Generalized Calibration of the Hargreaves Equation for Evapotranspiration under Different Climate Conditions

Jignesh PATEL[1], Himanshu PATEL[1] and Chetan BHATT[2]

[1]Nirma University, Ahmedabad, India; [2]Vishwakarma Government Engineering College, Chandkheda, Ahmedabad, India

Abstract

Patel J., Patel H., Bhatt C. (2014): **Generalized calibration of the Hargreaves equation for evapotranspiration under different climate conditions**. Soil & Water Res., **9**: 83–89.

Accurate estimation of evapotranspiration (ETo) is a key factor in weather-based irrigation scheduling methods. To estimate ETo using the Hargreaves equation, just the data on the minimum and maximum temperature and solar radiation are required. However, this procedure cannot offer consistent accuracy for different climate conditions. To attain the accuracy, calibration of the equation constants (C_H and E_H) for different climate conditions have successfully been attempted by many researchers. Because these calibration procedures are lengthy and location-specific, there is a need of a generalized calibration method to make the Hargreaves equation more pertinent and effective. In this paper, fuzzy logic based calibration method for the Hargreaves equation is proposed and validated. The fuzzy inference system is developed to compute appropriate values of the constants C_H and E_H on the basis of past data on humidity and wind velocity of a selected location. The underlying relationship between weather conditions and the best values of the constants C_H and E_H are used to establish a fuzzy rule base. The performance of the method is checked at eight geographically different locations of India with diverse climate conditions. The Mean Absolute Error (MAE) in ETo values estimated by the calibrated modified Hargreaves equation and the Penman-Monteith (PM) equation is in the range of 0.3220–1.0325. It is far more lower than if the error is calculated using the original Hargreaves equation. It confirms the correctness of the calibration method for different climate conditions.

Keywords: accurate estimation; fuzzy logic; irrigation scheduling

Irrigation scheduling became very significant in recent past due to ever decreasing water resources and increasing demand for agricultural productivity (Playán & Mateos 2004; Fraiture & Wichelns 2010). Three major approaches were found in the literature for irrigation scheduling. These are soil-based, plant-based, and weather-based methods (Krugera *et al.* 1999; Hanson *et al.* 2000; Sharon & Bravdo 1998; Goldhamer & Fereres 2004; Dukes & Scholberg 2005; Andales *et al.* 2011; CROPWAT 2012). Of these three approaches, the weather-based approach is gaining attention among research communities as it does not require costly and specific sensors for the measurement of e.g. soil moisture, canopy temperature, leaf thickness, etc. (Jones 2004). On the other hand, weather-based methods depend on accurate data of reference evapotranspiration rate (ETo) (Naadimuthu *et al.* 1999; Leib *et al*. 2001; Fortes *et al*. 2005; Steele *et al.* 2010). Reference evapotranspiration rate depends on climate condition. Several attempts were made to establish analytical relationship between meteorological data and ETo. Comparison between ETo values measured by lysimeter with those calculated by eight different equations under humid condition is well presented in Yoder *et al.* 2005. The comparison shows the most accurate performance by the Penman-Monteith equation and the worst by the Hargreaves equation under humid condition. Several more such comparative studies between various models of ETo under different climate conditions were found in literature (Alexandris *et al.* 2008; Martinez & Thepadia 2010).

In spite of lower accuracy, the Hargreaves equation was found to be more suitable in actual implementation to estimate evapotranspiration because it needs minimum weather data. These are maximum day temperature (T_{max}), minimum day temperature (T_{min}), and extraterrestrial solar radiation (R_a). These data are normally available at most of the weather stations. The equation is as follows (Hargreaves & Allen 2003):

$$\text{ETo} = C_H(T_{max} - T_{min})^{E_H}(T_{mean} + 17.8)R_a \qquad (1)$$

Under the nominal climate condition, the values of the constants C_H and E_H are proposed as 0.0023 and 0.5, respectively. Limitation of the Hargreaves equation is its inability to estimate accurate ETo under extreme weather conditions. It overestimates under hot and humid conditions (Subburayan *et al.* 2011). Error in the ETo estimation from the Hargreaves equation under non-ideal climate condition is reported by many authors under different climate conditions (Hargreaves 1989; Jensen *et al.* 1997). As presented in the chronological evolution of Hargreaves equation (Hargreaves & Allen 2003); it is reported that the effect of humidity, cloudy condition, and wind gust is indirectly considered under the difference of maximum and minimum temperature. As these effects are not considered explicitly, the Hargreaves equation does not provide accurate estimates of ETo in extreme weather. The calibration of C_H and E_H for different climate conditions is an accepted approach to accomplish an error-free estimation from the Hargreaves equation. A large number of attempts on calibration of the Hargreaves equation were found in the literature. The calibration of C_H and E_H was presented for different climate conditions like arid-cold (Tabari & Talaee 2011), dry-hot (Vanderlinden *et al.* 2004), arid-semiarid (Mohawesh 2011), and different locations like high and low elevation (Ravazzani *et al.* 2012) and coastal and inland (Mendicino & Senatore 2012).

The calibration methods published are quite lengthy and valid for confined location only. Further, there is a wide variation in the climate condition of a single location during different seasons of a year. Localized calibration is not a convenient approach. There is a need of a generalized and simplified method of calibration of the Hargreaves equation. A fuzzy logic based approach is presented to obtain appropriate values of C_H and E_H used in the Hargreaves equation, to improve the accuracy of evapotranspiration estimation. A fuzzy inference system is developed to correlate C_H and E_H values with past data on humidity, wind velocity, and temperature. The proposed generalized approach eliminates the need of location specific calibration methods. Development of the fuzzy ruled base is discussed further on in more details.

Fuzzy logic based calibration method. Very soon after the first proposal of the fuzzy set and theory (Zadeh 1965), it became a very useful tool for modelling, analyzing, and controlling of partially known or under-modelled systems. The Hargreaves equation is under-modelled as it does not explicitly consider humidity and wind velocity. Therefore fuzzy logic is a suitable approach for generalized calibration of C_H and E_H values of the Hargreaves equation. Fuzzy Inference System (FIS) to suggest a modified value of Hargreaves constants C_H and E_H is developed and verified. The conceptual diagram of the proposed scheme is presented in Figure 1. More details on fuzzification and defuzzification are presented subsequently.

Fuzzification. Fuzzy sets are a basic building block of the fuzzy theory. It contains Degree of Membership (DoM) of variables of interest. A fuzzy set is defined by the following expression:

$$D = \{(x, \mu_D(x) | x \in X\} \qquad (2)$$

where:

$\mu_D(x) \in [0, 1]$ – Membership Function (MF) of fuzzy set D
X – universal set
x – element in X
D – fuzzy subset in X

Degree of membership (DoM) for any set ranges from 0 to 1. The value 1 represents 100% membership, while the value 0 represents 0% membership.

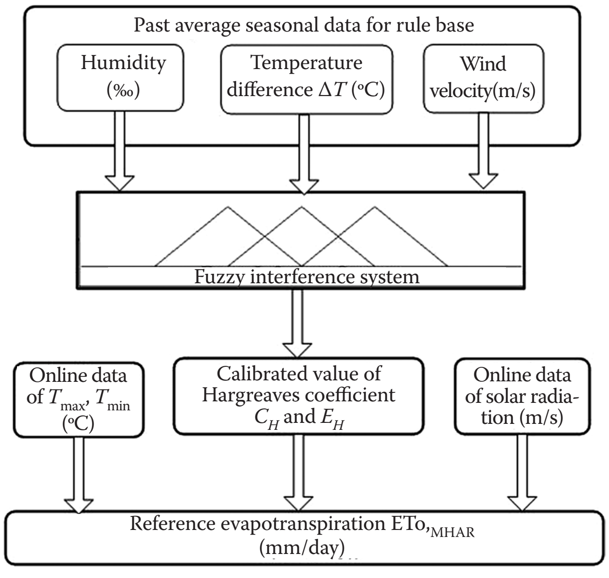
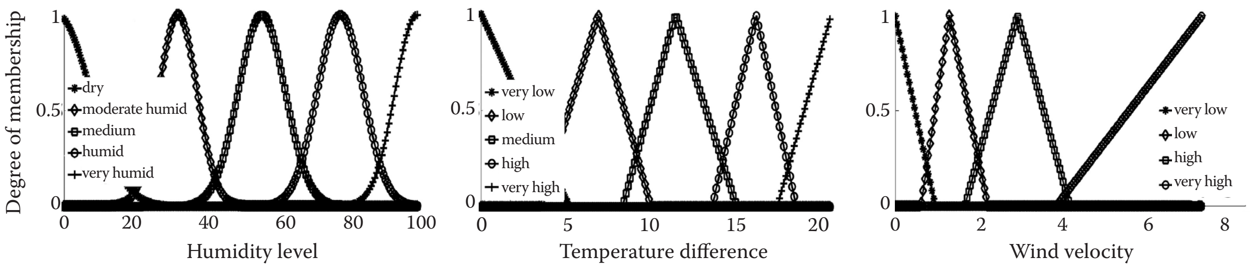


Figure 1. Conceptual diagram of fuzzy based calibration



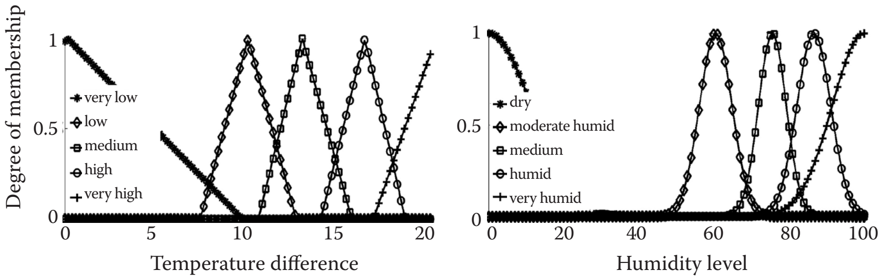


Figure 2. Membership Function (MF) of input variables – humidity, temperature difference, and wind velocity

MF is a curve that defines how each point in the input space is mapped to a membership value between 0 and 1. There are many forms of MFs such as Triangular, Trapezoidal, and Gaussian, etc. Selection of appropriate MF is based on the influence of the input variable on the output. Triangular and Gaussian type MFs are used for FIS for C_H and E_H as shown in Figures 2 and 3.

The if-then rule statements are used to build fuzzy logic. The structure of the single if-then rule is as follows:

If x is A then z is B

where:

A, B – input and output representation

More generally, the rules have more than one premise, that is:

R_i: if x_i is A_i and y_i is B_i then z_i is C_i

where:

A_i, B_i, C_i – fuzzy sets for the inputs (x_i and y_i) and the output z_i for the i^{th} rule (R_i)

Membership values of sets A_i, B_i, and C_i are the linguistic terms such as very low, low, medium, high, very high, etc. (Xu *et al.* 2002).

In FIS, three conditions are used in the if-part of the rules for C_H (humidity (5 levels), temperature difference (5 levels), and wind velocity (4 levels)), while two variables (humidity (5 levels) and temperature difference (5 levels)) are used for E_H. Fuzzy rule base is developed on the basis of the influence of these variables on C_H and E_H values. Research literature on the Hargreaves equation was referred to develop these equations. 100 rules for C_H and 25 rules for E_H have been developed. The rules are presented in Table 1.

Defuzzification. An output from FIS is obtained by defuzzification. Defuzzification methods such as the Center of Gravity (CoG), mean of maximum, first of maximum, etc. are well documented in literature. The present work uses the CoG method as it is considered one of the precise methods for defuzzification. The method is briefly explained by the Eq. (3) (Xu *et al.* 2002).

$$G = \frac{\sum_{i=1}^{n} a_i \times c_i}{\sum_{i=1}^{n} a_i} \qquad (3)$$

where:

a_i – areas of the truncated triangular under the aggregated functions

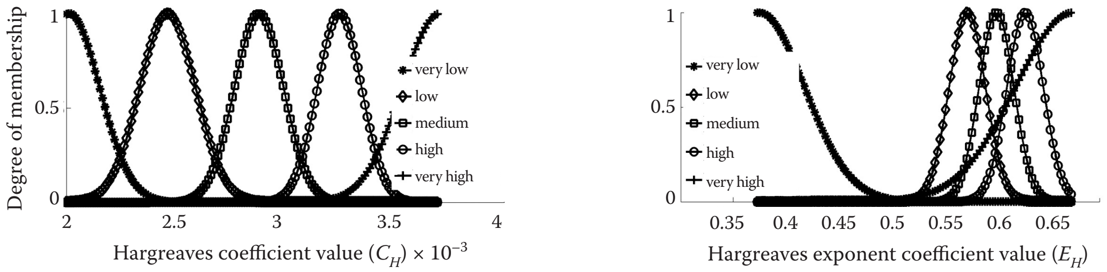


Figure 3. Membership Function (MF) of output variables C_H and E_H

Table 1. Fuzzy rules to evaluate the C_H and E_H values

Rule No.	Rule
C_H values	
1	if (environment condition is dry) and (temperature difference is very low) and (wind velocity is very low) then (C_H value is low)
2	if (environment condition is dry) and (temperature difference is very low) and (wind velocity is low) then (C_H value is medium)
3	if (environment condition is dry) and (temperature difference is very low) and (wind velocity is low) then (C_H value is high)
50	if (environment condition is medium-humid) and (temperature difference is medium) and (wind velocity is low) then (C_H value is medium)
99	if (environment condition is medium-humid) and (temperature difference is very high) and (wind velocity is high) then (C_H value is medium)
100	if (environment condition is medium-humid) and (temperature difference is very high) and (wind velocity is high) then (C_H value is high)
E_H values	
1	if (environment condition is dry) and (temperature difference is very low) then (E_H value is low)
2	if (environment condition is dry) and (temperature difference is low) then (E_H value is low)
15	if (environment condition is medium) and (temperature difference is medium) then (E_H value is high)
25	if (environment condition is very humid) and (temperature difference is medium) then (E_H value is very high)

C_i – coordinates of their centres on the x-axis
n – number of areas
G – centroid of the aggregated area

The location of CoG determines the value of output. In the present application these represent Hargreaves coefficient C_H and E_H.

RESULTS

To verify its generalized nature, the proposed method is validated for eight different locations of India. The locations are selected such that each of them represents different climate conditions, altitude, and vicinity to water bodies. The locations considered are Agra (hot and humid), Ahmedabad (hot and dry), Ajmer (hot and semi-arid), Mumbai (humid), Chennai (hot, humid, and costal), New Delhi (hot, dry, and inland), Bhuj (arid and dry), and Jammu (cold and dry). Monthly average data of the minimum temperature, maximum temperature, humidity, solar radiation, wind velocity, and humidity of the locations are taken from CLIMWAT (Martin 1993). The past one year data on humidity, wind velocity, and temperature difference are used to typify the location. Once the location is classified, the proposed

Table 2. Error analysis for the original Hargreaves (HAR) and modified Hargreaves (MHAR) equations in comparison to the Penman-Monteith (PM) equation

Location	Mean Absolute Error (MAE)		Mean Absolute Percentage Error (MAPE)		Systematic Estimated Error (SEE)	
	HAR	MHAR	HAR	MHAR	HAR	MHAR
Ajmer	1.9210	0.8601	3.5575	1.5929	2.5235	1.0801
Mumbai	1.8192	0.5516	3.7744	1.1444	1.9530	0.6907
Madras	1.7200	0.4335	3.3206	0.8369	1.8279	0.5402
New Delhi	2.5489	0.8055	4.2061	1.3293	3.0004	1.1256
Jammu	1.3591	0.3220	3.2207	0.763	1.5369	0.4265
Bhuj	2.9050	1.0325	4.2534	1.5118	3.3653	1.5856
Ahmadabad	2.5508	0.7030	3.9609	1.0917	2.9745	0.9274
Agra	1.0284	0.4783	2.3167	1.0777	1.3868	0.5888

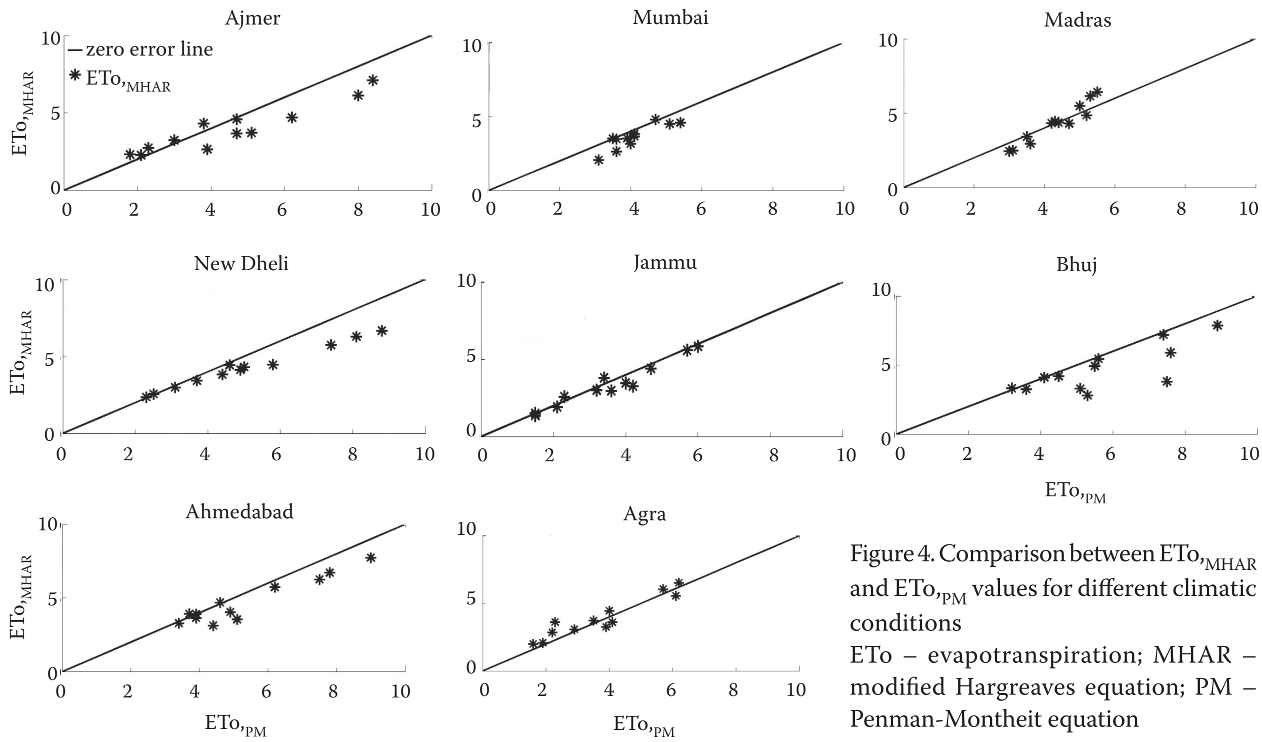


Figure 4. Comparison between ETo,$_{MHAR}$ and ETo,$_{PM}$ values for different climatic conditions

ETo – evapotranspiration; MHAR – modified Hargreaves equation; PM – Penman-Montheit equation

fuzzy based calibration method evaluates the values of C_H and E_H. Evapotranspiration based on the modified Hargreaves equation (ETo,$_{MHAR}$) is calculated. Similar climate data are used for calculation of ETo using the Penman-Monteith equation (ETo,$_{PM}$) and the original Hargreaves equation (ETo,$_{HAR}$). Comparison between ETo,$_{MHAR}$ and ETo,$_{PM}$ for one-year data is presented in Figure 3. It shows that a majority of ETo,$_{MHAR}$ points is located near to zero error lines of ETo,$_{PM.}$ Figure 4 shows the performance of the modified Hargreaves equation in comparison with the original Hargreaves equation on overall data of different locations. Statistical analysis of the error in ETo calculated using the original and the modified Hargreaves equation considering the Penman-Monteith equation for standard is presented in Table 2.

DISCUSSION

The practical limitation concerning the non-availability of current weather data like humidity, wind velocity etc. is well thought-out in the proposed fuzzy rule based calibration method. The calibration of the constants C_H and E_H needs only past data on humidity, temperature difference, and wind velocity. Once the C_H and E_H are established for the concerned location, then ETo estimation requires only current air temperature values. The above result confirms better accuracy of ETo estimation at all eight locations. It also suggests the generalized nature of the calibration method as all the eight locations under consideration have different climate conditions and geographic location. The proposed fuzzy rule based calibration method helps to get rid of lengthy and localized calibration methods required in the Hargreaves equation. Consistency in accuracy of round the year for individual location suggests that the proposed calibration method takes care of seasonal variation of the particular location. This is very essential as the majority of the subcontinent loca-

(a)

(b)

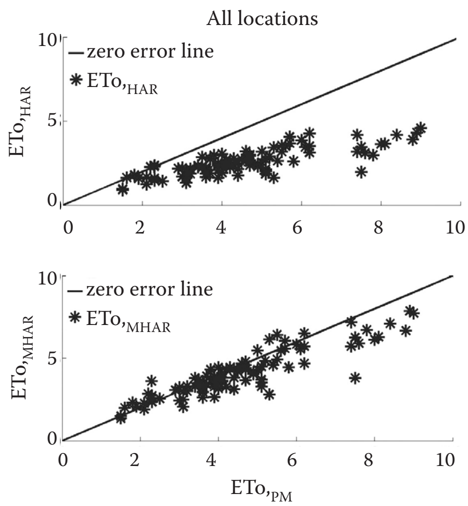


Figure 5. Comparisons with evapotranspiration (ETo) estimation using the Penman-Monteith equation: (a) – original Hargreaves equation, (b) – modified Hargreaves equation with calibrated C_H and E_H values

tions undergo a vast variation in climatic conditions during a year.

CONCLUSION

A fuzzy based generalized calibration method for the Hargreaves equation is developed. As this method needs only past weather data to characterize the location, it has a potential to be used for the locations where only current air temperature data are available. The method is verified at eight locations of India with diverse climate conditions and geographic locations. The results are presented in the form of comparison of evapotranspiration evaluated using the Penman-Monteith equation, original Hargreaves equation, and modified Hargreaves equation. The result confirms better accuracy with the modified Hargreaves equation compared to the original Hargreaves equation. The proposed calibration method provides a successful solution of ever persisted problem of inaccuracy of the Hargreaves equation and development of the location specific calibration method. It also takes into consideration a wide variation in the climate conditions of the specific location during a year and thus it provides better accuracy than location-specific calibration methods which are based on average values of C_H and E_H.

References

Alexandris S., Stricvic R., Petovic S. (2008): Comparative analysis of reference evapotranspiration from the surface of rainfed grass from cental Serbia, calculated by six empirical metods against Penman-Montieth formula. European Water, **21/22**: 17–28.

Andales A.A., Chávez J.L., Bauder T.A. (2011): Irrigation Scheduling: The Water Balance Approach. Colorado State University, Fort Collins.

CROPWAT (2012): CROPWAT. Available at http://www.fao.org/nr/water/infores_databases_cropwat.html (accessed March 10, 2012).

Dukes M.D., Scholberg J.M. (2005): Soil moisture controlled subsurface drip irrigation on sandy soils. Applied Engineering in Agriculture, **21**: 89–101.

Fortes P., Platonov A., Pereira L. (2005): GISAREG – A GIS based irrigation scheduling simulation model to support improved water use. Agricultural Water Management, **77**: 159–179.

Fraiture C.D., Wichelns D. (2010): Satisfying future water demands for agriculture. Agricultural Water Management, **97**: 502–511.

Goldhamer D.A., Fereres E. (2004): Irrigation scheduling of almond trees with trunk diameter sensors. Irrigation Science, **23**: 11–19.

Hanson B.R., Orloff S., Peters D. (2000): Monitoring soil moisture helps refine irrigation management. California Agriculture, **54**: 38–42.

Hargreaves G. (1989): Accuracy of estimated reference crop evapotranspiration. Journal of Irrigation and Drainage Engineering, **115**: 1000–1007.

Hargreaves G.H., Allen R.G. (2003): History and evaluation of hargreaves evapotranspiration equation. Journal of Irrigation and Drainage Engineering, **129**: 53–63.

Jensen D.T., Hargreaves G.H., Temesgen B., Allan R.G. (1997): Computation of ETo under nonideal condition. Journal of Irrigation and Drainage Engineering, **123**: 394–400.

Jones H.G. (2004): Irrigation scheduling: advantages and pitfalls of plant-based methods. Journal of Experimental Botany, **55**: 2427–2436.

Krugera E., Schmidta G., Bruckner U. (1999). Scheduling strawberry irrigation based upon tensiometer measurement and a climatic water balance model. Scientia Horticulturae, **81**: 409–424.

Leib B.G., Elliott T.V., Matthews G. (2001): WISE: a web-linked and producer oriented program for irrigation scheduling. Computers and Electronics in Agriculture, **33**: 1–6.

Martin S. (1993): CLIMWAT for CROPWAT: A climatic database for irrigation planning and management. FAO Irrigation and Drainage Paper No. 116. FAO, Rome.

Martinez C.J., Thepadia M. (2010): Estimating reference evapotranspiration with minimum data in Florida. Journal of Irrigation and Drainage Engineering, **136**: 494–501.

Mendicino G., Senatore A. (2012): Regionalization of the Hargreaves coefficient for the assesment of distributed reference evapotranspiration in Southern Italy. Journal of Irrigation and Drainage Engineering, **139**: 50–55.

Mohawesh O.E. (2011): Evaluation of evapotranspiration models for estimating daily reference evapotranspiration in arid and semiarid environments. Plant Soil and Environment, **57**: 145–152.

Naadimuthu G., Raju K.S., Lee E.S. (1999): A heuristic dynamic optimization algorithm for irrigation scheduling. Mathematical and Computer Modelling, **30**: 169–183.

Playán E., Mateos L. (2004): Modernization and optimization of irrigation systems to increase water productivity. In: Proc. 4th Int. Crop Science Congress. Brisbane, 1–13.

Ravazzani G., Corbari C., Morella S., Gianoli P., Mancini M. (2012): Modified Hargreaves-Samani equation for the assessment of reference evapotranspiration in Alpine River Basins. Journal of Irrigation and Drainage Engineering, **138**: 592–599.

Sharon Y., Bravdo B. (1998): Automated orchad irrigation based on monitoring tugor potential with leaf sensor. International Water and Irrigation Review, **18**: 14–19.

Steele D.D., Scherer T.F., Hopkins D.G., Tuscherer S., Wright J. (2010): Spreadsheet implementation of irrigation scheduling by the checkbook method for North Dakota and Minnesota. Applied Engineering in Agriculture, **26**: 983–995.

Subburayan S., Murugappan A., Mohan S. (2011): Modified Hargreaves equation for estimation of ETo in a hot and humid location in Tamilnadu State, India. International Journal of Engineering Science and Technology, **3**: 592–600.

Tabari H., Talaee P.H. (2011): Local calibration of the Hargreaves and Priestley-Taylor equations for estimating reference evapotranspiration in arid and cold climates of Iran based on the Penman-Monteith Model. Journal of Hydrologic Engineering, **16**: 837–845.

Vanderlinden K., Giráldez J.V., Meirvenne M.V. (2004): Assessing reference evapotranspiration by the Hargreaves method in Southern Spain. Journal of Irrigation and Drainage Engineering, **130**: 184–191.

Xu B., Dale D.S., Huang Y. (2002): Cotton color classification by fuzzy logic. Textile Research Journal, **72**: 504–509.

Yoder R.E., Odhiambo L.O., Wright W.C. (2005): Evalution of methods for estimating daily reference crop evaporanspiration at a site in the humid southeast United States. Applied Engineering in Agriculture, **21**: 197–202.

Zadeh L. (1965): Fuzzy sets. Informatioion and Control, **8**: 338–353.

Received for publication May 6, 2013
Accepted after corrections October 2, 2013

Corresponding author:

Assoc. Prof Jignesh Patel, Nirma University, 382481 Ahmedabad; India; e-mail: jbpatel@nirmauni.ac.in