Agricultural Water Management 184 (2017) 145–155

Contents lists available at ScienceDirect

Agricultural Water Management

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

Comparison of 16 models for reference crop evapotranspiration against weighing lysimeter measurement

Xiaoying Liu[a,*], Chunying Xu[a], Xiuli Zhong[a], Yuzhong Li[a,*], Xiaohuan Yuan[b], Jingfeng Cao[a]

[a] Institute of Environment and Sustainable Development in Agriculture, Chinese Academy of Agricultural Sciences/Key Laboratory of Dryland Agriculture, MOA, 100081, Beijing, China
[b] Beijing Research & Development Center for Grass and Environment, 100097, Beijing, China

ARTICLE INFO

Article history:
Received 23 November 2016
Accepted 31 January 2017

Keywords:
Reference crop evapotranspiration
Weighing lysimeter measurement
Penman-Monteith
Blaney-Criddle
Priestley-Taylor
Hargreaves

ABSTRACT

Accurate estimation of reference crop evapotranspiration (ET_0) is important due to its crucial role in determining crop water requirement in irrigated agriculture. Though a great number of models have been developed, their rigorous evaluation with measurements is still lacking, leading to confusion and arbitrariness in model selection. In this paper daily estimates of 16 ET_0 models, including five combination-, six radiation and five temperature-based ones, were compared with weighing lysimeter measurements during crop growing season (April through October) in 2012 at a semiarid site in China. Daily ET_0 was measured by two weighing lysimeters (area 1.3 m × 1.3 m, depth 2.3 m) located in a fescue grass (*Festuca arundinacea* Schreb) plot (100 m × 100 m) surrounded by a 167 ha crop, winter wheat rotated with summer maize. We found the models were ranked decreasingly as: FAO-ppp-17 Penman > 1963 Penman > FAO-24 Blaney-Criddle (BC) > 1996 Kimberly Penman > FAO-24 radiation > FAO-56 Penman-Monteith (PM) > FAO-24 Penman > Turc > DeBruin-Keijman > Jensen-Haise > Priestley-Taylor > Hargreaves > Makkink > Hamon > Blaney- Criddle > Mcloud on basis of RMSE (root mean square error). Overall, the combination models performed best with RMSE ranging from 0.93 to 1.32 mm d^{-1}, followed by the radiation models with RMSE from 1.28 to 1.79 mm d^{-1}, and the temperature models with RMSE from 1.09 to 2.48 mm d^{-1}. The best combination model (FAO-ppp-17 Penman) was respectively 29% and 17% more accurate than the best radiation (FAO-24 radiation) and temperature (FAO-24 BC) models. Better performance of the combination and radiation models resulted because they explicitly contain the dominant factors influencing ET_0. All models tended to overestimate under low evaporative demand while underestimating the measured values under high demand, but on average the combination and radiation methods underestimated by 0.46 mm d^{-1} and 0.60 mm d^{-1}, respectively, whereas the temperature method overestimated by 0.21 mm d^{-1}. All combination and radiation models, and the Hargreaves and FAO-24 BC in temperature method showed robust structure. To improve them future efforts should be on local calibration, but for temperature models showing structure failure focus should be on its optimization. The coefficients of commonly used models were calibrated and related to meteorological variables. Particularly, those of the Priestley-Taylor, Makkink, Turc and the Hamon were enhanced, while those of the Hargreaves and BC were decreased. In climate similar to the current site in China we suggest continued use of the older Penman equations for combination method and the FAO-24 radiation or Turc for radiation method. Meanwhile, two questions need to be addressed in future studies: i) adoption of the FAO-56 PM equation as the sole standard for computing ET_0 and the proper value for surface resistance; and ii) the effectiveness of the later modifications to the original wind function in the Penman equation.

1. Introduction

Evapotranspiration (ET) is one of the dominant components in water cycling in soil–plant– atmosphere continuum. Its reliable information is of vital importance in water related studies and applications such as irrigation system designing, irrigation schedul-

* Corresponding authors.
E-mail addresses: liuxiaoying@caas.cn (X. Liu), liyuzhong@caas.cn (Y. Li).

http://dx.doi.org/10.1016/j.agwat.2017.01.017

ing, water resource planning and management, water allocation, water balance calculation, crop yield prediction (Perera et al., 2015), etc. Though ET can be measured by a variety of methods, they are laborious, time-consuming and costly. So for most applications it is estimated, particularly by the well known two-step approach (Allen et al., 1998) as a product of reference crop evapotranspiration (ET_0) and crop coefficient. Therefore, accurate calculation of ET_0 becomes a critical step in obtaining ET.

ET_0 refers to the rate of evapotranspiration from an extended surface of 8–15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water (Doorenbos and Pruitt, 1977). The concept stems from potential evaporation of Penman (1948) and Thornthwaite (1948), and is first introduced by Doorenbos and Pruitt (1977) in the FAO (Food and Agriculture Organization) publication No. 24. It is later extended by Jensen et al. (1990) who brought all the methods computing potential evaporation (e.g., Blaney and Criddle, 1950; Jensen and Haise, 1963; Turc, 1961; Priestley and Taylor, 1972; Hargreaves and Samani, 1985) into this category. Physically, ET_0 reflects the atmospheric demand for water and represents the integrated effect of various meteorological elements on vegetation water use.

Numerous ET_0 models, approximately 50 according to Lu et al. (2005), have been developed and revised so far. Based on assumption and data input they are roughly classified as: combination- (Penman, 1948, 1963; Monteith, 1965), radiation- (Priestley and Taylor, 1972), temperature- (Thornthwaite, 1948; Hargreaves and Samani, 1985), pan evaporation based and Dalton (1802) type (also called mass transfer or aerodynamic) method. The large number of models has undoubtedly brought convenience for applications, but they have also caused confusion as to which one to choose under a particular climate and region due mainly to their limited evaluation against measurement. Understanding the behavior of these models has been a major subject of concern under various climates, e.g., Jensen et al. (1990), Kashyap and Panda (2001), Castellvi et al. (2001), Liu and Lin (2005), Yoder et al. (2005), Liu et al. (2006), López-Urrea et al. (2006), Perera et al. (2015), and many others.

Though a great number of evaluations on ET_0 model can be found in literature, they were mostly made against estimates of the FAO-56 PM (Martínez-Cob and Tejero-Juste, 2004; Temesgen et al., 2005; Gavilán et al., 2006; Liu et al., 2006; Cao et al., 2015), while relatively few (Jensen et al., 1990; Howell et al., 1998; Ventura et al., 1999; Yoder et al., 2005) for limited countries and climates were rigorously made against data from weighing lysimeters. Jensen et al. (1990) evaluated 20 models using measured data from weighing lysimeter at 11 locations, mostly from the U.S. and only three from other countries. More recent studies with weighing lysimeter were also mainly from US (Howell et al., 1998; Yoder et al., 2005) and Mediterranean climates, including Davis, California (Ventura et al., 1999; Vaughan et al., 2007) and Spain (Berengena and Gavilán, 2005; López-Urrea et al., 2006), whereas evaluations from other places remain scarce. In China, thorough investigation on ET_0 methods has never been conducted with weighing lysimeter, which sharply contrasts with its water shortage situation as a big agricultural country.

Furthermore, results of existing studies with weighing lysimeter are inconsistent. Jensen et al. (1990) reported that the PM performed best and the Thornthwaite performed poorest, while the FAO-24 Blaney-Criddle (BC) performed better, being ahead of five forms of the combination models and all the three radiation models evaluated. Yoder et al. (2005) assessed eight models at a humid site in the southeast U.S and reported the best performance of the FAO-56 PM, followed by the 1948 Penman and Turc, and the Hargreaves was the poorest. López-Urrea et al. (2006) assessed seven ET_0 methods with weighing lysimeter in a semiarid climate in Spain, concluding that the FAO-56 PM was the best, while the FAO-24 Penman and the FAO-24 BC significantly over- and the 1963 Penman significantly under- estimated daily ET_0. Another study in similar climate in southern Spain (Berengena and Gavilán, 2005), however, indicated that the locally adjusted Penman performed best, followed by the FAO-56 PM, and the Priestley-Taylor (PT) performed poorest. In semiarid environment in Texas, Howell et al. (1998) also revealed a slightly better performance of the original Penman (1948) than the FAO-56 PM.

The above inconsistencies highlight the difficulty and uncertainty in understanding the true difference and relation of various ET_0 models under different regions and climates. To gain a high degree of certainty and to build a thorough knowledge on behaviors of these models, this paper compared 16 ET_0 models of varying complexity against weighing lysimeter measurements at a semiarid site in China, aiming at guiding their proper choice and reducing possible uncertainty in applications.

2. Materials and methods

2.1. ET_0 models and calculations

A total of 16 ET_0 models were selected for comparison, including five combination models, i.e. the original Penman (1963), FAO 24 Penman (Doorenbos and Pruitt, 1977), FAO-ppp-17 Penman (Frére and Popov, 1979), 1996 Kimberly Penman (Wright, 1996) and FAO-56 PM (Allen et al., 1998), respectively, six radiation models, i.e. the Priestley-Taylor (Priestley and Taylor, 1972), De Bruin-Keijman (De Bruin and Keijman, 1979), Makkink (1957), Jensen-Haise (Jensen and Haise, 1963), FAO-24 radiation (Doorenbos and Pruitt, 1977) and Turc (1961), respectively, and five temperature-based models, i.e. the Hargreaves (Hargreaves and Samani, 1985), Hamon (1961), McCloud (1955) and FAO-24 Blaney-Criddle (Doorenbos and Pruitt, 1977), original Blaney and Criddle (1950), respectively. Specific equations of these models and their abbreviations were listed in Table 1. Given the long development history of evaporation models, the various modifications they have undergone and the constant change in units for the involved variables, it is important to ensure that the selected model form matches with variable's units. For this we mainly referred to Doorenbos and Pruitt (1977), Jensen et al. (1990), Allen et al. (1998), Allen (2001), Kashyap and Panda (2001), De Bruin and Stricker (2000), and detailed descriptions can be found in these sources.

In many cases the parameters explicitly appeared in ET_0 models need to be estimated. Though procedures are provided in the original references, we applied the same algorithms to all models to avoid possible errors associated with unit conversions. The computation details were outlined in Allen et al. (1998), which was re-summarized in a compact Table in Liu et al. (2009). The specific coefficients involved were: albedo $\alpha = 0.23$, von Karman constant $k = 0.41$, Stefan – Boltzmann constant $\sigma = 4.903 \times 10^{-9}$ MJ K^{-4} m^{-2} d^{-1}, specific heat of water at constant temperature $c_p = 1.013 \times 10^{-3}$ MJ kg^{-1} °C^{-1}, $\lambda = 2.45$ MJ kg^{-1} and $G = 0$ MJ m^{-2} d^{-1}. The saturation vapor pressure was calculated as the mean based on T_x and T_n. The only difference from the FAO-56 procedure was that we incorporated the local coefficients into computation of the clear sky solar radiation R_{s0}, needed for calculating the net outgoing longwave radiation (R_{nl}), i.e. $R_{s0} = (a_s + b_s) \cdot R_a$, where a_s and b_s are calibrated Ångström-Prescott coefficients with data of Beijing (a = 0.1680, b = 0.5775) (Liu et al., 2012).

2.2. ET_0 measurement

Field observation was made in the Experiment and Demonstration Site of the National Precision Agriculture located in Xiaotangshan, Changping, Beijing (40.18°N, 116.43°E, 36 m above sea level) in North China Plain. The whole site occupies an area of