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Software for estimating reference evapotranspiration using limited weather data

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ABSTRACT

The FAO-56 Penman–Monteith combination equation (FAO-56 PM) has been recommended as the standard equation for estimating reference evapotranspiration (ET_0). The FAO-56 PM equation requires the numerous weather data that are not available in the most of the stations. The main goal of this paper is to present the software for estimating reference evapotranspiration, focusing on the feature of using limited weather data. This is simple Windows-based and user-friendly software provides methods to estimate extra-terrestrial radiation, maximum sunshine hours, daily net radiation and daily/monthly ET_0. The program is written in C# and includes comprehensive technical documentation. The software is available for free download.

The weather data for this study were obtained from CIMIS for Davis weather station. The reduced-set FAO-56 PM approaches and adjusted Hargreaves equation were compared to the full-set FAO-56 PM equation. The FAO-56 reduced-set PM ET_0 estimates were in closest agreement with FAO-56 full-set PM ET_0 estimates. The adjusted Hargreaves equation (AHARG) was found to be in very good agreement with the full-set FAO-56 PM. This program is the first software facilitating calculation of ET_0 only with air temperature parameter.

1. Introduction

Numerous equations, classified as temperature-based, radiation-based, pan evaporation-based and combination-type, have been developed for estimating reference evapotranspiration (ET_0). Relationships were often subject to rigorous local calibrations and proved to have limited global validity.

The estimation of the ET_0 is of great importance for the management of water resources, for agricultural production forecasting, for irrigation scheduling and for solving problems in the field of hydrology and meteorology.

Many studies have confirmed the superiority of Penman–Monteith equation (Ventura et al., 1999; Pereira and Pruitt, 2004; Lopez-Urrea et al., 2006; Gavilan et al., 2007). The Penman–Monteith equation has two advantages over many other equations. First, it can be used globally without any local calibrations due to its physical basis. Second, it is a well documented equation that has been tested using a variety of lysimeters.

The FAO-56 Penman–Monteith combination equation (FAO-56 PM) has been recommended by the Food and Agriculture Organization of the United Nations (FAO) as the standard equation for estimating ET_0. The main shortcoming of FAO-56 PM equation is that it requires numerous weather data that are not always available for many locations. This is especially true in developing countries where reliable weather data sets of radiation, relative humidity and wind speed are limited.

To overcome this problem, Allen et al. (1998) recommend procedures to estimate the parameters of the FAO-56 PM equation when some weather data are missing. The absence of weather data can also be overcome by using ET_0 equations with fewer weather data requirements. Allen et al. (1998) have proposed that when sufficient data to solve the FAO-56 PM equation are not available then the Hargreaves equation can be used. However, this equation generally overestimates ET_0 at humid locations (Jensen et al., 1990). These results motivated Trajkovic (2007) to develop the adjusted Hargreaves equation which provides the close agreement with FAO-56 PM estimates at Serbian humid locations.

There are a few software solutions in computing reference evapotranspiration. DailyET (Hess, 1996) is a Windows-based software tool which provides a quick and simple daily and monthly reference evapotranspiration. The minimum input data required are maximum and minimum air temperature, relative humidity, sunshine duration, wind speed and the location of the weather station (latitude, height above sea level). It cannot replace any full featured software which was developed to predict crop water requirements.

GSRad (Donatelli et al., 2006a; Donatelli et al., 2006b) is a software component containing models to estimate extra-terrestrial

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and ground-level solar radiation from alternative methods. This software is free and is illustrated in a fully documented hypertext help file, focusing on the features of reusability and extensibility.

The objectives of this study are: first, to develop software for estimating daily or monthly reference evapotranspiration using limited weather data, second, to examine whether it is possible to successfully use FAO-56 PM equation when some weather input data are not available; and third, to determine minimum weather data requirements for estimating ET_0.

2. Materials and methods

2.1. Study areas and data collection

The weather data for this study were obtained from CIMIS for Davis weather station (#6, latitude 38°32′09″N, longitude 121°46′32″W, elevation 18 m) located in Sacramento Valley Region Yolo County (Central District). The CIMIS was developed in 1982 by the California Department of Water Resource and the University of California at Davis to assist California's irrigators manages their water resources efficiently using a network of over 120 automated weather stations.

2.2. FAO-56 Penman–Monteith equation

FAO-56 Penman–Monteith reference evapotranspiration (FAO-56 PM ET_0) for estimating reference evapotranspiration assumes the reference evapotranspiration as that from a hypothetical crop with an assumed crop height (0.12 m) and a fixed canopy resistance (70 s m^{-1}) and albedo (0.23), closely resembling the evapotranspiration from an extensive surface of green grass cover of uniform height, actively growing, and not short of water, which is given by Allen et al. (1998):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \lambda \frac{900}{T+273} U_2 \text{ VPD}}{\Delta + \lambda(1 + 0.34U_2)} \quad (1)$$

where ET_0 = reference evapotranspiration (mm day^{-1}); Δ = slope of the saturation vapor pressure function (kPa °C^{-1}); R_n = net radiation (MJ m^{-2} day^{-1}); G = soil heat flux density (MJ m^{-2} day^{-1}); γ = psychometric constant (k Pa °C^{-1}); T = mean air temperature (°C); U_2 = average 24 h wind speed at 2 m height (m s^{-1}); and VPD = vapor pressure deficit (kPa).

The FAO-56 PM equation requires numerous weather data: sunshine hours (or solar radiation), actual vapor pressure (or maximum and minimum relative air humidity), wind speed at 2 m height, and maximum and minimum air temperature. In the absence of a full data set, Allen et al. (1998) propose alternative procedures to estimate the missing weather data.

2.2.1. Procedure for estimating missing radiation data

Radiation is an infrequently measured weather parameter, compared to temperature. Another problem is that the pyranometers and net radiometers are the most delicate of the sensors used in weather stations. They are very expensive and they deteriorate rapidly in comparison with other sensors (Llasat and Snyder, 1998). As a result, solar radiation is often estimated from sunshine data using Angstrom equation:

$$R_s = \left(0.25 + 0.5\frac{n}{N}\right) R_a \quad (2)$$

where R_s = solar radiation (MJ m^{-2} day^{-1}); n = sunshine hours (h day^{-1}); N = daylight hours (h day^{-1}); R_a = extra-terrestrial radiation (MJ m^{-2} day^{-1}). Extra-terrestrial radiation and daylight hours are computed as a function of the local latitude and Julian data (Allen et al., 1998). In this paper, the sunshine data have been used as substitute for measured solar radiation data and that is the standard procedure when there is no measured radiation data (Allen et al., 1998; Todorovic, 1999; Vanderlinden et al., 2004; Nandagiri and Kovoor, 2005; Cai et al., 2007).

Where sunshine data are lacking the difference between the maximum and minimum temperature can be used for the estimation of solar radiation (Hargreaves et al., 1985; Allen, 1997):

$$R_s(T) = K(T_{max} - T_{min})^{0.5} R_a \quad (3)$$

where $R_s(T)$ = solar radiation estimated from air temperature differences (MJ m^{-2} day^{-1}); R_a = extra-terrestrial radiation (MJ m^{-2} day^{-1}); T_{max} and T_{min} = maximum and minimum air temperature (°C), respectively; and K = adjustment coefficient. Allen et al. (1998) recommended using K = 0.16 for "interior" locations and K = 0.19 for "coastal" locations.

2.2.2. Procedure for estimating missing vapor pressure data

Vapor pressure (VP) is difficult to measure accurately. Measurement of relative humidity by electronic sensors is commonly plagued by hysteresis, nonlinearity and calibration errors (Allen, 1996). If humidity data are not available, an estimate of actual vapor pressure can be made by assuming minimum air temperature is equal to dew-point temperature (Jensen et al., 1997; Kimball et al., 1997). If T_{min} is used to represent T_{dew} then:

$$VP(T_{min}) = 0.611 \exp\left[\frac{17.27T_{min}}{T_{min} + 237.3}\right] \quad (4)$$

where VP(T_{min}) = actual vapor pressure obtained from minimum air temperature (kPa).

2.2.3. Procedure for estimating missing wind speed data

Wind speed is one of the least easily estimated and least available parameters needed for estimating ET_0. Wind speed is not routinely measured at many weather stations especially in developing countries and may need to be estimated when ET_0 equation is applied. Approach for estimating missing wind speed data consists of using local long-term average wind speed value at each location. In this study, the global default wind speed of 2 m s^{-1} was not used because of poor results presented in Trajkovic (2005).

2.2.4. Air temperature

Air temperature is the essential weather parameter for estimating reference evapotranspiration. Many of the suggested procedures for estimating other parameters rely upon maximum and minimum air temperature measurements. These measurements are simple and are not subject to high errors as opposed to the other weather parameters. Also the air temperature is measured at almost all the stations and these data are easily accessed. There is no dependable way to estimate air temperature when it is missing.

2.2.5. FAO-56 reduced-set PM ET_0 approaches

According to these procedures for estimating missing weather data, in this study the following FAO-56 reduced-set approaches have been used: PM_{teu} [FAO-56 PM ET_0 values obtained without measured sunshine data, estimating R_s using Eq. (3)], PM_{tnu} [FAO-56 PM ET_0 values estimated without measured humidity data, estimating VP using Eq. (4)], $PM_{ten,l}$ [ET_0 values estimated without measured wind speed data, estimating wind speed using local default wind speed value], $PM_{ten,r}$ [ET_0 values estimated without measured wind speed data, estimating wind speed using regional default wind speed value], PM_{tu} [FAO-56 PM ET_0 estimates obtained without sunshine and humidity data, estimating R_s using Eq. (3) and estimating VP using Eq. (4)], $PM_{te,l}$ [FAO-56 PM ET_0 values estimated with temperature and humidity data and