Agricultural Water Management 97 (2010) 300–308

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Prediction of annual reference evapotranspiration using climatic data

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ARTICLE INFO

Article history:
Received 1 January 2009
Received in revised form 6 October 2009
Accepted 6 October 2009
Available online 31 October 2009

Keywords:
Prediction
Reference evapotranspiration
Pan evaporation
Penman–Monteith equation
Modified Mann–Kendall method

ABSTRACT

It is important to determine how well ET_o can be estimated from easily observed E_{pan} (free water evaporation measured by a pan) measurements and the other climatic data. Our objectives are to predict annual ET_o with E_{pan} data (with a calibrated k_p (=ET_o/E_{pan})) and with a 4-variable regression function method. The significance of the trends of E_{pan}, ET_o and k_p series were detected. The whole data series (ET_o, E_{pan}, mean temperature, sunlight hours, relative humidity and wind speed) were divided into the early (L-5) years for calibrating k_p and coefficients of a 4-variable function and the last 5 years for predicting ET_o. From the results, significance of series trends decreased when using the modified Mann–Kendall (MMK) test compared to the Mann–Kendall (MK) method. For ET_o, five out of six sites showed significant trends according to the MK statistic Z, and two sites were significant in trend combining with the MMK statistic $Z^*(j)$. For E_{pan}, two sites were significant in trends according to Z, and zero sites were significant in trends combining with $Z^*(j)$. For k_p, two sites were significant in trends according to Z, and no sites were significant in trends combining with $Z^*(j)$. Thus the calibrated k_p can be treated as a constant when using the E_{pan} method. The predicted annual ET_o using the E_{pan} and the multi-variable methods showed generally good agreements with the estimated annual ET_o (based on monthly PM equation) with low relative errors (RE). Mean ET_o values were well predicted by both methods. When using E_{pan} method, RE ranged from −14.7 to −3.3% for Urumqi, from 17.6 to 21.7% for Xning, from 1.8 to 10.7% for Lanzhou, from 4.7 to 17.0% for Huhehaote, from −7.4 to 9.1% for Beijing, and from −8.6 to 2.3% for Changchun. RE of predicting annual ET_o with 4-variable regression function were even lower compared to E_{pan} method. The main error source of the predictions came from the deviation between calibrated k_p and the actual k_p of the predicted years when using E_{pan} method and from random fluctuations of climatic data when using the 4-varible regression function. In conclusion, the MMK test was a robust method for trend detection because it considered serial time dependence. Insignificant trend of the k_p series supports the choice of a mean value as the calibrated k_p and for ET_o predictions. The E_{pan} method is recommended for prediction of annual ET_o.

1. Introduction

The north region of China receives low rainfall and has high evaporative demand. In these arid and semiarid regions, irrigation is required to meet water needs for crop growth and production. Therefore, accurate estimation of crop evapotranspiration (ET_c) is necessary in order to schedule irrigations for high water use efficiency. For a region where crops are irrigated, the difference of rainfall and ET_c in a certain period (year, season or month) can be a reference for irrigation. The estimation of ET_c was also used in estimating ecological water requirement of forests (Min et al., 2004) and vegetations. Estimation of water shortage for typical vegetations in a region is also possible when ET_c values are calculated and combined with remote sensing of vegetation. Moreover, estimation of ET_c is included in most hydrologic models used for water resources planning to quantify fluxes of water into, out of, and within the hydrologic system (Sumner and Jacobs, 2005).

However, direct measurements of ET_c are rarely available (Sumner and Jacobs, 2005). ET_c is often estimated via a method that quantities water use for a well-watered, non-stressed crop by multiplying reference evapotranspiration (ET_o) with a crop coefficient (K_c). ET_o can be estimated theoretically or empirically. Since Penman (1948) developed an equation for estimating

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doi:10.1016/j.agwat.2009.10.001

reference evaportranspiration under the condition of no horizontal transfer of vapor, some modifications of the equation (Monteith, 1965; Doorenbos and Pruitt, 1975) and other methods were developed because the original Penman equation was not purely theoretical. Among the various methods for estimating ET_o, the FAO 56 Penman–Monteith (PM) equation (Allen et al., 1998), ASCE standard equation (Walter et al., 2000), the modified Priestley–Taylor (PT) method (1972), pan evaporation method (Snyder, 1992; Pereira et al., 1995) and Hargreaves–Samani (HS) equation (Hargreaves and Samani, 1982, 1985) were extensively used for estimating ET_o at different periods. Multi-variable regression functions were also useful for estimating ET_o (Li et al., 2005). If properly calibrated, pan evaporation method can be a practical tool for estimating ET_o (Pereira et al., 1995). The HS equation is simple and has minimum requirements of data, so it is somewhat popular in some developing countries (ElDeen and Abdelaal, 2002). The PT formula is useful for estimating open water evaporation for operational procedures such as reservoir management but is presented for zero or small advection conditions which is a main restriction for using the model (Arasteh and Tajrishy, 2008). Weiß and Menzel (2008) showed that FAO 56 PM equation, PM equation, PT equation and HS equation provided a range of ET_o estimates. Determining the most physically reasonable method is difficult due to the limited availability of validation data.

Allen et al. (1998) reported the modified PM equation, and the Food and Agriculture Organization (FAO) adopted the equation as the standard ET_o equation (FAO-56 PM equation). The equation has been accepted globally as a good ET_o estimator when compared with other methods (Blaney and Criddle, 1950; Allen, 1996; Garcia et al., 2004; Sumner and Jacobs, 2005; Temesgen et al., 2005; Alexandris et al., 2006; Donatelli et al., 2006; Gong et al., 2006; Cai et al., 2007). The FAO-56 PM equation is a physically-based approach that requires climatic data including maximum and minimum air temperatures, relative humidity, solar radiation (or sunshine duration) and wind speed (Allen et al., 1998).

The major drawback of using the FAO-56 PM equation is that it requires site specific meteorological data. In places where all of the meteorological data needed to calculate ET_o are not available, it is common to use pan evaporation (E_{pan}, the free water evaporation under sufficient water supply). Data for periods of 10 days or longer can serve as a surrogate for ET_o (McVicar et al., 2007). Using E_{pan} to estimate ET_o removes the need for having climate data to use the FAO-56 PM equation. E_{pan} is observed by a special pan and is often linearly related with ET_o characterized by a slope coefficient k_p (Allen et al., 1998). In western countries, class-A pan (120.7 cm in diameter and 25 cm deep) (Allen et al., 1998) is universally used for E_{pan} measurements (Allen, 1996; Naoum and Tsanis, 2003).

However, small pans of 20-cm-diameter and 10-cm-height have been used for a long time at many Chinese weather stations. Only a few studies have reported E_{pan} measurements based on the 20-cm diameter Chinese pans. Xu et al. (2006a) reported spatial distributions of ET_o and E_{pan} in the Yangtze river catchment. Fan et al. (2006) found that there were obvious correlations between E_{pan} and ET_o determined by the PM equation based on Loess Plateau climatic data. McVicar et al. (2007) performed spatial and sensitivity analysis of monthly ET_o and E_{pan} in the Yellow River basin. Wang et al. (2006) and Wang et al. (2007) studied E_{pan} variations of the Yangtze River basin.

The rank-based non-parametric Mann–Kendall (MK) statistical test (Mann, 1945; Kendall, 1975) has been commonly used to assess the significance of trends in hydro-meteorological time series such as streamflow (Yue et al., 2002; Topaloglu, 2006), rainfall (Cannarozzo et al., 2006) and E_{pan} and ET_o (Xu et al., 2006b). Most trend detection studies have ignored the role of serial auto-correlation among data sets (Topaloglu, 2006). Yue and Wang (2002) found that the existence of serial auto-correlation affects the power of statistical tests such as the MK test to assess the significance of trends. The presence of positive serial correlation leads to a higher probability of rejecting the null hypothesis of no trend when it might be true, so serial auto-correlation should be considered when performing trend test analyses. Topaloglu (2006) considered effects of lag-1 serial auto-correlations on the MK statistic for flow series. However, when the lag of time dependence is larger than 1, it is insufficient to only include lag-1 correlations.

Trends of ET_o and E_{pan} have been detected globally. Decreasing trends of ET_o and E_{pan} were found in Yangtze River basin in China over the past 4 decades (Wang et al., 2007). Trends of ET_o in Tibetan Plateau in China were decreasing (Wu et al., 2007). Observations from the Northern Hemisphere showed a decreasing trend of E_{pan} over the past 5 decades (Roderick and Farquhar, 2004). Peterson et al. (1995) also reported a post-WWII decrease in pan evaporation over a significant portion of the extratropical land area of the Northern Hemisphere, later the same research group reported opposite signs of E_{pan} in Russian, Latvian and U.S. experimental sites (Golubev et al., 2001). The reasons for the decrease in E_{pan} or ET_o could be large and widespread decreases in sunlight (Roderick and Farquhar, 2002), increase in wind speed (Wang et al., 2007), or vapor pressure deficit changes (Johnson and Sharma, 2009). Cong and Yang (2008) concluded that reasons for changes of trends of E_{pan} were different before and after 1985 in China.

Pan evaporation data are preferred when full climatic data are not available for estimating ET_o. Parameter k_p is very important when using observed E_{pan} to predict ET_o. A good calibration of k_p will generally result in an accurate prediction of ET_o. To date little research has focused on analyzing the trend of k_p series with the modified MK (MMK) method and using it for predicting ET_o. Prediction of annual ET_o using a multi-variable function can be used provided that required climatic data are available. Our objectives are: (1) to detect the trends of annual E_{pan}, ET_o and k_p series using both the MK and the MMK tests for 6 selected stations in north China; (2) to predict annual ET_o with calibrated k_p and annual E_{pan}; (3) to predict annual ET_o using calibrated multi-variable functions of other climatic data and compare its accuracy with the E_{pan} method.

2. Theory

2.1. The standard reference evapotranspiration equation

The FAO-56 form of the Penman–Monteith equation is (Allen et al., 1998):

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

where ET_o is the reference evapotranspiration (mm day^{-1}), G is soil heat flux (MJ m^{-2} day^{-1}), T is mean air temperature at 2 m (°C), u_2 is wind speed at 2 m (m s^{-1}), e_s is saturation vapor pressure (kPa), e_a is actual vapor pressure (kPa), e_s–e_a is saturation vapor pressure deficit (kPa), Δ is slope of vapor pressure curve (kPa °C^{-1}), γ is psychrometric constant (kPa °C^{-1}), and R_n is net radiation (MJ m^{-2} day^{-1}). The net radiation (R_n) is the difference between the incoming radiation (R_{ns}, MJ m^{-2} day^{-1}) and the outgoing radiation (R_{nl}, MJ m^{-2} day^{-1}). Net radiation can be estimated from Eqs. (21) to (25), (34)–(36), (38)–(40) in Allen et al. (1998). Monthly G is estimated by (Allen et al., 1998)

$$G_i = 0.07(T_{i+1} - T_{i-1}) \quad (2)$$

where subscripts $i+1$, i and $i-1$ are the numbers of month. Annual ET_o is cumulated from the calculated monthly values.