name

Based on comparative analysis on a few literatures (Keller et al, 1990; Kenneth, 1988; Smajstrla et al, 1991; Brouwer, et al, 1989), default irrigation application efficiencies for the estimate of agricultural water use in the State of Utah will be adopted according the following table.

Table B-2. Default Irrigation Method Application Efficiency

ID	IRMD	IRMDEF	IRMDDES
1	Sprinkler_1	70	Sprinkler: Side Roll/Wheel Line
2	Sprinkler_2	75	Sprinkler: Solid Set
3	Sprinkler_3	70	Sprinkler: Hand Move
4	Sprinkler_4	80	Sprinkler: Center Pivot/Linear Move
5	Sprinkler_5	70	Sprinkler: Other
6	Gravity_1	50	Gravity: Flooding From Ditches
7	Gravity_2	60	Gravity: Open Ditch, Siphon Tube
8	Gravity_3	65	Gravity: Gated Solid Pipe Direct From Source
9	Gravity_4	65	Gravity: Lay-flat Pipe Direct From Source
10	Gravity_5	70	Gravity: Sub-irrigation (controlled drainage)
11	Gravity_6	75	Gravity: Level Basin
12	Micro_1	80	Micro: Surface Micro-Spray
13	Micro_2	85	Micro: Surface Drip/Trickle
14	Micro_3	85	Micro: Subsurface Drip/Trickle
15	Micro_4	80	Micro: Other

In above table, default application efficiency values for each possible method are provided. However, the users can adjust all these values through developed interface based on their own experiences for specific conditions of the interested region.

(2) IRMD table

It gives application efficiency of irrigation on a zone-by-zone basis

Table B-3. Structure of IRMD table

Field Name	Field Description
ID	order number
ZONEUNIT	sub-divisions requiring water use estimation
IRMD	default names for possible methods
IRMDEF	application efficiency of each method in percentage in the particular zone
IRMDDES	detailed description of each IRMD name

(3) IR_Dis_1 table

It gives percentage of the particular zone irrigated different irrigation methods.

Table B-4. Structure of IRMD table

Field Name	Field Description
ID	order number
ZONEUNIT	sub-divisions requiring water use estimation
Sprinkler_1	percentage of the particular zone irrigated by method '*Sprinkler _1*'
…	…

(4) IR_Dis_2 table

It gives percentage of the specific crop irrigated by particular method at the particular zone

Table B-5. Structure of IRMD table

Field Name	Field Description
ZONEUNIT	sub-divisions requiring water use estimation
CROPTYPE	crop type at the particular zone
Sprinkler_1	percentage of the specific crop irrigated by method '*Sprinkler _1*' at the particular zone
…	…

Appendix C Description of selected reference ET calculation methods

- ✓ FAO 56 Penman-Monteith (grass)
- ✓ Standardized ASCE Penman-Monteith equation(s) (short / tall grass)
- ✓ Hargreaves 1985
- ✓ SCS modified Blaney-Criddle equation
- ✓ Priestley-Taylor

1. FAO56 Penman-Monteith equation

Definition of Reference Crop

The definition of reference crop in FAO56 is different from other methods. It is not Grass or Alfalfa, but *"A hypothetical crop with an assumed height of 0.12^m, with a surface resistance of 70 s m^{-1} and an albedo of 0.23, closely resembling the evaporation from an extensive surface of green grass of uniform height, actively growing and adequately watered."*

Equation for reference evapotranspiration

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 [e_s - e_a]}{\Delta + \gamma(1 + 0.34u_2)}$$

where

ET_0	reference evapotranspiration [mm day^{-1}],
R_n	net radiation at the crop surface [MJ m^{-2} day^{-1}],
G	soil heat flux density [MJ m^{-2} day^{-1}],
T	air temperature at 2 ^{m} height [°C],
u_2	wind speed at 2 ^{m} height [m s^{-1}],
e_s	saturation vapor pressure [kPa],
e_a	actual vapor pressure [kPa],
e_s - e_a	saturation vapor pressure deficit [kPa],
Δ	slope vapor pressure curve [kPa °C^{-1}],
γ	psychrometric constant [kPa °C^{-1}].

Derivation of some parameters

<u>soil heat flux density, *G*</u>

To estimate the change in soil heat content for a given period, G, the following approaches can be used:

Approach from Handbook of Hydrology

$$G = c_s d_s \frac{(T_2 - T_1)}{\Delta t}$$

where

G	the average daily soil heat flux [$MJm^{-2}day^{-1}$],
T_2	temperature at the end of the period [^0C],
T_1	temperature at the beginning of the period [^0C],
Δt	length of periods [days],
c_s	soil heat capacity(2.1 MJ $m^{-3}\ ^oC^{-1}$) for average moist soil
d_s	estimated effective soil depth [m].

For daily temperature fluctuations (effective soil depth typically 0.18 m), the above formula becomes

$$G = 0.38(T_{day2} - T_{day1})\ MJm^{-2}day^{-1}$$

For monthly temperature fluctuations (effective soil depth typically 0.20 m), the above formula becomes

$$G = 0.14(T_{month2} - T_{month1})\ MJm^{-2}month^{-1}$$

Approach from ASCE: *Evapoatranspiration and Irrigation Wtaer Requirements*

$$G = 4.2\frac{(T_{i+1} - T_{i-1})}{\Delta t}$$

where

G	the average daily soil heat flux in $MJm^{-2}day^{-1}$,
T_i	the mean air temperature in °C for time period *i*,
Δt	the days between the midpoints of the two periods.

<u>Wind speed, u_2</u>

To adjust wind speed data obtained from instruments placed at elevations other than the standard height of 2^m, a logarithmic wind speed profile may be used for measurements above a short-grassed surface:

$$u_2 = u_z \frac{4.87}{\ln(67.8z - 5.42)}$$

where

u_2 wind speed at 2 m above ground surface [m s^{-1}],
u_z measured wind speed at z m above ground surface [m s^{-1}],
z height of measurement above ground surface [m].

Saturation vapor pressure, e_s, and Actual vapor pressure, e_a

Saturation vapor pressure e_s can be calculated by following formula

$$e_s(T) = 0.6108 \exp\left(\frac{17.27T}{T + 237.3}\right)$$

where

$e_s(T)$ saturation vapor pressure at the air temperature T [kPa],
T air temperature [°C].

Actual vapor pressure (e_a) can be derived from dew-point temperature

As the dew-point temperature is the temperature to which the air needs to be cooled to make the air saturated, the actual vapor pressure (e_a) is the saturation vapor pressure at the dew-point temperature (T_{dew}) [°C],

$$e_a = e_s(T_{dew}) = 0.6108 \exp\left(\frac{17.27T_{dew}}{T_{dew} + 237.3}\right)$$

slope vapor pressure curve, Δ

$$\Delta = \frac{4098\left[0.6108 \exp\left(\frac{17.27T}{T + 237.3}\right)\right]}{(T + 237.3)^2}$$

where

Δ slope of saturation vapor pressure curve at air temperature T [kPa $°C^{-1}$],

T air temperature [°C],

Psychrometric constant

$$\gamma = \frac{c_p P}{\varepsilon\lambda} = 0.665 \times 10^{-3} P$$

where

γ	psychrometric constant [kPa °C^{-1}],
P	atmospheric pressure [kPa],
λ	latent heat of vaporization, 2.45 [MJ kg^{-1}],
c_p	specific heat at constant pressure, 1.013 10^{-3} [MJ kg^{-1} °C^{-1}],
ε	ratio molecular weight of water vapor/dry air = 0.622.

2. ASCE Standardized Reference Evapotranspiration Equation(s)

The standardized ASCE Penman-Monteith reference evapotranspiration equation for daily calculation time steps has the form

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

where

ET_{ref}	Short / tall reference crop evapotranspiration [mm day^{-1}]
R_n	net radiation at the crop surface [MJ m^{-2} day^{-1}]
G	soil heat flux density at the soil surface [MJ m^{-2} day^{-1}]
T	mean daily air temperature at 1.5 to 2.5-m height [°C],
u_2	mean daily wind speed at 2-m height [m s -1],
e_s	mean saturation vapor pressure at 1.5 to 2.5-m height [kPa]; for daily computation, value is the average of e_s at maximum and minimum air temperature,
e_a	mean actual vapor pressure at 1.5 to 2.5-m height [kPa],
Δ	slope of the vapor pressure-temperature curve [kPa °C $^{-1}$],
γ	psychrometric constant [kPa °C $^{-1}$],
C_n	numerator constant for reference type and calculation time step
C_d	denominator constant for reference type and calculation time step.

Definition of Reference Crop

Short grass: A hypothetical crop with an assumed height of 0.12^{m}, with a surface resistance of 70 s m^{-1} and an albedo of 0.23, closely resembling the evaporation from an extensive surface of green grass of uniform height, actively growing and adequately watered.

Tall grass: A hypothetical crop with an assumed height of 0.50^m, with a surface resistance of 45 s m^{-1} and an albedo of 0.23, closely resembling the evaporation from an extensive surface of green grass of uniform height, actively growing and adequately watered.

Value of C_n and C_d for different reference crop types are recommended as the follows:

Calculation Time Step	Short Grass		Tall Grass		Units for ETo/ETr	Units for Rn, G
	C_n	C_d	C_n	C_d		
Daily or monthly	900	0.34	1600	0.38	mm d^{-1}	MJm-2d^{-1}

3. Hargreaves 1985 Equation

$$\lambda E_{t0} = 0.0023 R_A TD^{1/2}(T + 17.8)$$

where

E_{to} potential evapotranspiration [mm day^{-1}],

λ latent heat of vaporization of water [MJ kg^{-1}],

T average temperature [^0C],

R_A extraterrestrial radiation in equivalent evaporation units[mmday^{-1}],

TD the difference between mean monthly maximum and mean monthly minimum temperatures [^0C].

Derivation of some parameters

Monthly or daily values of R_A can be calculated using following equations:

$$R_A = (24(60)/\pi) G_{sc} d_r [(\omega_s)\sin(\phi)\sin(\delta) + \cos(\phi)\cos(\delta)\sin(\omega_s)]$$

where

ω_s is sunset hour angle in radians

$$\omega_s = \arccos(-\tan(\phi)\tan(\delta))$$

The argument in above equation must be limited to less than or equal to 2.0 in extreme latitudes (>55 ^{o}) during winter months. If the argument is less than –1.0 in extreme latitudes (>55 ^{o}) during summer months, then the argument should be set equal to $[\tan(\phi)\tan(\delta) - 2.0]$.

ϕ is latitude of the station in radians(negative for southern latitudes)

δ is the declination in radians

$$\delta = 0.4093\sin\left(2\pi\left(284 + J\right)/365\right)$$

J is the day of the year (January 1st = 1)

d_r is the relative distance of the earth from sun,

$$d_r = 1 + 0.033\cos\left(2\pi J / 365\right)$$

G_{sc} is the solar constant , **0.0820** $MJm^{-2}min^{-1}$ (**1.959**$calcm^{-2}min^{-1}$)

4. SCS Modified Blaney-Criddle

Equation for monthly crop consumptive use

$$u = k_c k_t \left(tp/100\right)$$

where

u	monthly crop consumptive use in inch month^{-1}
t	mean monthly air temperature in ^0F
p	mean monthly percentage of annual daytime hours
k_c	mean monthly crop growth stage coefficient
k_t	mean monthly climatic(temperature) coefficient ^0F

Derivation of some parameters

Mean monthly climatic(temperature) coefficient

$$k_t = 0.0173t - 0.314$$

where

t is mean monthly air temperature in ^0F

Mean monthly percentage of annual daytime hours, *p*

For any day of the year,J, the percentage of daily daylight hours is

$$p = \frac{h_J}{\sum_{i=1}^{365} h_i}$$

where

- p the percentage of annual daylight hours for any day of the year
- h_J the number of daylight hours on day J
- h_i the number of daylight hours on day i

$$h_i = \omega_s \left(\frac{24}{\pi} \right)$$

ω_s is sunset hour angle in radians

$$\omega_s = \arccos(-\tan(\phi)\tan(\delta))$$

in above formula:

ϕ is latitude of the station in radians(negative for southern latitudes)
δ is the declination in radians

$$\delta = 0.4093 \sin(2\pi(284 + J)/365)$$

J is the day of the year (January 1st = 1)

The monthly percentage of annual daytime hours as used in the SCS Blaney-Criddle method can be calculated by multiplying the value of p for the middle of each month by the number of days in the month. A more accurate approximation would entail integration of above equation over the entire month.

5. Priestley-Taylor

$$\lambda E_p = \partial \frac{\Delta}{\Delta + \gamma} (R_n - G)$$

Where

- λ latent heat of vaporization of water [MJ kg^{-1}],
- E_p potential evapotranspiration [mm day^{-1}],
- Δ slope vapor pressure curve [kPa $°C^{-1}$],
- γ psychrometric constant [kPa $°C^{-1}$].

R_n net radiation at the crop surface [MJ m^{-2} day^{-1}],
G soil heat flux density [MJ m^{-2} day^{-1}],
∂ adjustment coefficient ($\partial = 1.26$).

Derivation of some parameters

Parameters G, Δ, γ used in this method can be calculated as FAO56 Penman-Monteith .

Latent heat of vaporization of water

$$\lambda = 2.501 - 0.002361 T_s$$

where

T_s the surface temperature of the water in degrees Celsius(^0C)