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Hargreaves Equation as an All-Season Simulator of Daily FAO-56 Penman-Monteith ETo

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Abstract: This work showed the Hargreaves equation (HG) can be modified into a highly efficient computational replacement for the FAO-56 Penman-Monteith equation and its auxiliary functions for the computation of daily reference evapotranspiration (ETo) estimation when only available data are daily temperature data. By modifying all the constants (i.e., '0.0023', '0.5' and '17.8') in HG and adding a new constant, a modified HG (HG1234) gave almost identical estimates of daily ETo as FPM, with modified coefficient of efficiency, E_1 = 0.99, r^2 = 1.00, and MAE of 0.00 mm/d for a weather station in Accra, Ghana. HG1234 and ten other less drastic modifications of HG were compared against FPM at simulated average wind speeds, u_2, of 0.5 m/s, 2.0 m/s and 4.0 m/s for daily estimates of ETo. In general the uncalibrated HG predicted FPM with very low E_1 at u_2 other than the global average of 2 m/s, and the more drastic the modification of HG the higher its efficiency at simulating FPM ETo at all wind velocities. Thus although HG was not originally developed for daily ETo estimation, modifying it to HG1234 can turn it into a very efficient and much faster simulator of FPM daily ETo estimation that would be very useful in applications, such as areal ETo estimation research using satellite images, where fast and frequent re-evaluations of FPM ETo for millions of points are necessary.

Keywords: calibration; coefficient of efficiency; evaporation; reference evapotranspiration; temperature; water; weather station; wind speed

1. Introduction

The FAO-56 Penman-Monteith equation (FPM) is the most widely recommended equation for daily reference grass evapotranspiration (ETo) computations from meteorological data (Allen *et al*., 1998a, ASCE-EWRI, 2005). In addition to temperature data, FPM requires humidity, wind speed and radiation data which when not available for a particular weather station, are usually estimated from several temperature-based empirical functions. These auxiliary computations to estimate missing data make FPM more cumbersome to use than simpler empirical equations such as the Hargreaves equation (HG) which requires only maximum and minimum temperature (Hargreaves *et al*., 1985; Hargreaves & Allen, 2003).

Although HG is often used as a simple method of avoiding the involved computations of FPM, using it without local calibration and for daily time steps may result in very misleading ETo estimates. Because HG is an empirical equation, it can be used to obtain reliable ETo estimates only after being calibrated with local ETo data – a very rare data for many parts of the world. In addition calibrated HG is usually recommended only for minimum estimation time intervals that are much longer than one day.

The purpose of this study was to develop a method for correctly using HG as a mathematical alternative to the usual FPM daily ETo estimation computations when the only available data are those of temperature. In the absence of local lysimeter daily ETo data HG can be calibrated for local use by means of secondary FPM ETo data. For the same ETo data various modifications of HG can be developed based on which parameters are allowed to vary when HG is optimized against FPM.

HG modifications in the literature include modifying the "0.0023" coefficient through a linear regression equation with or without a constant term (Fooladmand & Haghighat, 2007; Razzaghi & Sepaskhah, 2012; Mohawesh & Talozi, 2012; Wang *et al*., 2011; Allen *et al*., 1998).

Others include adjusting two parameters (Droogers and Allen, 2002) or all the parameters that could be changed in the HG equation (Allen, 1993), or the "0.5" exponent (Trajkovic, 2007). The objective of this study was to determine which of eleven different types of HG could serve as the most accurate computationally simple alternative to FPM for daily ETo estimation for a weather station in Accra, Ghana.

Because wrong ETo estimates can be financially and environmentally disastrous, the computational challenges associated with the use of FPM do not justify using simpler equations in a risky way. This study is part of ongoing research to develop less computationally intensive equations for computing FPM daily ETo estimates when only temperature data are available. The main objective of this study was to determine the feasibility of modifying HG to compute daily ETo estimates that are almost identical to those of FPM for all seasons of the year for a weather station in Accra, Ghana.

Although attempts to simplify the computation of FPM ETo for minimal data situations have been reported in the literature (e.g., Kra, 2010; ElNesr & Alazba, 2012; Valiantzas, 2006), the advantage of a modified HG as a simplification of FPM over the other simplifications is that HG, been better-known, has a better chance of being adopted in practice.

It is expected that the use of the results of this study would promote more efficient management of water by making it easier to compute FPM-like daily ETo estimates where only minimal data are available, through the use of the described modified Hargreaves equation. The computational speedups realized from using the modified HG would benefit computer applications where ETo is required to be recomputed very frequently, such as in areal estimation of actual evapotranspiration using applications such as METRIC and SEBAL (Allen *et al*., 2007). It would also make it easier to compute more realistic daily ETo estimates for pedagogical purposes.

The hypothesis for this study is that because the equations used by both FPM and HG for temperature data situations are all functions of temperature it must be possible to modify HG in such a way that it computes essentially the same ETo estimates as FPM.

2. Method

The collective name of HGX is given to all the modified HG versions used in this study, where the 'X' is replaced by numerals to identify individual modifications as described below. Following Legates and McCabe (1999) the HGX were evaluated using the far more stringent measure of model performance, the modified coefficient of efficiency, E_1, rather than r^2. The method used to determine the best modification of HG was:

1. Develop ten modifications of HG that differ by the parameters to be modified during calibration;
2. Calibrate each HGX against FPM for a particular set of data (average 1998-2006 data) by optimizing the value of E_1;
3. Test the calibrated HGX by applying it to fresh data (2007 data) and determine its E_1;
4. Determine if other model performance parameters such as MAE, SEE, MxAE and r^2 described below, agree with the conclusion from the test E_1;

5. Determine which HGX achieved the highest E_1 when tested.

The FAO-56 Penman-Monteith equation (FPM), Equation (3), was used to compute daily reference grass evapotranspiration, ETo, using measured 1998-2007 daily temperature data from a weather station at the Water Research Institute (WRI), Accra, Ghana, located on latitude 5.55°N and longitude 0.5 °W. Daily vapor pressure and radiation data required for FPM daily ETo computation were estimated using the relevant equations outlined in Allen et al. (1998). ETo estimates were computed for average daily wind speeds 0.5, 2.0, and 4.0 m/s. Part of the data (average 1998-2006) was used to calibrate the various Hargreaves equations (HGX) described below, while the 2007 data were used to test the performance of the calibrated HGX. For each wind speed, each HGX was optimized by numerically adjusting its relevant parameters to obtain the best fit between it and FPM.

2.1 Modified Hargreaves Equations

The uncalibrated version of Hargreaves equation used as the original in this study was the so-called 1985-Hargreaves equation (HG) (Hargreaves & Samani, 1985):

$$ET_{o,HG} = 0.0023(T_x - T_n)^{0.50}(T + 17.8)R_a/\lambda \tag{1}$$

where $ET_{o,HG}$ = reference grass evapotranspiration estimated by HG (mm d $^{-1}$); T_x = maximum daily temperature (°C), T_n = minimum daily temperature (°C), T = average daily temperature, $T = (T_x + T_n)/2$; R_a = extraterrestrial radiation (MJ m $^{-2}$d $^{-1}$), λ = latent heat of vaporization (MJ kg $^{-1}$); For the purpose of this work, Eq. (1) was re-written in general form (for modification HGX) as:

$$ET_{o,HGX} = k_1(T_x - T_n)^{k_2}(T + k_3)R_a/\lambda + k_4 \tag{2}$$

where $ET_{o,HGX}$= reference grass evapotranspiration estimated by HG equation HGX (mm d $^{-1}$), with original, uncalibrated parameter values of k_1 = 0.0023, k_3 = 17.8, k_2= 0.5 and k_4 = 0. Eleven different HGXs were developed in this study and were named by replacing the "X" in HGX by the subscripts of the parameters that were varied during optimization against FPM, e.g., HG1234 was developed by adjusting parameters, k_1, k_2, k_3, and k_4 (see Table 1 for HGX definations).

Table 1. Characteristics of the modified Hargreaves equations (HGX)

No.	HGX Type	k_1 (0.0023)	k_2 (0.5)	k_3 (17.8)	k_4 (0)
1	HG0	x	x	x	x
2	HG1	√	x	x	x
3	HG14	√	x	x	√
4	HG2	x	√	x	x
5	HG24	x	√	x	√
6	HG3	x	x	√	x
7	HG34	x	x	√	√
8	HG12	√	√	x	x
9	HG124	√	√	x	√
10	HG123	√	√	√	x
11	HG1234	√	√	√	√

Note: The original parameter values are in parenthesis and the parameters values that are optimized to obtain each HGX are indicated by a tick (√) while the ones held contstant are indicated by ‘x’. See Table 2 for optimized results.

2.2 The FAO-56 Penman-Monteith Equation

The FAO-56 Penman-Monteith (FPM) equation (Allen *et al*., 1998; ASCE-EWRI, 2005) is:

$$\mathrm{ET_{o,FPM}} = \frac{0.408\Delta(\mathrm{R_n}-\mathrm{G})+\gamma\frac{900}{(\mathrm{T}+273)}\mathrm{u_2}(\mathrm{e_s}-\mathrm{e_a})}{\Delta+\gamma(1+0.34\mathrm{u_2})} \tag{3}$$

where, $ET_{o,FPM}$ = reference grass evapotranspiration estimated by FPM (mm d $^{-1}$); R_n = net radiation (MJ m $^{-2}$d $^{-1}$); G = soil heat flux density (MJ m $^{-2}$d $^{-1}$); T = mean daily air temperature at 2 m above ground (°C); u_2 = wind speed at 2 m above ground surface (m s $^{-1}$); e_s = saturation vapor pressure (kPa), e_a = actual vapor pressure (kPa), Δ = slope of the saturated vapor pressure versus temperature curve (kPa ° C $^{-1}$), γ = psychrometric constant (kPa ° C $^{-1}$). For the temperature-dependent equations used to estimate the missing data required by FPM the reader is referred to Allen *et al*. (1998).

2.3 Model Performance Indexes

In addition to the commonly reported coefficient of determination, r^2 (Cai *et al*., 2007; Tabari *et al*., 2013), the following statistical indexes were employed to evaluate the performance of the various HGX equations as simulators of FPM:

2.3.1 Modified Coefficient of Efficiency

The modified coefficient of efficiency (also known as Legates and McCabe's index), $\mathrm{E_1}$, (Legates & McCabe, 1999; Bardsley & Purdie, 2007), was computed from

$$\mathrm{E_1} = 1 - \frac{\sum_{i=1}^{n}\left|\mathrm{ET_{o,FPM}^{i}}-\mathrm{ET_{o,HGX}^{i}}\right|}{\sum_{i=1}^{n}\left|\mathrm{ET_{o,FPM}^{i}}-\overline{\mathrm{ET_{o,FPM}}}\right|} \tag{4}$$

with N = total number of days of the year, i = the particular day of the year, and $\overline{\mathrm{ET_{o,FPM}}}$ is the average $\mathrm{ET_{o,FPM}}$ for the year. $\mathrm{E_1}$, in this study, served as the main index of model performance.

2.3.2 Mean Absolute Error

The mean absolute error (MAE) was computed as:

$$\mathrm{MAE} = \frac{1}{\mathrm{n}}\sum_{i=1}^{n}\left|\mathrm{ET_{o,FPM}^{i}} - \mathrm{ET_{o,HGX}^{i}}\right| \tag{5}$$

where the variables are as defined in Eq. (4) (Willmott and Matsuura, 2005).

2.3.3 Standard Error of Estimate

The standard error of the estimate (SEE) of daily ETo between FPM and HGX, used to compute the deviation of the HG ETo estimates from the line of best fit for HGX vs FPM ETo plots, was computed using

$$SEE = \sqrt{\left[\frac{1}{n(n-2)}\right]\left[n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2 \frac{\left[n\sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \times \sum_{i=1}^{n} y_i\right]^2}{n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2}\right]} \tag{6}$$

where $\mathrm{x_i} = \mathrm{ET_{o,FPM}^{i}}$, and $\mathrm{y_i} = \mathrm{ET_{o,HGX}^{i}}$, and n = number of data points (Irmak *et al*., 2003).

2.3.4 *Maximum Absolute Error*

The maximum absolute error (MxAE), for estimating the maximum daily difference between HGX and FPM ETo, was obtained from

$$MxAE = \max\left(\left|ET_{o,FPM}^{i} - ET_{o,HGX}^{i}\right|\right) \quad (7)$$

MxAE was useful in determining the worst performance of a particular HGX equation on a daily basis which MAE is unable to measure because of long-term averaging.

3. Results

Table 2. Optimized parameter values (k_1, k_2, k_3 & k_4) and performance measures (E_1, r^2, MAE, MxAE, and SEE) for HGX vs FPM daily ETo data estimated from fresh weather data (2007 data) at simulated wind speeds of 0.5, 2.0 and 4.0 m/s, for a weather station in Accra, Ghana

Parameter	u_2 (m/s)	Hargreaves equation type										
		HG0	HG1	HG14	HG2	HG24	HG3	HG34	HG12	HG124	HG123	HG1234
k_1	0.5	0.0023	0.0021	0.0020	0.0023	0.0023	0.0023	0.0023	0.0024	0.0029	0.0029	0.0028
	2.0	0.0023	0.0023	0.0025	0.0023	0.0023	0.0023	0.0023	0.0021	0.0018	0.0021	0.0021
	4.0	0.0023	0.0025	0.0031	0.0023	0.0023	0.0023	0.0023	0.0018	0.0011	0.0016	0.0010
k_2	0.5	0.5000	0.5000	0.5000	0.4606	0.4543	0.5000	0.5000	0.4325	0.3862	0.4162	0.3902
	2.0	0.5000	0.5000	0.5000	0.5022	0.5196	0.5000	0.5000	0.5521	0.5946	0.5469	0.5993
	4.0	0.5000	0.5000	0.5000	0.5422	0.5840	0.5000	0.5000	0.6566	0.8259	0.6725	0.8367
k_3	0.5	17.8000	17.8000	17.8000	17.8000	17.8000	14.2458	9.3782	17.8000	17.8000	11.1640	19.3280
	2.0	17.8000	17.8000	17.8000	17.8000	17.8000	17.9620	21.8529	17.8000	17.8000	17.8020	10.0127
	4.0	17.8000	17.8000	17.8000	17.8000	17.8000	21.9196	37.2104	17.8000	17.8000	24.1849	3.0255
k_4	0.5	0.0000	0.0000	0.2773	0.0000	0.0474	0.0000	0.4527	0.0000	-0.3610	0.0000	-0.3715
	2.0	0.0000	0.0000	-0.2747	0.0000	-0.1554	0.0000	-0.3598	0.0000	0.2441	0.0000	0.4211
	4.0	0.0000	0.0000	-1.0032	0.0000	-0.3990	0.0000	-1.4132	0.0000	0.7521	0.0000	1.0337
E_1	0.5	0.22	0.87	0.91	0.93	0.95	0.86	0.92	0.96	0.98	0.96	0.98
	2.0	0.92	0.93	0.95	0.93	0.96	0.93	0.95	0.97	0.96	0.97	0.99
	4.0	0.43	0.79	0.87	0.84	0.91	0.78	0.85	0.93	0.92	0.92	0.97
r^2	0.5	0.99	0.99	0.99	1.00	1.00	0.99	0.99	1.00	1.00	1.00	1.00
	2.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	4.0	0.98	0.98	0.98	0.99	0.99	0.98	0.98	1.00	0.99	1.00	1.00
MAE (mm/d)	0.5	0.31	0.05	0.03	0.03	0.02	0.06	0.03	0.02	0.01	0.02	0.01
	2.0	0.04	0.04	0.02	0.04	0.02	0.04	0.03	0.02	0.02	0.02	0.00
	4.0	0.36	0.13	0.08	0.10	0.06	0.14	0.09	0.04	0.05	0.05	0.02
MxAE (mm/d)	0.5	0.81	0.38	0.29	0.23	0.19	0.37	0.20	0.12	0.04	0.10	0.06
	2.0	0.23	0.21	0.18	0.20	0.16	0.21	0.23	0.15	0.10	0.14	0.02
	4.0	1.33	0.84	0.46	0.63	0.33	0.80	0.69	0.25	0.34	0.28	0.22
SEE (mm/d)	0.5	0.06	0.06	0.05	0.04	0.03	0.05	0.04	0.02	0.01	0.02	0.01
	2.0	0.03	0.03	0.03	0.03	0.02	0.03	0.03	0.02	0.02	0.02	0.01
	4.0	0.08	0.09	0.11	0.08	0.07	0.09	0.11	0.05	0.06	0.06	0.03

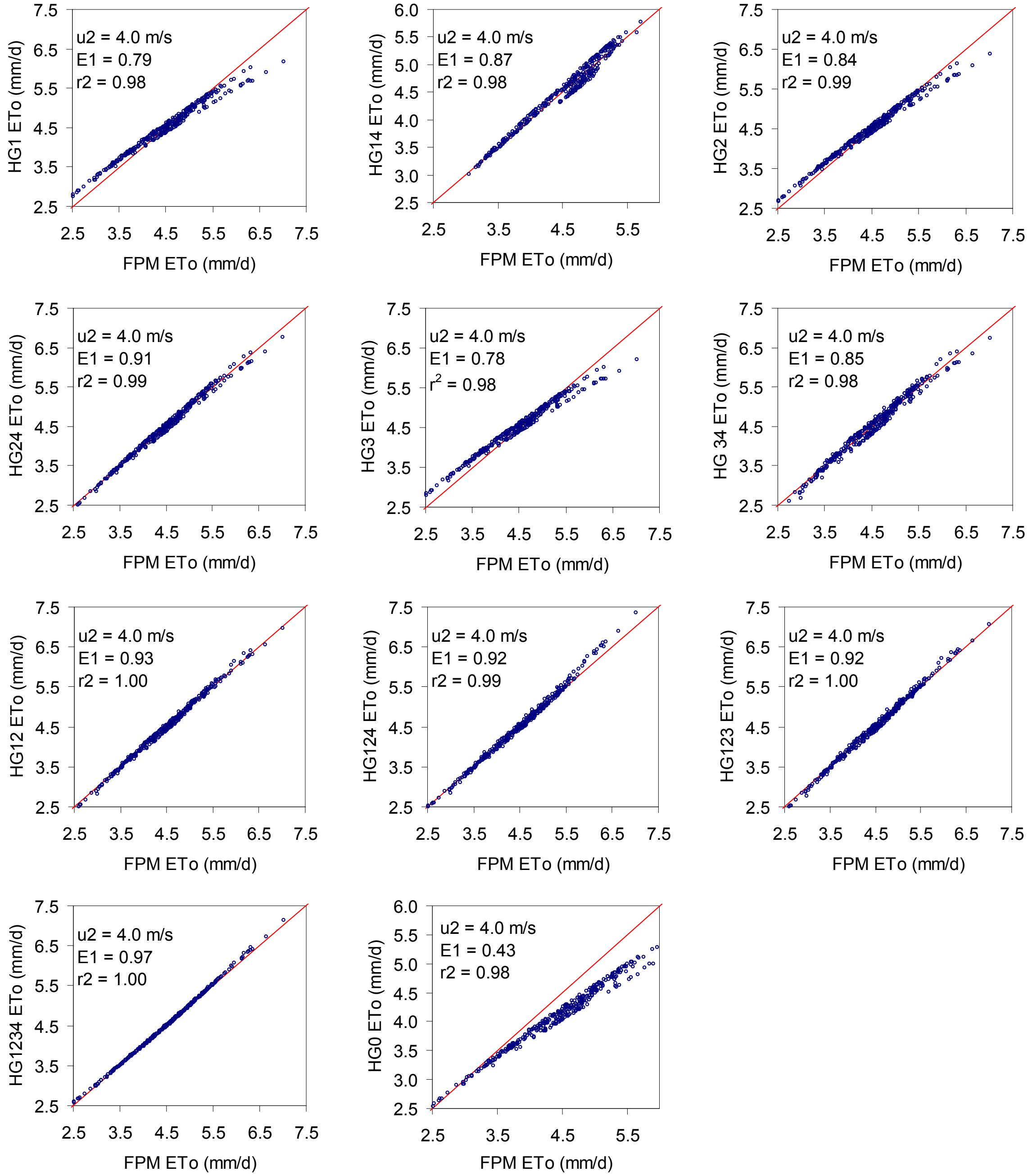

Figure 1. HGX versus FPM daily ETo for u_2 of 4 m/s for an Accra weather station 2007 weather data, showing HG1234 as the best simulator of FPM daily ETo estimates.

4. Discussion

Hargreaves equation (HG) can be modified into a mathematical substitute for FPM and its auxiliary equations for estimating daily ETo with negligible loss of accuracy when the only available data are those of daily minimum and maximum temperature. The most efficient modification of HG was

HG1234 according the main measure of HGX performance, E_1, which was as high as 0.99 for average wind speed u_2= 2.0 m/s; the MAE was zero, and the MxAE was negligible at merely 0.02 mm/day. For all practical purposes there was no difference between the estimates of ETo by HG1234 and FPM. Most of the HG1234 ETo estimates were exactly the same as those of FPM to two decimal places, with the maximum disparity, MxAE, being merely 0.02 mm/day (at u_2= 2.0 m/s) for the whole year (Table 2).

HG1234 was consistently the most efficient simulator of FPM at the simulated wind speeds below (0.5 m/s) and above (4.0 m/s) the global average wind speed (2 m/s) (Table 3). There was no clear second best HGX by E_1, but the uncalibrated HG, HG0, was clearly the worst performer, with very poor E_1 except for u_2 of 2 m/s. In fact for the global average wind speed of 2.0 m/s all HGX's performed very well with little difference in efficiency between the best (HG1234) and the worst (HG0), agreeing with the conclusion of reports such as Allen (1993) and Droogers and Allen (2002) that do not recommend changing the original HG parameters because they did not find significant improvements to HG from recalibration of the original parameter values.

However, from this work, HG's efficiency was significantly improved by altering the original parameters of HG for wind speeds other than the global average value of 2 m/s. For example at the simulated wind speed of 4 m/s in spite of the relatively high values of r^2 (0.98-1.00) it is clear from the scatter-plots and the other performance measures that HG1234 simulated FPM more precisely than HG0 and all the other HGX's (Figure 1).

The introduction of the new constant term into HG to produce HG1234 resulted in significant improvements in E_1 that ranged from 0.07 (for u_2 = 2 m/s) to 0.76 (for u_2 = 0.5 m/s), and made HG1234 as accurate as the empirical simplification described in (Kra, 2010). In addition HG1234 has the added advantage that it has the same form as the very widely used HG differing only by the constant term k_4 (see Equation (2)) and will therefore be easier to adopt as a computational alternative to FPM for temperature data only situations.

Although various comparisons could be made between the various HGX models, HG1234 vs HG14 is of special interest because HG14 is the form recommended by Allen *et al*. (1998a) for calibrating Hargreaves equation against FPM using a simple linear regression equation of the form

$$\mathrm{ET_{o,calibrated\ Hargreaves}} = \mathrm{a} + \mathrm{b} \times \mathrm{ET_{o,Uncalibrated\ Hargreaves}} \quad (8)$$

where a and b are optimized linear calibration constants which in this study were represented by $\mathrm{k_4}$ and $\mathrm{k_1}$, respectively. The performance of HG14 was not as good as that of HG1234, with its relative performance rank, using the various measures, ranging from a worst of value of 10 to a best of 6 (Table 3). The scatterplots clearly showed that HG1234 performed better than HG14 (Figure 1) even though the numerical values of $\mathrm{r^2}$ were not as powerful as the $\mathrm{E_1}$ values in showing the performance differences.

It was noted that even the uncalibrated HG0 had the same $\mathrm{r^2}$ (0.98) as HG14, even though the other performance measures registered larger differences that reflectred the differences observed in the scatterplots. For example, HG0 underestimated FPM at higher ETo values while HG14 did not, but both HG14 and HG0 had the same $\mathrm{r^2}$ value of 0.98. However, $\mathrm{E_1}$ captured the underestimation by giving $\mathrm{E_1}$= 0.87 to HG14 but a significantly lower value of $\mathrm{E_1}$= 0.43 to HG0. Similarly, using the r^2 difference of only 2 between HG1234 and HG14 leads to the wrong conclusion that the difference between HG14 and HG1234 is not significant at u_2 = 4 m/s, while E_1= 0.97 for HG1234 is significantly higher than the E_1= 0.87 for HG14. These observations of the shortcomings of $\mathrm{r^2}$ in distinguishing model performance agree with the conclusions of other research (e.g., Willmott, 1982; Legates & McCabe 1999), but further discussion of the unsuitability of r^2 for comparing performance of models is beyond the objectives of this study.

For some purposes, especially those that require long term estimates of ETo, the differences between HG1234 and HG14 or any of the other models may not be significant to justify the extra effort required to use HG1234. However, in situations where daily differences in ETo are important, such as irrigation scheduling in arid regions where water expensive, the higher efficiency of prediction of HG1234 makes it a far better choice than the simpler linear regression model based HG14.

This work was based on FPM ETo data computed from temperature data and therefore the superiority of HG1234 to the other modifications of HG cannot be generalized to the case of lysimeter ETo data until after tests have been made with actual ETo data. But the fact that FPM is regarded as a good estimator of actual ETo suggests that for actual data, too, HG1234 would perform better than the other HGX's tested in this work.

This work was not another comparison of HG with FPM but rather the use of the mathematical form of HG as a means of drastically reducing the number of intermediate calculations required to estimate daily ETo by FPM. Because HG1234 and FPM give practically the same daily ETo estimates even though HG1234 requires a lot less computation than FPM, the former could be used to speed up computations in situations where millions or billions of daily ETo estimations have have to be repeated often such as in satellite image applications involving evapotranspiration estimates.

Although it was not originally developed for daily reference evapotranspiration (ETo) estimation, the Hargreaves equation (HG) can be modified to produce essentially the same daily ETo estimates as the FAO-56 Penman-Monteith equation (FPM) for a given weather station when the only available weather data are daily temperature data. Optimizing all the constants in HG and introducing a new constant term transforms HG into a highly efficient short-cut equation for computing FPM daily ETo estimates when only temperature data are available. The daily ETo estimates obtained from HG1234 are essentially the same as those obtained from FPM for practical purposes.

Table 3. Rankings (1 – best, 11 – worst) of the ability of various HGX equations to simulate FPM daily ETo based on certain performance measures (E_1, r^2, MAE, MxAE, and SEE) for 2007 weather data for a weather station in Accra

	u_2(m/s)	HG0	HG1	HG14	HG2	HG24	HG3	HG34	HG12	HG124	HG123	HG1234
E_1	0.5	11	9	8	6	5	10	7	3	2	4	1
	2.0	11	9	6	8	4	10	7	3	5	2	1
	4.0	11	9	6	8	5	10	7	2	4	3	1
r^2	0.5	10	11	9	6	5	8	7	4	2	3	1
	2.0	8	9	10	6	5	7	11	2	4	3	1
	4.0	9	11	9	6	5	7	8	2	4	3	1
MAE	0.5	11	9	8	6	5	10	7	3	2	4	1
(mm/d)	2.0	11	9	6	8	4	10	7	3	5	2	1
	4.0	11	9	6	8	5	10	7	2	4	3	1
MxAE	0.5	11	10	8	7	5	9	6	4	1	3	2
(mm/d)	2.0	10	9	6	7	5	8	11	4	2	3	1
	4.0	11	10	6	7	4	9	8	2	5	3	1
SEE	0.5	11	10	8	6	5	9	7	4	2	3	1
(mm/d)	2.0	7	9	10	6	5	8	11	2	4	3	1
	4.0	7	9	10	6	5	8	11	2	4	3	1

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