A NEW SIMPLER METHOD TO CALCULATE EVAPOTRANSPIRATION

Vasileios Liakos
George Vellidis
Wesley Porter
Crop and Soil Sciences, University of Georgia
Tifton, GA
Andre Torre Neto
Embrapa Instrumentation
São Carlos, Brazil
Dimitris Pavlou
Anna Orfanou
Crop and Soil Sciences, University of Georgia
Tifton, GA

Abstract

Population and economic growth as well as social values have changed the importance of water quality and the environment. Moreover, American water right claims will continue to increase conflicting demand for U.S. water resources. Furthermore, projected climate change – through warming temperature and shifting precipitation patterns – is expected to reduce water supplies and increase water demand. If irrigated agriculture is to survive in this demanding environment, we must use irrigation water efficiently and cost-effectively. Many studies have proved that the calculation of daily evapotranspiration (ET) can estimate the daily water loses from plants and soil. However, despite the huge number of the suggested evapotranspiration models, most of them require high levels of input data. This makes the use of these models very difficult. The purpose of this study was to evaluate a modified Hangreaves – Samani method for estimating evapotranspiration which utilizes readily available weather data and compare the results of this method to the Priestly – Taylor method and the Penman- Monteith method. The two latter methods are considered standard methods for estimating ET but require a larger number of meteorological parameters some of which are not readily available at many weather stations. The rationale for doing this work was to make estimated ET more readily available for ET-based irrigation scheduling tools. The results showed significant differences in evapotranspiration between the original Hangreaves – Samani method and the other two methods. Thus the Hangreaves – Samani method was modified through the use of historical data from seven different weather stations in Georgia. The paper presents the modifications that were made to the Hangreaves – Samani method to make it more accurate for the Southeast and presents results comparing the three methods. The comparison of the evapotranspiration results proved a strong correlation among the new modified Hangreaves – Samani method, the Penman – Monteith method and Priestly – Taylor method. Evapotranspiration results of places far from the ocean where there are no often changes in wind and humidity were more accurate than places near oceanic influences. However evapotranspiration error was very low.

Introduction

Water demands worldwide

Demands on agricultural water supplies are likely to increase over time as alternative nonfarm uses of water continue to grow. Energy-sector growth is expected to significantly increase water demands for an expanding biofuels sector, utility-scale development of solar power, innovation in thermoelectric generating capacity, and commercial oil-shale and deep shale natural gas development. Expansion in these competing water demands, especially with water supply/demand impacts expected with climate change, presents new challenges for agricultural water use and conservation.

While substantial technological innovation has increased the efficiency of irrigated agriculture over the past several decades, significant potential exists for continued improvement. At least half of the irrigated cropland acreage across the United States is still irrigated with less efficient, traditional irrigation application systems. Farmers in most regions are used to having a seemingly unlimited supply of available fresh water and this supports the existence of a growing competition for available fresh water supplies. However, during the last decades ground water has depleting at an alarming rate in many agriculture areas, while the increasing levels of industrial activity demands huge amounts of fresh water. Additionally, the increasing world population makes the problem more intensive because in the future, agriculture will need to produce more food to address the population needs. If irrigated agriculture is the solution to this problem then new irrigation practices and tools should be developed for more efficient water use.

Different decision support tools have been developed and applied in the most intensive agriculture areas in the world. Most of the decision support tools include evapotranspiration (ET) calculations. ET is the simultaneous process of transfer of water to the atmosphere by transpiration and evaporation in a soil-plant system (Rosenberg et al., 1983; Allen et al., 1998; Mavi and Tupper, 2004). During a growing season, water is lost by soil evaporation when crops are small. On the other hand transpiration begins when crops develop enough canopy and cover the soil.

ET calculation

The actual crop ET can be directly measured with lysimeters (Williams and Ayars, 2005; Benli et al.,2006; Miranda et al., 2006), and by eddy covariance method (Aubinet et al., 2000; Wilson et al., 2001; Amayreh and Al-Abed, 2004;Schume et al., 2005; Kosugi and Katsuyama, 2007; Sun et al., 2008; Novick et al., 2009; Scott, 2010). Moreover, the Bowen Ratio Energy Balance System is an alternative way for the measurement of the actual ET (Bowen,1926; Irmak and Irmak, 2008; Irmak et al., 2008, 2010, 2013; Kabenge et al., 2013). Additionally, actual ET has been measured through the use of atmometers (Chen and Robinson, 2009; Irmak et al., 2005; Broner and Law, 1991).

Several ET models have been proposed through the years for areas with different climate characteristics. Allen et al. 1998 stated that ET is affected by weather parameters such as solar radiation, air temperature, wind speed, vapor pressure deficit and crop parameters such as crop type, variety and growth stage. Additionally, irrigation management, soil tillage and weed management can affect ET. For all these reasons the performance of the models vary spatially and temporally. However, adequate estimation of reference ET (ET_o) is of paramount importance in irrigation scheduling.

The existing models which use weather data to calculate ET_o can be classified into 3 categories. The temperature models which are based on temperature data (Thornthwaite, 1948; Doorenbos and Pruitt, 1977), radiation models which utilize solar radiation data (Doorenbos and Pruitt, 1977; Hargreaves and Samani, 1985) and combination models which use several weather parameters (FAO - 56) (Allen et al., 1998). The accuracy of the models has been assessed by several authors. Trajkovic and Kolakovic 2009, after the evaluation of ET_o equations in humid regions stated that the best equations were the Penman Monteith (PM) (FAO - 56) and Turc. The rank of the other equations were Priestley–Taylor (PT), Jensen–Haise, Thornthwaite, and Hargreaves. Martinez and Thepadia (2010) demonstrated that in the absence of regionally-calibrated Turc equation is recommended to estimate ET_o by using measured maximum and minimum air temperature and estimated radiation in Florida. Jensen et al. (1990) reported that among twenty models, the Turc method is ranked second after the Penman–Monteith equation for monthly ET_o estimation. From a cross comparison of 31 reference ET_o methods, Tabari et al. (2011) showed that the five best methods, as compared to the PM model, were the two radiation-based models, the temperature-based Blaney–Criddle, the Hargreaves-M4, and the Snyder pan evaporation based equations. Previously from an evaluation of four reference ET_o models with the least required weather parameters (Makkink, Turc, Priestley–Taylor and Hargreaves) under four climates, Tabari (2010) reported that the Turc method was the best suited model in cold humid and arid climate; and the Hargreaves equation was the most accurate model under humid and semi-arid condition.

There is a high demand from farmers for reliable recommendations and optimum water. A solution to this problem is an understanding of the plant needs through ET. Despite the numerous ET_o models, most of them require high levels of input data. An ET_o method that requires less input data is the Hangreaves Samani (HS) method but this method is not always accurate. To deal with these issues, this paper describes a modified HS method and demonstrates the results of the ET_o comparison resulted from the modified HS, PT and PM (FAO – 56) methods.

Materials and methods

Historical weather data

Weather data was acquired from Georgia Automated Environmental Monitoring Network (GAEMN) for different locations in South and North Georgia, USA since 1997. GAEMN was established in 1991 by the College of Agricultural and Environmental Sciences of the University of Georgia. The objective of the GAEMN is to collect reliable weather information for agricultural and environmental applications. It consists of 83 weather stations around Georgia. Each station monitors air temperature, relative humidity, rainfall, solar radiation, wind speed, wind direction, soil temperature at 2, 4, and 8 inch depths, atmospheric pressure, and soil moisture every 1 second. Data are summarized at 15 minute intervals and at midnight a daily summary is calculated. Weather data are presented on the GAEMN website and are downloadable.

The locations in South Georgia were Arlington, Tifton, Camilla, Donalsonville, Douglas, Dallas and Odum. At the North Georgia there were historical data only for Dallas (Figure 1).

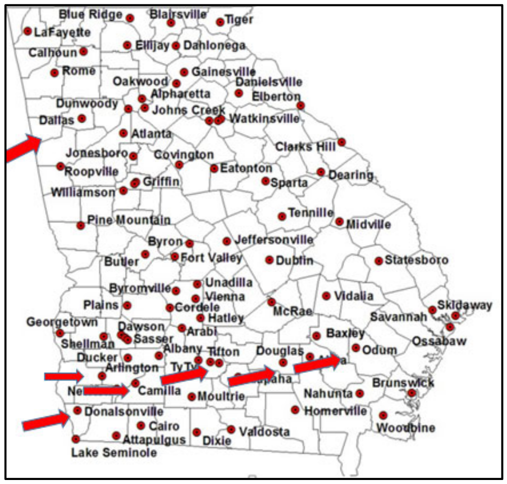

Figure 1. The 83 weather stations in Georgia. The red arrows indicate the research areas.

<u>Penman Monteith (FAO – 56) ET_o</u>

In 1948, Penman combined the energy balance with the mass transfer method and derived an equation to compute the evaporation from an open water surface from standard climatological records of sunshine, temperature, humidity and wind speed. This so-called combination method was further developed by many researchers and extended to cropped surfaces by introducing resistance factors (FAO, 2016).

A consultation of experts and researchers was organized by FAO in May 1990, in collaboration with the International Commission for Irrigation and Drainage and with the World Meteorological Organization, to review the FAO methodologies on crop water requirements and to advise on the revision and update of procedures. The panel of experts recommended the adoption of the Penman-Monteith combination method as a new standard for ET_o and the FAO Penman-Monteith method was developed. The method overcomes shortcomings of the previous FAO Penman method and provides values more consistent with actual crop water use data worldwide (FAO, 2016).

For the calculation of the PM ET_o the equation was:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \quad (6)$$

Where:

ET_o reference evapotranspiration [mm day^{-1}],
R_n net radiation at the crop surface [MJ m^{-2} day^{-1}],
G soil heat flux density [MJ m^{-2} day^{-1}],
T mean daily air temperature at 2 m height [°C],
u_2 wind speed at 2 m height [m s^{-1}],
e_s saturation vapour pressure [kPa],
e_a actual vapour pressure [kPa],
e_s - e_a saturation vapour pressure deficit [kPa],

D slope vapour pressure curve [kPa °C^{-1}],
g psychrometric constant [kPa °C^{-1}].

Priestley –Taylor (PT) ET_o

GAEMN, along with the weather data also provides daily ET_o data. These data are calculated with a modified version of the PT equation which was developed to eliminate the need for input data other than radiation. The PT equation is below, however in the current work the ET_o data were obtained directly from the GAEMN website:

$$LE = \alpha((\Delta(R_n - G))/(\Delta+\gamma)) + \beta$$

Where:
α & β calibration factors assuming values of 1.26 and 0 respectively,
Δ slope vapour pressure curve [kPa °C^{-1}],
R_n net radiation at the crop surface [MJ m^{-2} day^{-1}],
G soil heat flux density [MJ m-2 day-1],
g psychrometric constant [kPa °C^{-1}].

Modified Hangreaves-Samani (HS) ET_o

Hargreaves was using precise lysimeters and weather data over a period of eight years. In 1972 an equation was developed to calculate evapotraspiration by using solar radiation and temperature data. After 10 years the equation was modified and a clearness index replaced the requirements for solar radiation data. However in 1985 the equation took the final form:

$$ET_O = 0.0135\ K_T\,(T+17.78)(T_{max} - T_{min})^{0.5}R_a$$

Where: K_T assumes the value of 0.17,
R_a extraterrestrial radiation [mm day^{-1}],
T average daily temperature [°C],
T_{max} maximum daily temperature [°C],
T_{min} minimum daily temperature [°C].

Since the HS method was originally calibrated for the semi-arid conditions of California, and does not explicitly account for relative humidity, it has been observed that it can overestimate ET_o in humid regions such as the Southeastern US (Amatya et al. 1995 and Lu et al. 2005). For validation purposes the authors applied the original HS equation on the historical data of the places mentioned at a previous section. The results confirmed the results from Lu et al. 2006 and Amataya et al 1995. Thus the authors modified the HS equation based on the historical data. Specifically the ET_o was calculated for each of the seven places by the original HS equation and PM (FAO – 56) while the ET_o based on the PT were downloaded from the GAEMN website. Continuously the HS equation was empirically modified so was the resulted ET_o to match with resulted ET_o from the other two methods. The HS equation remained the same. However the clearance index was modified. Particularly, the clearance index is computed by a function which is based on the ET_o provided from GAEMN and differs among the months (Table 1). This work is focused on the ET_o calculation for the months of April to October because this is the typical production time frame for most major row crops produced in the Southeast and farmers are interested in knowing the ET_o during these months.

Table 1. The clearance index equations that the new HS method use for each month

Month	Clearance Index
April	$(ET_{(GAEMN)}*0.23)/6.57$
May	$(ET_{(GAEMN)}*0.2)/6.57$
June	$(ET_{(GAEMN)}*0.185)/6.57$
July	$(ET_{(GAEMN)}*0.185)/6.57$
August	$(ET_{(GAEMN)}*0.23)/6.57$
September	$(ET_{(GAEMN)}*0.25)/6.57$
October	$(ET_{(GAEMN)}*0.32)/6.57$

Data analysis
The analysis of the data was a very important point for the research in order to validate the new clearance index. The ET_o calculated from the new HS method was compared with the ET_o calculated from PM (FAO – 56) and PT methods. The comparison analysis was done in Excel software by using the R^2 method and the root-mean-square error (RMSE) method. When the coefficient of determination R^2 is close to 1.0 then most of the variation of the observed values can be explained by the model. The root mean square error, RMSE characterizes the variance of the errors; the smaller RMSE the better is the model's performance.

Results and discussion

Data ET patterns
Figure 2 presents graphs which were selected randomly. The graphs show the comparison of the ET_o calculated from the three different methods during the 1997 growing season. The graphs show clearly that the data of the three methods follow the same pattern while there are very minor differences present in daily ET.

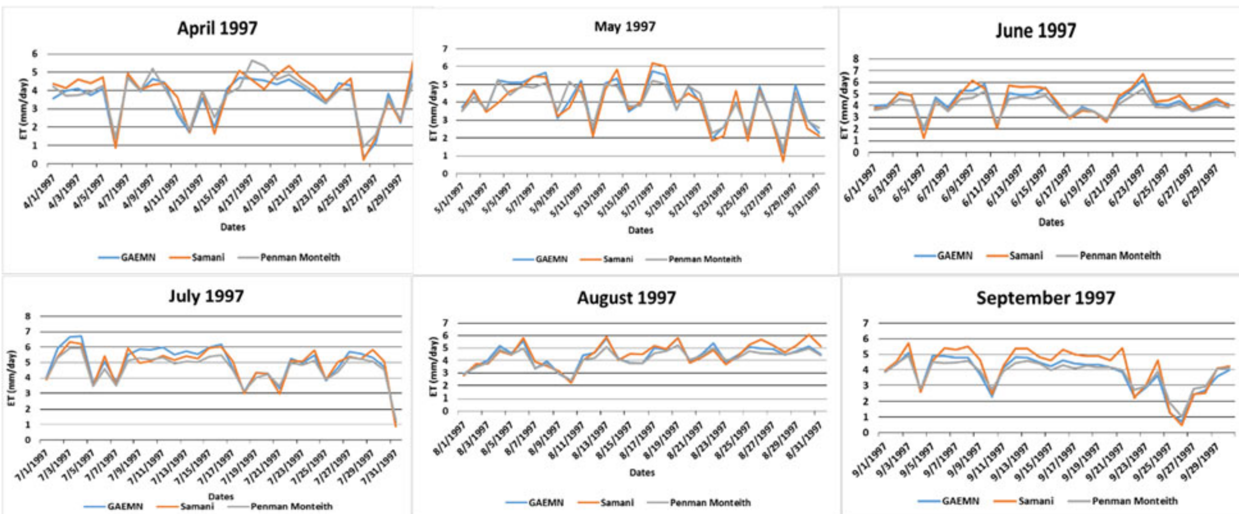

Figure 2. Graphs show the pattern of the ET_o data. The blue line shows the results from the PT method, the orange from the HS method and the blue from the PM (FAO -56) method

Comparison of the ET computed with the three methods
Table 2 demonstrates the average results of the comparison of the ET_o among the three methods for each place. RMSE index expressed in in/day and shows the ET_o error of the HS method compared to the other methods.

Table 2. R^2 and RMSE as resulted from the data analysis

Location	mHS vs PT		mHS vs PM	
	R^2	RMSE	R^2	RMSE
Arlington	0.92	0.018	0.84	0.027
Camilla	0.93	0.019	0.9	0.025
Dallas	0.94	0.016	0.92	0.017
Donalsonville	0.91	0.02	0.85	0.025
Douglas	0.93	0.018	0.85	0.029
Odum	0.92	0.017	0.9	0.02
Tifton	0.93	0.019	0.84	0.024

Table 2 shows that the new modified HS method works well in all the places included in this research. The R^2 is close to 1 which means that there is strong correlation between the examined methods while the ET_o errors are very low. However the best results were calculated from the Dallas station. Dallas is located in northwest Georgia and it was the only northern place which was included in the current work. The better correlation at the Dallas site could be due to Dallas being further from the sea than the other places. HS method does not take into consideration the wind speed and the humidity. These two parameters have a larger impact at the places closer to ocean rather than places that are more land locked.

Despite the fact that HS method does not take into consideration wind speed and humidity it was noted that the variability of the RMSE index was not high through the years. Table 3 shows the R^2 and the ET_o errors for Arlington which is located in southern Georgia.

Table 3. R^2 and RMSE index for Arlington from 1997 to 2009

Year	mHS vs PT		mHS vs PM	
	R^2	RMSE	R^2	RMSE
1997	0.92	0.019	0.87	0.024
1998	0.94	0.018	0.9	0.024
1999	0.93	0.02	0.87	0.026
2000	0.93	0.019	0.77	0.034
2001	0.91	0.018	0.8	0.027
2002	0.93	0.018	0.85	0.028
2003	0.93	0.016	0.82	0.027
2004	0.94	0.016	0.88	0.022
2005	0.91	0.018	0.74	0.031
2006	0.93	0.018	0.87	0.026
2007	0.9	0.016	0.75	0.035
2008	0.95	0.017	0.86	0.028
2009	0.94	0.018	0.9	0.024

Based on the results of the comparison of the ET_o calculated from the three methods the differences in ET_o between the new modified HS method and the PT method varied from 0.016 in/day to 0.02 in/day. While the difference in ET_o between the new modified HS method and the PM (FAO – 56) method is ranged from 0.22 in/day to 0.035 in/day. However, for more accurate predictions, the ET_o error can be considered in the ET_o calculations because the ET_o error is consistent (HS – PT) through the years

Besides the fact that the PM (FAO-56) method is considered very accurate the authors used the PT method to modify the HS method. This happened because GAEMN provides ET_o data calculated with the PT method. The concept of this work is to simplify the use of the HS method and to make it more accurate for the State of Georgia. Potential users of the new HS method are farmers in Georgia who have temperature sensors in their field. The recorded temperatures in the fields and the daily ET_o from GAEMN are enough data in order for farmers to predict the daily reference ET_o of their fields. Moreover the new HS method can be used by the SmartIrrigationApps which use weather data (including ET_o) to calculate the daily soil water deficit.

Conclusions

ET is a very important factor in agriculture and especially in irrigation scheduling. There are many ways to compute ET_o. The most common way is the use of models. Several studies have evaluated the existing models from different regions. However there are many factors that affect ET, thus the results of the models vary spatially from region to region. The best model is the PM (FAO – 56) but it requires a lot of input data. The need for simple and accurate methods led the author to modify the HS method. The new modified method requires temperature and ET_o data which are easily available from GAEMN. The use of historical weather data from seven places around Georgia proved that the ET computed with the new HS method is strongly correlated with the ET_o computed with the other two methods. However differences in ET_o were found between the northern and southern regions of Georgia. Specifically, the ET_o results from the northern region were more accurate than the ET_o in the southern region of Georgia. This happened because the wind and humidity change very often during the day. Finally, the comparison of the ET_o error through the years showed that the error does not vary, thus the computed ET_o error can be used to calculate the ET_o accurately.

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