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Simulation of actual evapotranspiration from agricultural landscapes in the Canadian Prairies

Myra Martel[a,b], Aaron Glenn[c], Henry Wilson[c], Roland Kröbel[a,*]

[a] *Agriculture and Agri-Food Canada, Lethbridge Research and Development Centre, Lethbridge, Alberta, Canada*
[b] *Chemical and Biological Engineering Department, University of Saskatchewan, 57 Campus Drive, Saskatoon, SK S7N 5A9, Canada*
[c] *Agriculture and Agri-Food Canada, Brandon Research and Development Centre, Brandon, Manitoba, Canada*

A R T I C L E I N F O

Keywords:
Actual evapotranspiration
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Crop coefficient
Reference evapotranspiration model

A B S T R A C T

Study region: This study was carried out in southwestern Manitoba, in the prairie region of Canada.
Study focus: Mathematical models are routinely used to estimate evapotranspiration (ET) when measurements are lacking. This study was conducted to select the most relevant models for estimating ET in the Canadian Prairies. Eight reference ET models (i.e., Penman-Monteith, Priestley-Taylor, Makkink, Turc, Maulé et al., Blaney-Criddle, Hargreaves-Samani, and Hamon models) were evaluated. This study also assessed the applicability and transferability of the growing degree day (GDD)-based crop coefficients for estimating crop ET in the Canadian Prairies.
New hydrological insights: The equation developed by Maulé et al. (2006) was found to be the best reference ET alternative to the Penman-Monteith equation with a mean relative error of 11%. However, when models were validated against measured crop ET, the simpler radiation-based Turc and Makkink models were found to be the most useful models with daily mean relative errors ranging from 16% to 49%, outperforming the widely accepted Penman-Monteith model. Discrepancies in the GDD-based crop coefficients were found to also contribute to errors; however, results show the potential transferability of GDD-based coefficients across different locations and climatic conditions.

1. Introduction

Evapotranspiration (ET) is a key component of the hydrological cycle due to the vital role it plays in energy-moisture exchanges between the earth and the atmosphere. It is a combined process where water is lost from the soil surface through evaporative processes as well as water transpired through growth and temperature regulation processes of plants. Since more than 99% of the water taken by plants is lost through transpiration (Lambers et al., 2008), ET is often used to determine crop water requirement as part of regional water resource planning and management exercises. However, despite numerous methods available for its measurement and calculation, obtaining accurate estimates of ET remains challenging (Amatya et al., 2016).

Direct measurements of ET include weighing lysimeters and eddy covariance methods. These techniques can be difficult to successfully employ and expensive to install, maintain, and operate (Allen et al., 1998; Shi et al., 2008; Gebler et al., 2015). High costs and time-consuming tasks associated with these methods make them unsuitable for routine measurements (Allen et al., 1998); however, they remain useful for the evaluation of ET estimated from indirect methods such as the residual energy balance (Halldin

* Corresponding author.
E-mail address: roland.kroebel@agr.gc.ca (R. Kröbel).

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and Lindroth, 1992), Bowen ratio energy balance (BREB) (Bowen, 1926; Angus and Watts, 1984), soil water balance (Ritchie, 1985), and other (predictive) mathematical models (see also Rana and Katerji, 2000 for more details).

Rates of evapotranspiration are determined through various climatic factors that describe the energy available to evaporate water (e.g., radiation and temperature) and those that affect the movement of the evaporated water away from the evaporating surface (e.g., wind speed and humidity). Thus, when field ET measurements are not available, mathematical models built around those factors are employed to estimate ET using climate and land surface data. A common approach to simulate crop ET (ET_c) is the crop coefficient technique presented in FAO56 (Allen et al., 1998); with this approach ET_c is estimated using the (average) ET of a reference crop [ET_o (ET_r in this study)] and an adjusting crop coefficient (K_c) for the crop grown. The effect of climate on ET is reflected by the ET_r while the effect of crop growth and development is given by the coefficient K_c.

The K_c values are derived from measured crop characteristics and, thus, vary throughout the season in correspondence to the growth stage of the crop. Crop coefficient curves can be developed as a function of time (Irmak et al., 2013b; Reddy et al., 2015), plant growth stage (Allen et al., 1998; Piccinni et al., 2009), thermal unit or growing degree days (GDD) (Irmak et al., 2013a; Alberta Agriculture and Forestry, 2017b), and leaf area index or canopy cover (Irmak et al., 2013b). While Irmak et al. (2013b) found that different base scales show no significant differences when predicting crop coefficients for soybeans in Nebraska, other studies suggested that GDD-based crop coefficients should be transferable to other locations with different climatic conditions with an assumption that differences in plant development characteristics are related mainly to temperature (Sammis et al., 1985; Irmak et al., 2013a).

The ET_r estimate, on the other hand, is independent of crop type and management practices as it only accounts for climate effects. It is defined as the ET rate from a reference surface of a uniform and actively growing vegetation, not short of water, and having specified height and surface resistance (ASCE, 2005). The two standards for "reference evapotranspiration" are: (1) a short crop with an approximate height of 0.12 m and a daily surface resistance of 70 s/m (similar to clipped grass), and (2) a tall crop with an approximate height of 0.5 m and a daily surface resistance of 45 s/m (similar to full cover alfalfa) (ASCE, 2005).

Reference evapotranspiration models can be generally categorized into temperature-based models (e.g., Blaney-Criddle, Hargreaves-Samani, Hamon, Thornthwaite, Baier-Robertson, and Linacre equations); radiation-based models (e.g., Makkink, Priestley-Taylor, and Turc equations); mass-transfer-based models (e.g., Rohwer and Trabert-Mahringer equations); and combinations of the above modeling approaches (e.g., Penman, Monteith, Kimberly-Penman, and Penman-Monteith equations). Due to the differences in assumptions, data requirements, and climatic conditions in which these ET_r models were developed, they may result in inconsistent values (Grismer et al., 2002; Lu et al., 2005). Thus, several studies attempted to calibrate and validate these models under local conditions. Most of these studies (e.g., Alexandris et al., 2008; Bogawski and Bednorz, 2014; Djaman et al., 2015) calibrated and validated these models against the Penman-Monteith equation, which is the globally recognized and accepted standard equation for estimating ET_r (Allen et al., 1998). The Penman-Monteith equation requires detailed climatic parameters that are not always available in historical weather station records (e.g., relative humidity, wind speed, incoming solar radiation) in Canada. Although relative humidity, wind speed, and solar radiation are now being routinely measured by many Canadian weather stations, only humidity and wind speed data are readily available across the country. Solar radiation measurements have been made by provincial agricultural weather networks in Alberta (Alberta Agriculture and Forestry, 2017a) and Manitoba (Manitoba Agriculture, 2017) over the past decade or so which has recently increased the availability of this important parameter for modeling ET in those specific regions of Canada.

However, it may not be advisable to validate ET models using another model as other studies (Xu and Singh, 2005; Guo et al., 2017) indicated that different ET_r models (including the widely accepted Penman-Monteith model) perform differently in different climatic conditions. Also, when validation is done against measured crop ET, correction factors for crop characteristics and water availability have to be applied.

A number of studies have attempted to validate ET_r models for the different climatic and agricultural conditions in Canada. De Jong and Tugwood (1987) compared different ET_r models for locations across the country and evaluated models against Class A pan evaporation data. Though the authors also estimated actual ET_c, they did not compare the results to measure ET_c. More recently, Maulé et al. (2006) developed ET_r models for the agricultural conditions of the Canadian Prairies using regression against the Penman-Monteith equation, but also did not validate model outputs against measured data. Xing et al. (2008) compared the accuracy of three ET_r models (i.e., Penman-Monteith, Priestley-Taylor, and Penman equations) in estimating ET from a non-irrigated potato crop field in New Brunswick using BREB data. However, there might have been a bias in the comparison as different K_c values were employed for the different models. Moreover, ET_c estimates, which were not adjusted for water availability, were compared to actual measurements, which might have been influenced by soil moisture content. Gervais et al. (2012) compared two ET_r models [i.e., Penman-Monteith model and second generation Prairie Agrometeorological Model (PAMII)] for their performance in estimating ET from various sites in Saskatchewan and Manitoba. Although actual ET_c estimates were used for comparison, they were compared to ET_c measured indirectly from the difference between the change in soil moisture storage and precipitation (soil water balance method), with an assumption that runoff and deep drainage were negligible. Brimelow et al. (2010), however, evaluated the ability of the PAMII to simulate actual daily ET against eddy covariance measurements at a grassland and a cropland site in southern Alberta. In that study, the authors found that the model underestimated ET (i.e., significant negative bias) in both ecosystems (Brimelow et al., 2010), which underscores the need for further ET model comparisons with actual ET measurements on the Canadian Prairies for model and technique refinement. Further, as the Canadian Prairies or the Northern Great Plains in general are vast, it is important to have more studies from different locations comparing models to measurements.

This study was conducted to (1) qualitatively and quantitatively compare a selection of ET_r models and assess their ability to estimate ET from annual crops in the Canadian Prairies with respect to accuracy in comparison to measured ET_c and (2) assess the