

Development of an ArcMap Toolbar for Regional Evapotranspiration Modeling¹

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Abstract

Evapotranspiration (ET) is important to hydrologists as well as regional planners. Methods for the calculation of ET require land use as well as weather and solar energy inputs. In this paper we present an ArcMap toolbar for the calculation of spatially distributed ET from ground based weather data. The toolbar provides functionality to interpolate weather data over the region of interest and calculate reference ET from a selection of standard reference methods. This is then combined with the crop coefficient based on land cover to estimate potential ET for use in hydrologic modeling and water use planning.

1 Introduction

Evapotranspiration (ET) is an elementary component of the regional water and energy balance. Its spatial and temporal distribution is of importance to water resources managers, planners, and researchers. ET 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 Otle 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 not 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.

ArcObjects (Zeiler 2001), part of the ESRI ArcGIS package, provides a way to integrate GIS with external models. It provides an object system through which the functionality in the end-

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user-application of ArcGIS can be accessed by programming. With ArcObjects it is technically feasible to develop an integrated environment for the specific task of regional ET modeling. This paper presents an approach for modeling regional and long-term ET from widely available ground meteorological data and crop patterns implemented as an ArcMap toolbar (ArcET) using the ESRI ArcGIS ArcObjects modeling environment.

2 Development of ArcET

2.1 Conceptual Framework of the GIS-based approach for regional ET modeling

The conceptual Framework of the GIS-based approach for regional ET modeling is given in figure 1. 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.

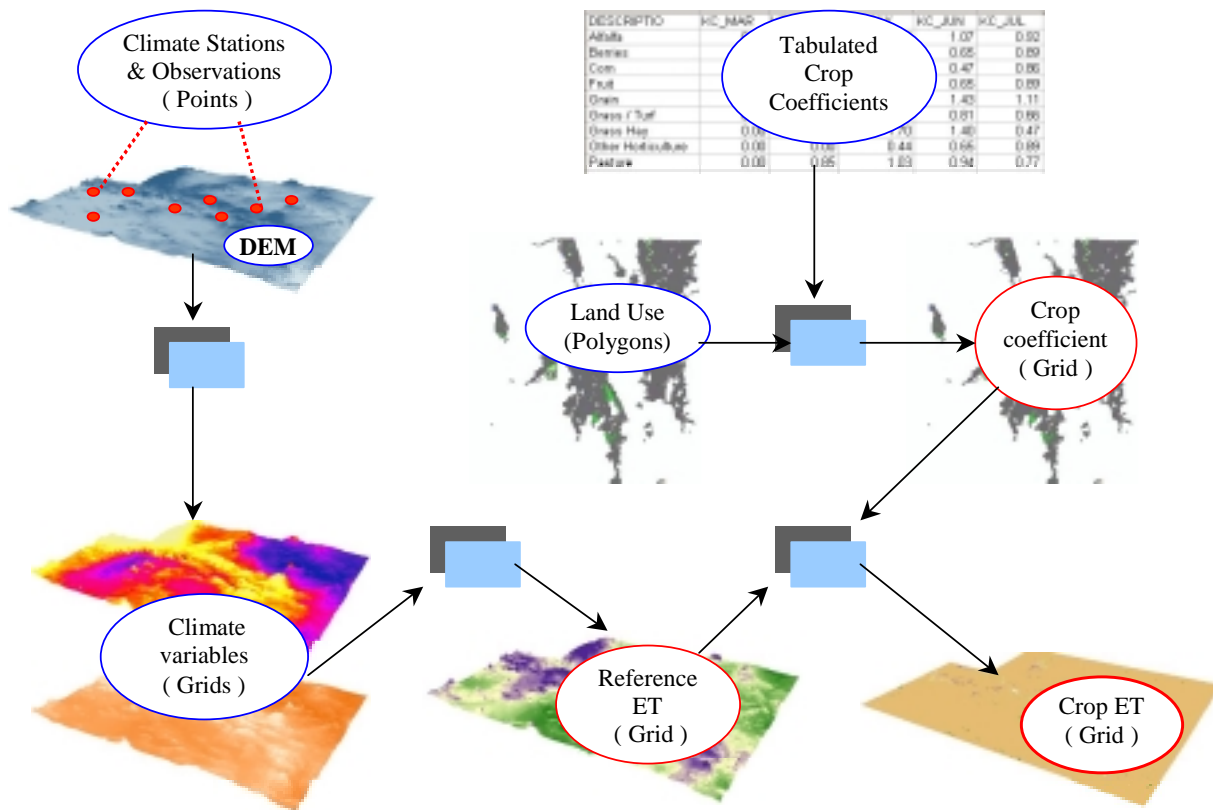


Figure 1. Illustration of the GIS-based approach for regional ET modeling (The boxes depict the ArcET function modules)

2.2 Development of the toolbar to implement the above approach

2.2.1 Functionality design

ArcET consists of the following four modules shown in figure 2 with specific functionality 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

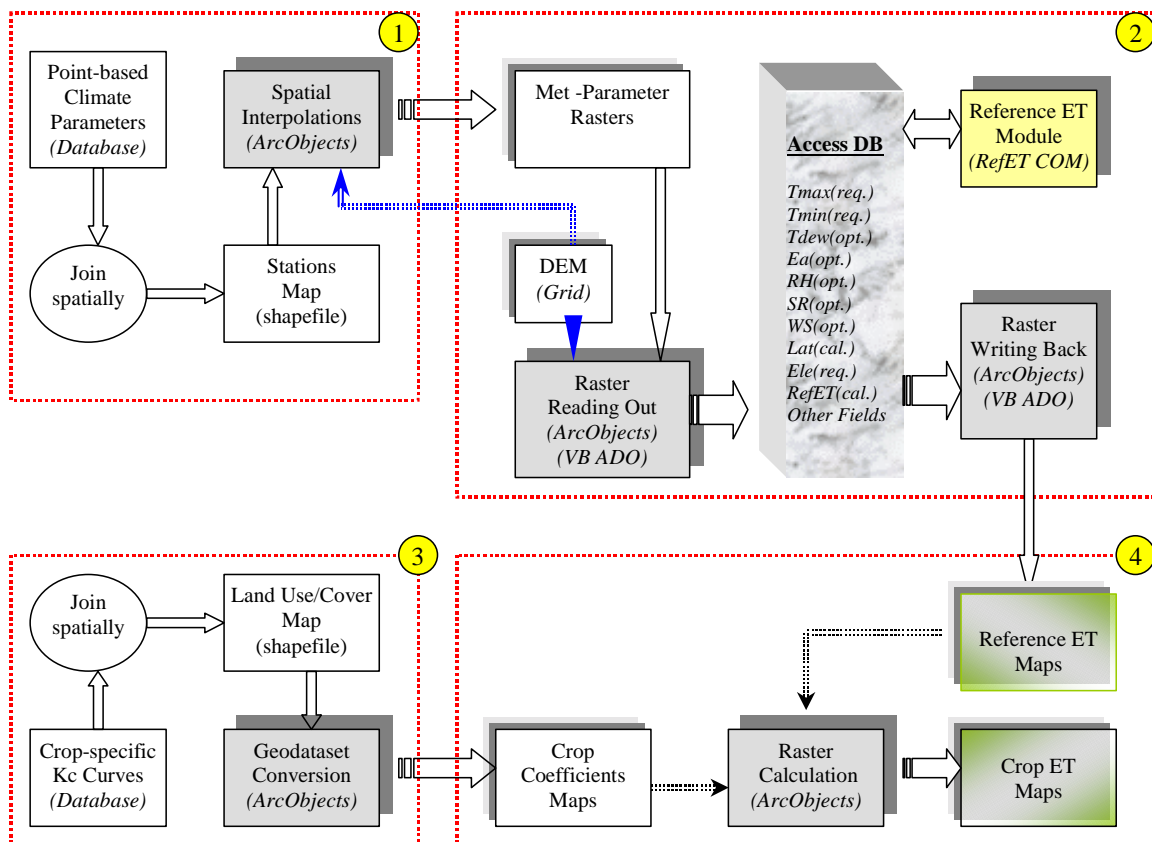


Figure 2. Overall design of ArcET

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 chosen needs to recognize the physical attributes of the quantity being interpolated and the relationship to topography. ArcET implements interpolation schemes for temperature, humidity, solar radiation and wind.

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 *Elevationally Detrended Kriging* 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

$$T(u) = T_H(u) + T_V(u) \quad (1)$$

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

$$T_V(u) = f(Z(u)) \quad (2)$$

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

Taking a linear regression relationship, $f(Z(u)) = aZ(u) + b$ (3)

then, $T_V(u) = aZ(u) + b$ (4)

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

$$T_H(u) = \sum_{i=1}^n w_i T_H(g_i) \quad (5)$$

where $T_H(g_i) = T(g_i) - [aZ(g_i) + b]$ (6)

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

$$T(u) = aZ(u) + b + \sum_{i=1}^n w_i T_H(g_i) \quad (7)$$

where

- u represents any location within the study area
- g_i represents the i^{th} 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 i^{th} 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 $\bar{T} = a_i Z + b_i$

(2) Remove the elevational trend (\bar{T}_i) from the measured values based on the above regression, and get the residuals at gage locations, $T'_i = T_i - \bar{T}$

(3) Interpolate the residuals (T'_i) with ArcGIS built-in ordinary Kriging 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 (\bar{T}) at all other locations

(5) Obtain the estimation of temperature (T) at any location by adding the above two terms, $T = \bar{T} + T'$

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 solar radiation data is available, inverse distance weighting (IDW) is used to interpolate solar radiation data. When there are no solar radiation measurements the empirical approach recommended in FAO56 (Allen et al. 1998) based upon the temperature range is adopted.

$$R_s = K_s \times \sqrt{(T_{\max} - T_{\min})} \times R_a \quad (8)$$

Where

T_{\max} is maximum air temperature[°C]

T_{\min} is minimum air temperature[°C]

R_a is extraterrestrial radiation [MJm⁻²d⁻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, inverse distance weighting (IDW) is used to interpolate between the point measurements. When there is no wind data then a general 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.

2.2.2 Interface design

To free the modeler from complicated interactions with ArcGIS, all the functions for ET modeling are incorporated into a custom ArcGIS toolbar with categorized menu items (figure 3).

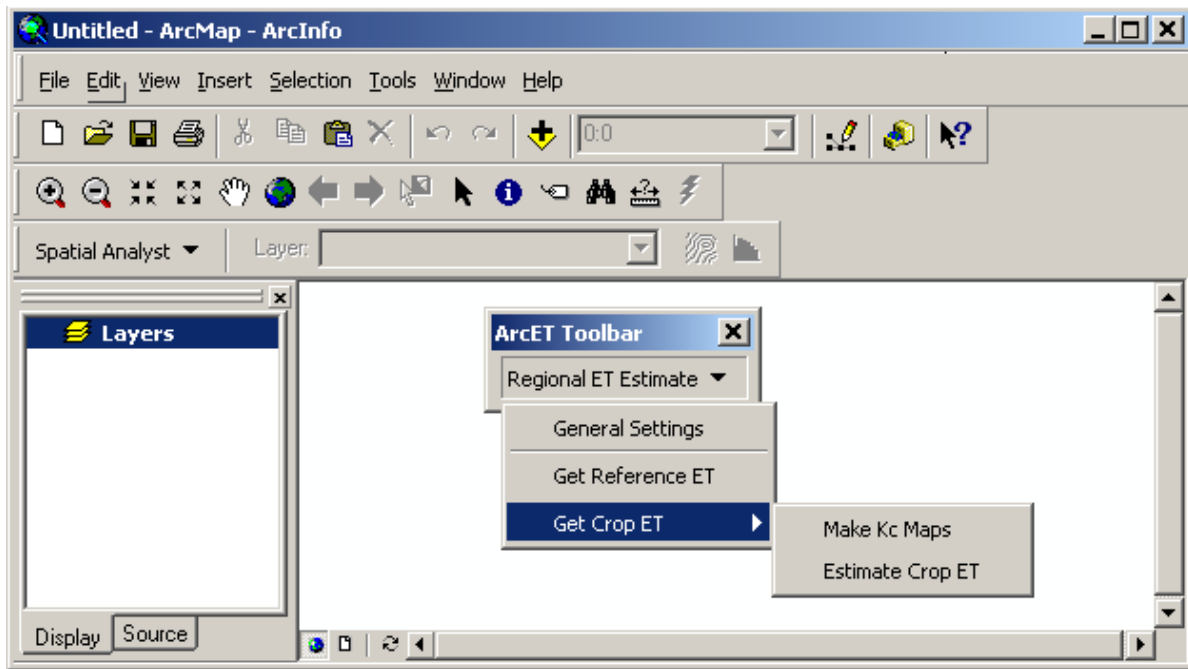


Figure 3. ArcET toolbar interface

The input data preparation and control settings are accessed through the “general Settings” menu item under the “reginal ET Estimate” menu (figures 4-6). These provide the interface to control the basic data preparation.

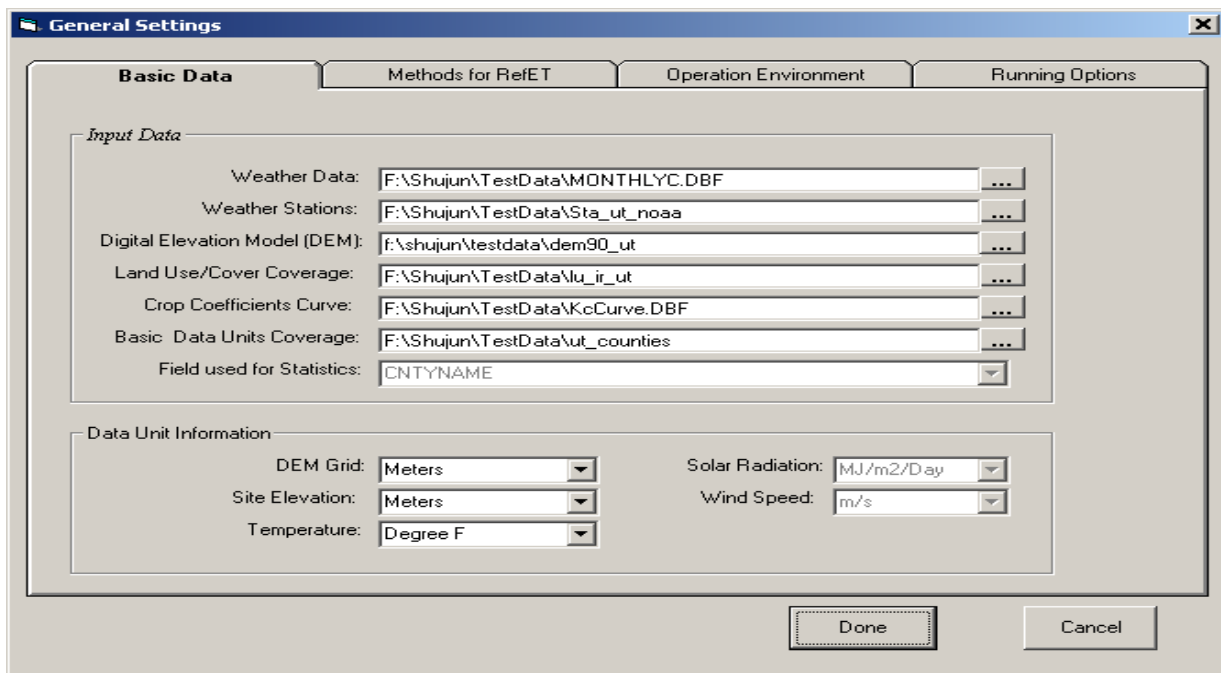


Figure 4. Individual interface for data input

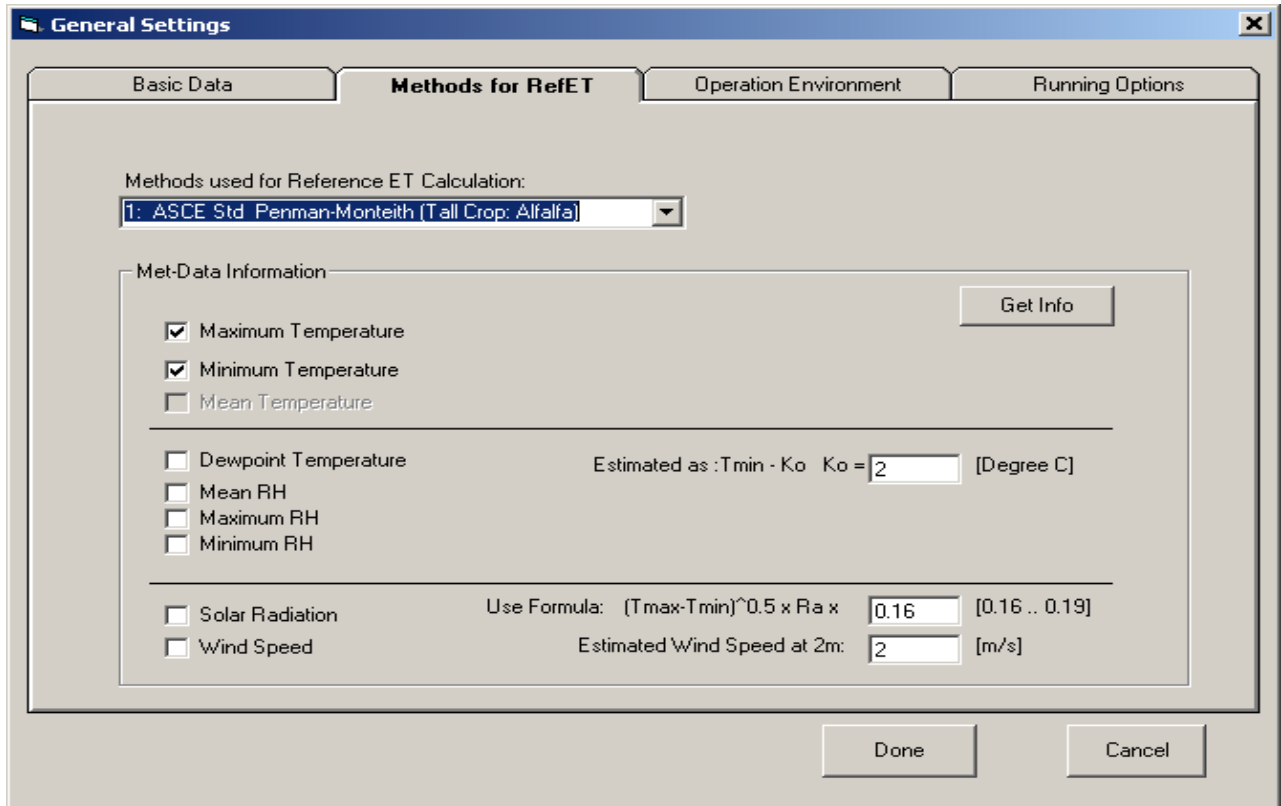


Figure 5. Individual interface for reference ET method settings

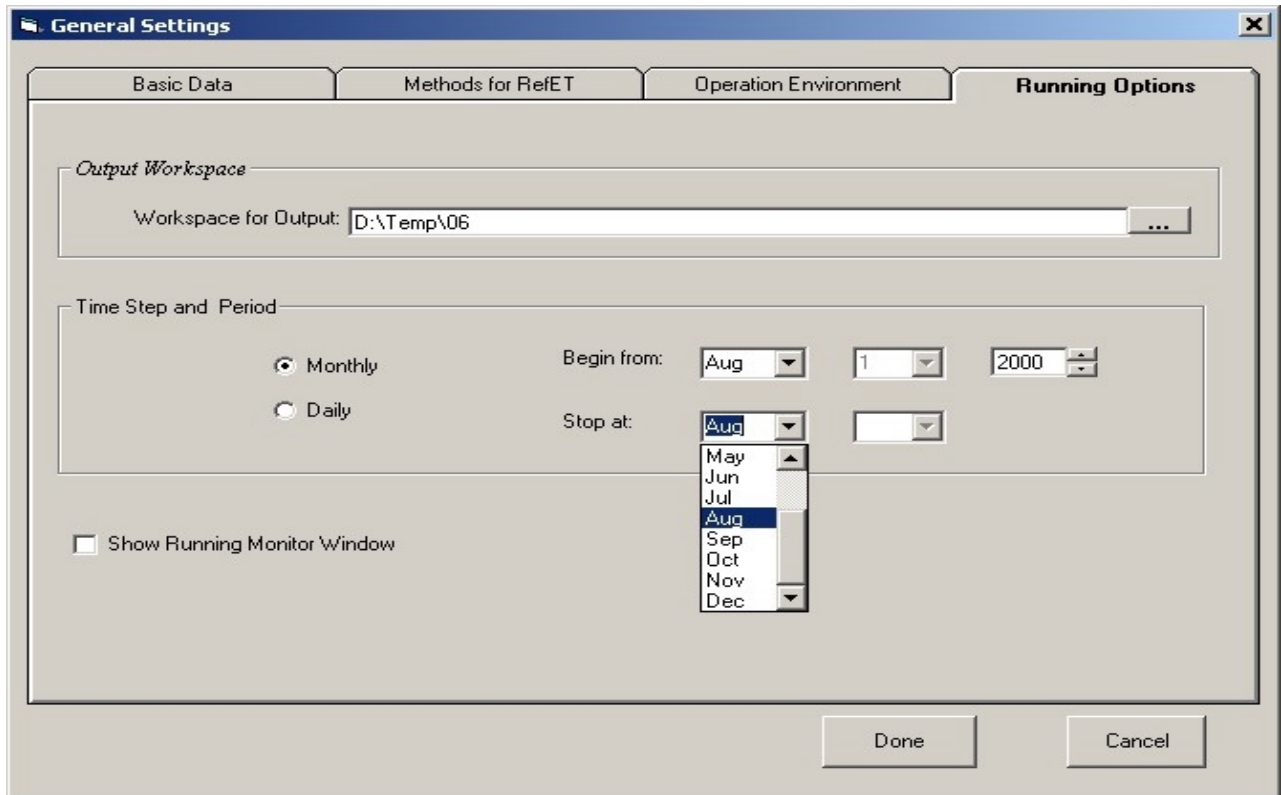


Figure 6. Individual interface for running control

Once the preparation work is done and settings is saved, the "Get Reference ET" menu invokes the modeling process.

During the generation of crop coefficient maps, some user's interactions are required to check provided data or append new data. The interface shown in figure 7 is used for this purpose.

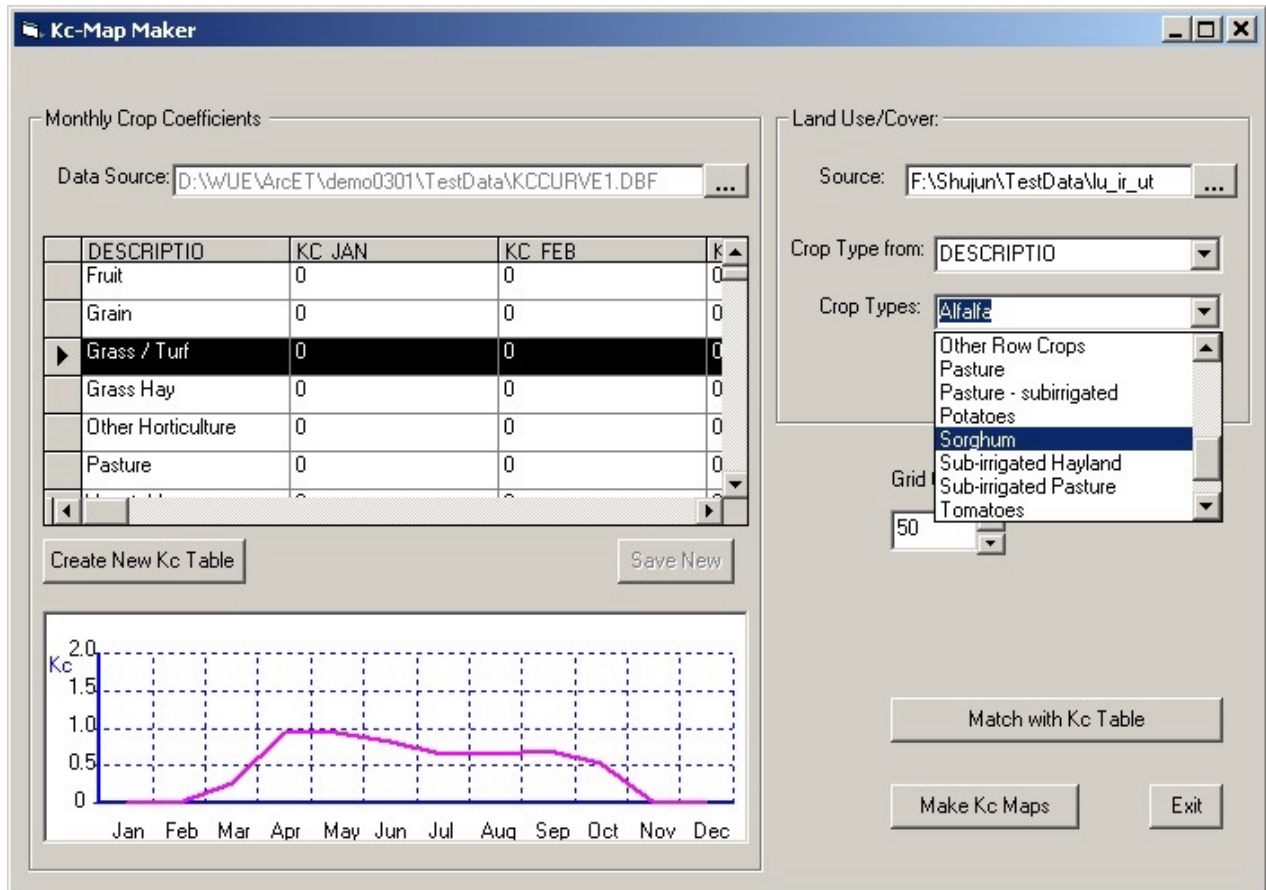


Figure 7. Individual interface for generating Crop Coefficient maps

Once the reference ET has been calculated the "Get Crop ET" menu invokes the crop ET calculation process.

The interfaces and GIS functionality of the toolbar have been programmed in Microsoft Visual Basic with GIS-related functionality coded through reference to the follows:

- ESRI Object Library
- ESRI ArcMap Object Library
- ESRI Spatial Analyst Shared Object Library
- ESRI Spatial Analyst Extension Object Library

The program is packaged as a dynamic link library (DLL) that can be easily customized into the main interface of ArcMap according to the standard procedure provided by ESRI.

3 Use of the toolbar

The toolbar described above provides the capability to perform ET calculations from within ArcGIS. For the calculation of reference ET only, users are required to input the following data:

- (1) An ESRI shapefile to show the location of climate stations within the region of interest
- (2) point-measurements of meteorological variables in the format of tabulated time-series
- (3) DEM in ESRI GRID format for the area of interest

To obtain crop ET, the following data are also required:

- (4) An ESRI polygon shapefile for Land Use/Cover information
- (5) A DBF table with crop coefficients data

The modeling results are provided in the formats of

- (1) monthly reference ET maps as figure 8
- (2) monthly crop ET maps as figure 9
- (3) tabulated monthly ET information zone by zone as figure 10

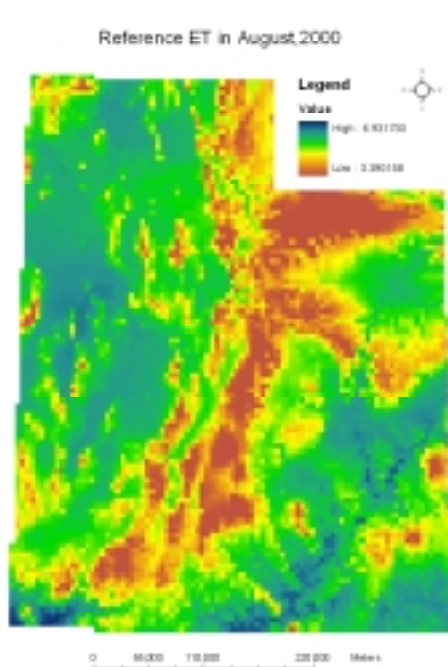


Figure 8. Monthly reference ET maps

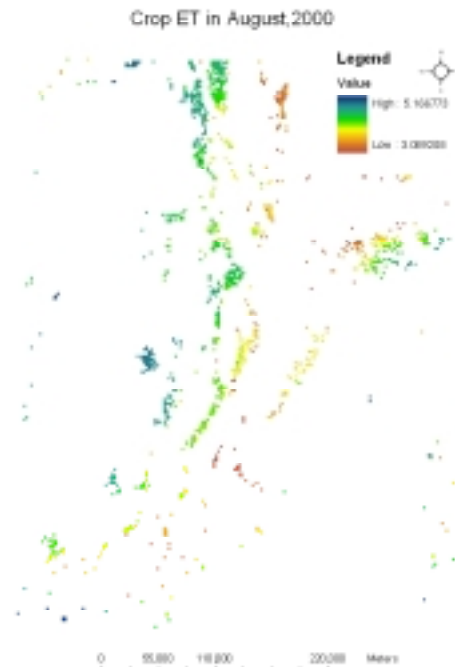


Figure 9. Monthly crop ET maps

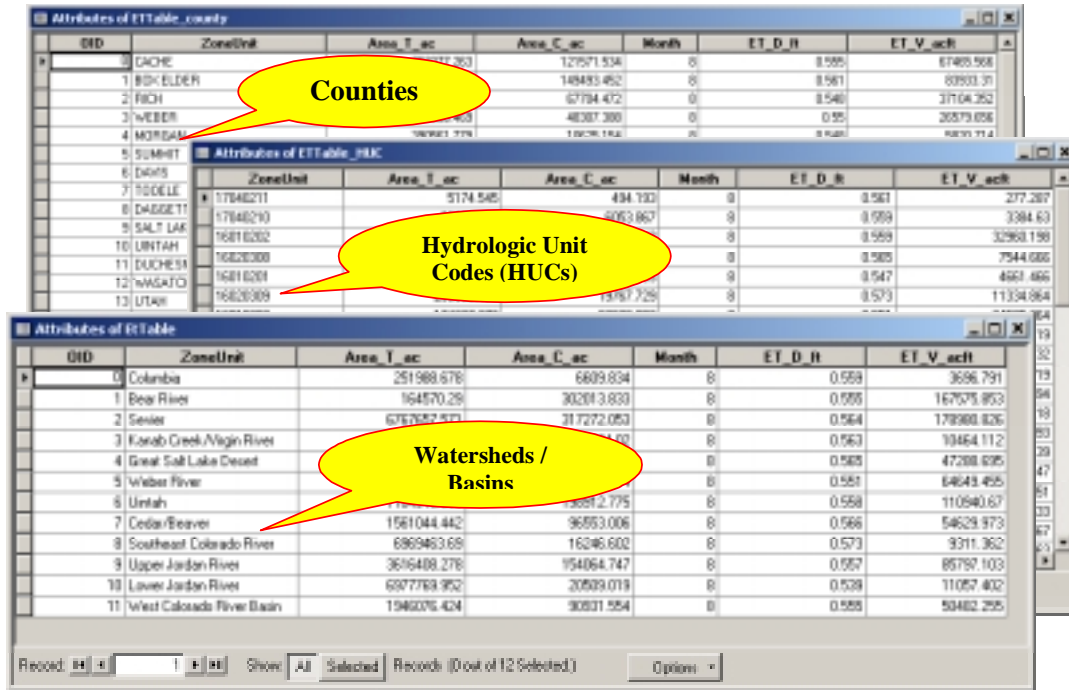


Figure 10. Tabulated monthly ET information

The toolbar, together with instructions for its use are available from <http://moose.cee.usu.edu/ArcET>

Summary

An ArcMap toolbar (ArcET) was developed to provide an integrated GIS environment for the derivation of the spatial distribution of ET. ArcET facilitates the implementation of various point-specific reference ET methods at regional scale through seamless integration of GIS with ET models and thus provides an effective and efficient operational tool to get the spatial and temporal distribution of evapotranspiration.

Acknowledgement

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