# Hargreaves versus Penman-Monteith under Humid Conditions

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**Abstract:** The Food and Agriculture Organization of the United Nations (FAO) has proposed using the Penman-Monteith equation as the standard for estimating reference evapotranspiration ($ET_0$), and for evaluating other equations. The basic obstacle to using the FAO-56 Penman-Monteith equation (FAO-56 PM) widely is the required weather data which are not available in most of the stations. In such circumstances, a simple empirical Hargreaves equation (HARG) is often used. However, this equation generally overestimates $ET_0$ at humid locations. Therefore, HARG requires local calibration. The main objective of this study is to investigate the possibility for calibrating the equation in the Western Balkans region, South East Europe through the adjustment of Hargreaves exponent (HE). Data from Palic, Sarajevo, and Nis have been used for estimating the adjusted HE. A value of 0.424 is proposed instead of the original 0.5 as one which should be used in the adjusted Hargreaves equation (AHARG) for the Western Balkan locations. The $ET_0$ values estimated by AHARG were compared with FAO-56 PM estimates for eight humid locations (Varazdin, Zagreb, Bihac, Novi Sad, Negotin, Kragujevac, Nis, and Vranje). Estimates by AHARG were in close agreement with FAO-56 PM estimates at most of the locations. The SEE ranged from 0.17 mm day$^{-1}$ for Varazdin to 0.24 mm day$^{-1}$ for Vranje, averaging 0.21 mm day$^{-1}$. The average overestimation was about 1%. These results strongly support the use of the adjusted Hargreaves equation at humid Western Balkan locations in the case when only the temperature data are available. Further research should be undertaken for evaluating the validity of the approach presented in this paper in other regions.

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**CE Database subject headings:** Evapotranspiration; Temperature; Calibration.

## Introduction

Accurate estimates of reference evapotranspiration ($ET_0$) are required for responsible irrigation engineering. $ET_0$ estimation is necessary for crop production, water resources management, irrigation scheduling, and environmental assessment. There are many methods for estimating reference evapotranspiration. Recently, the Food and Drug Organization of the United Nations (FAO)-56 Penman-Monteith equation (FAO-56 PM) has been proposed as the standard method for estimating reference evapotranspiration, and for evaluating other equations (Allen et al. 1998).

The FAO-56 PM is a physically based approach which requires measurements of air temperature, relative humidity, solar radiation, and wind speed. The number of stations where there are reliable data for these parameters is limited.

This lack of data motivated Hargreaves et al. (1985) to develop a simpler approach where only air temperatures are required. The Hargreaves equation (HARG) can be written

$$ET_{0,\mathrm{Harg}} = \mathrm{HC} \cdot R_a \cdot (T_{\max} - T_{\min})^{\mathrm{HE}}\left(\frac{T_{\max}+T_{\min}}{2} + \mathrm{HT}\right) \quad (1)$$

where $ET_{0,\mathrm{Harg}}$=$ET_0$ estimated by the Hargreaves equation (mm day$^{-1}$); $R_a$=extraterrestrial radiation (mm day$^{-1}$); $T_{\max}$=daily maximum air temperature (°C); $T_{\min}$=daily minimum air temperature (°C); HC=empirical Hargreaves coefficient; HE=empirical Hargreaves exponent; and HT=empirical temperature coefficient [HC=0.0023, HE=0.5, and HT=17.8 (Hargreaves 1994)].

Several studies have shown the Hargreaves equation may provide reliable estimates of reference evapotranspiration for five days or longer time steps (Hargreaves 1989; Jensen et al. 1997; Droogers and Allen 2002; Hargreaves and Allen 2003).

Allen et al. (1998) have proposed that when sufficient data to solve the FAO-56 PM equation are not available then the Hargreaves equation can be used. However, this equation generally overestimates $ET_0$ at humid locations. Trajkovic (2005) has conducted a study to evaluate the reliability of some temperature-based equations against FAO-56 PM for humid conditions in Serbia (South East Europe). The poor results for the Hargreaves equation have been in good agreement with data from humid locations reported by Jensen et al. (1990), Amatya et al. (1995), Itenfisu et al. (2003), and Temesgen et al. (2005).

Several studies attempted to improve accuracy of the Hargreaves equation. Allen (1993) and Droogers and Allen (2002) explored recalibration of coefficients. The writers themselves concluded that new coefficients [HC=0.0030, HE=0.4, and HT=20 (Allen (1993)) and HC=0.0025, HE=0.5, and HT=16.8 (Droogers and Allen (2002))] did not improve Hargreaves estimates substantially. Samani (2000) proposed a relationship be-

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**Table 1.** Summary of Weather Station Sites Used in Study

| Station | Country | Latitude (°N) | Altitude (m) | Period | Patterns | E/T | $T_{max}$ (°C) | $T_{min}$ (°C) | RH (%) | $U_2$ (m s$^{-1}$) | $ET_{0,pm}$ (mm d$^{-1}$) | $pET_{0,pm}$ (mm d$^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Varazdin | Croatia | 46.3 | 167 | 1971–1974 | 48 | T | 15.3 | 5.1 | 76 | 1.9 | 2.1 | 4.2 |
| Palic | Serbia | 46.1 | 102 | 1977–1983 | 84 | E | 15.5 | 6.1 | 74 | 1.7 | 2.2 | 4.4 |
| Zagreb | Croatia | 45.8 | 123 | 1971–1974 | 48 | T | 15.4 | 5.6 | 76 | 1.3 | 2.0 | 4.1 |
| Novi Sad | Serbia | 45.3 | 86 | 1981–1984 | 48 | T | 16.2 | 6.3 | 74 | 1.9 | 2.3 | 4.4 |
| Bihac | Bosnia | 44.8 | 48 | 1981–1984 | 48 | T | 16.0 | 5.5 | 71 | 1.5 | 2.2 | 4.2 |
| Negotin | Serbia | 44.2 | 42 | 1971–1974 | 48 | T | 16.3 | 5.9 | 74 | 1.7 | 2.3 | 4.8 |
| Kragujevac | Serbia | 44.0 | 190 | 1981–1984 | 48 | T | 16.4 | 6.0 | 75 | 1.1 | 2.1 | 4.2 |
| Sarajevo | Bosnia | 43.9 | 630 | 1977–1984 | 96 | E | 15.3 | 5.2 | 75 | 1.2 | 2.1 | 4.2 |
| Nis | Serbia | 43.3 | 202 | 1977–1984 | 96 | E | 17.0 | 6.2 | 71 | 1.0 | 2.2 | 4.3 |
| | | | | 1993–1996 | 48 | T | 18.4 | 6.8 | 68 | 1.1 | 2.4 | 4.8 |
| Vranje | Serbia | 42.6 | 433 | 1971–1974 | 48 | T | 15.9 | 5.7 | 72 | 1.5 | 2.3 | 4.5 |

Note: $E$=data from this location were used for estimating the adjusted Hargreaves exponent; $T$=data from this location were used for testing the adjusted Hargreaves equation; the last six columns represent mean values over the period of record.

tween the HC and the daily temperature range. However, Vanderlinden et al. (2004) founded that adjustment with Samani method did not produce more accurate estimates.

Therefore, the adjustment of the equation coefficients to local conditions is an alternative way to improve its estimation. Amatya et al. (1995) developed monthly adjusted HC1 for three weather stations in eastern North Carolina. A new HC value was suggested for Rawson Lake station in northwestern Ontario, Canada (0.0029; Xu and Singh 2001) and for nonwindy locations in semiarid middle Ebro River Valley region, Spain (0.0020; Martinez-Cob and Tejero-Juste 2004). Vanderlinden et al. (2004) developed adjusted HC for each weather station in Andalusia, southern Spain and proposed a linear relationship between adjusted HC and the ratio of the average temperature to the average daily temperature range for regional adjustment of the HC. According to the yearly means of wind speed and daily temperature range, Gavilan et al. (2006) suggested the adjustment of HC for some cases in a semiarid Andalusia, southern Spain.

According to Allen et al. (1994), Trajkovic (2005) used simple linear regression for regional calibration of the Hargeaves equation. However, the calibrated Hargreaves equation overestimated FAO-56 PM estimates even after calibration. The average of estimated values was about 13% above the average of FAO-56 PM estimates. These results indicate that the calibration of the equation for the Western Balkans region should be done through the adjustment of the Hargreaves exponent. The main objective of this study is to investigate the possibility for that kind of calibration of the equation in the Western Balkan region.

## Materials and Methods

### Meteorological Data

The ten humid weather stations selected for this study are located in the Western Balkans region (South East Europe). These locations are Varazdin, Palic, Zagreb, Novi Sad, Bihac, Negotin, Kragujevac, Sarajevo, Nis, and Vranje. Temperature, wind speed, humidity, vapor pressure, and sunshine hours were daily collected at these stations under reference conditions of standard grass height and well-watered environment. The weather station data for this study, except Nis (1993–1996), were obtained from the Federal Meteorological Institute. The data from Nis (1993–1996) were provided from the Serbian Meteorological Institute. The description of the different weather stations along with the observation periods, number of months, and mean weather data is given in Table 1.

Differences in the mean weather data for these locations are not very significant. The mean annual maximum and minimum temperatures ($T_{max}$ and $T_{min}$) for all locations varied between 15.3 and 18.4°C and 5.1 and 6.8°C, respectively. The mean relative humidity (RH) varied between 68 and 76% and the mean annual wind speed ($U_2$) ranged from 1.0 to 1.9 m s$^{-1}$.

### Estimating Adjusted Hargreaves Exponent

The following equation was applied for the FAO-56 PM:

$$\mathrm{ET}_{0,\mathrm{PM}} = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T+273} U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \tag{2}$$

where $\mathrm{ET}_{0,\mathrm{PM}}$=reference evapotranspiration estimated by FAO-56 Penman-Monteith equation (mm day$^{-1}$); $\Delta$=slope of the saturation vapor pressure function (kPa °C$^{-1}$); $R_n$=net radiation (MJ m$^{-2}$ day$^{-1}$); $G$=soil heat flux density (MJ m$^{-2}$ day$^{-1}$); $\gamma$=psychometric constant (kPa °C$^{-1}$); $T$=mean daily air temperature (°C); $U_2$=average 24-h wind speed at 2-m height (m s$^{-1}$); and ($e_s$-$e_a$)=vapor pressure deficit (kPa).

In this paper, the FAO-56 PM has been used as substitute for measured $\mathrm{ET}_0$ data and that is the standard procedure when there is no measured lysimeter data (Irmak et al. 2003; Utset et al. 2004; Gavilan et al. 2006; Nandagiri and Kovoor 2006).

The adjusted Hargreaves exponent was obtained from the following equation:

$$\mathrm{ET}_{0,\mathrm{PM}} = 0.0023 \cdot R_a \cdot (T_{max} - T_{min})^{\mathrm{HE}} \left( \frac{T_{max} + T_{min}}{2} + 17.8 \right) \tag{3}$$

Data from Palic (84 months; 1977–1983), Sarajevo (96 months; 1977–1984), and Nis (96 p months; 1977–1984) have been used for estimating adjusted HE. For these locations a value of 0.424 has been found. The Hargreaves equation (HARG, HE=0.5) overestimated FAO-56 PM $\mathrm{ET}_0$ estimates at these sites. The overestimation ranged from 14% (Palic) to 29% (Nis). The adjusted Hargreaves equation (AHARG, HE=0.424) performed very well in estimating $\mathrm{ET}_0$ for these locations with deviation of +6% (Nis),

**Table 2.** Statistical Summary of Monthly $ET_0$ Estimates for Validation Locations

| | Hargreaves (HARG) | | | | | Adjusted Hargreaves (AHARG) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Location | $ET_0$ (mm $d^{-1}$) | $ET_0/ET_{0,pm}$ | SEE (mm $d^{-1}$) | $pET_0$ (mm $d^{-1}$) | $pET_0/ET_{0,pm}$ | $ET_0$ (mm $d^{-1}$) | $ET_0/ET_{0,pm}$ | SEE (mm $d^{-1}$) | $pET_0$ (mm $d^{-1}$) | $pET_0/ET_{0,pm}$ |
| Varazdin | 2.5 | 1.21 | 0.56 | 5.0 | 1.19 | 2.1 | 1.01 | 0.17 | 4.1 | 0.98 |
| Zagreb | 2.6 | 1.29 | 0.70 | 5.1 | 1.27 | 2.1 | 1.06 | 0.22 | 4.2 | 1.04 |
| Novi Sad | 2.7 | 1.15 | 0.45 | 5.1 | 1.17 | 2.2 | 0.95 | 0.19 | 4.2 | 0.97 |
| Bihac | 2.6 | 1.21 | 0.64 | 5.4 | 1.28 | 2.2 | 1.00 | 0.21 | 4.4 | 1.04 |
| Negotin | 2.8 | 1.18 | 0.53 | 5.4 | 1.12 | 2.3 | 0.98 | 0.22 | 4.5 | 0.93 |
| Kragujevac | 2.7 | 1.29 | 0.71 | 5.1 | 1.22 | 2.2 | 1.07 | 0.21 | 4.2 | 1.01 |
| Nis | 3.0 | 1.27 | 0.80 | 6.1 | 1.27 | 2.5 | 1.05 | 0.22 | 5.0 | 1.03 |
| Vranje | 2.7 | 1.17 | 0.47 | 5.1 | 1.14 | 2.3 | 0.97 | 0.24 | 4.2 | 0.94 |
| Average | 2.7 | 1.22 | 0.61 | 5.3 | 1.21 | 2.2 | 1.01 | 0.21 | 4.4 | 0.99 |

Note: $ET_0/ET_{0,PM}$=the ratio of mean annual (A)HARG estimated $ET_0$ and FAO-56 PM estimated $ET_0$, $pETeq/ET_{PM}$=the ratio of (A)HARG estimated $ET_0$ and FAO-56 PM estimated $ET_0$ in the peak month (July).

−1% (Sarajevo), and −5% (Palic). According to this result, the adjusted Hargreaves equation for Western Balkans region (AHARG) can be written as

$$ET_{0,AHarg} = 0.0023 \cdot R_a \cdot (T_{max} - T_{min})^{0.424}\left(\frac{T_{max}+T_{min}}{2} + 17.8\right) \tag{4}$$

where $ET_{0,AHarg}$=$ET_0$ estimated by the adjusted Hargreaves equation (mm $day^{-1}$).

### *Evaluation Parameter*

In this study, the standard error of estimate (SEE) has been used for the evaluation of the $ET_0$ estimates. This statistical criterion was calculated as follows:

$$SEE = \left[\frac{\sum_{i=1}^{l}(ET_{0,PM}^{i} - ET_{0,(A)Harg}^{i})^2}{l-1}\right]^{0.5} \tag{5}$$

where SEE=standard error of estimate (mm $day^{-1}$); $ET_{0,PM}$ =$ET_0$ estimated by the standard (FAO-56 PM) equation (mm $day^{-1}$); $ET_{0,(A)Harg}$=corresponding $ET_0$ estimated by the original or adjusted Hargreaves equation (mm $day^{-1}$); and l=total number of months. Standard error of estimate indicates how well the original or adjusted Hargreaves equations estimated reference evapotranspiration over all months of record.

## Results and Discussion

The $ET_0$ values estimated by HARG and AHARG were compared with FAO-56 PM estimates for eight humid locations [Varazdin (1971–1974), Zagreb (1971–1974), Novi Sad (1981–1984), Bihac (1981–1984), Negotin (1971–1974), Kragujevac (1981–1984), Nis (1993–1996), and Vranje (1971–1974)]. The test data set had a total of 384 months that were not used for the calibration. Statistical summary of $ET_0$ estimates for these methods at each location are presented in Table 2. The HARG method greatly overestimated FAO-56 PM values at all sites. This overestimation varied from 15% (Novi Sad) to 29% (Zagreb and Kragujevac) for the entire year. It ranged from 12% (Negotin) to 28% (Bihac) for the peak month. As a result, HARG gave a very high standard error of estimate at all locations (SEE) varied from 0.45 mm $day^{-1}$ for Novi Sad to 0.80 mm $day^{-1}$ for Nis. The AHARG was found to be in very good agreement with the standard FAO-56 PM at all locations. SEE of this method varied from 0.17 mm $day^{-1}$ at Varazdin to 0.24 mm $day^{-1}$ at Vranje, averaging 0.21 mm $day^{-1}$. The AHARG consistently slightly overestimated FAO-56 PM values at Zagreb, Kragujevac, and Nis and slightly

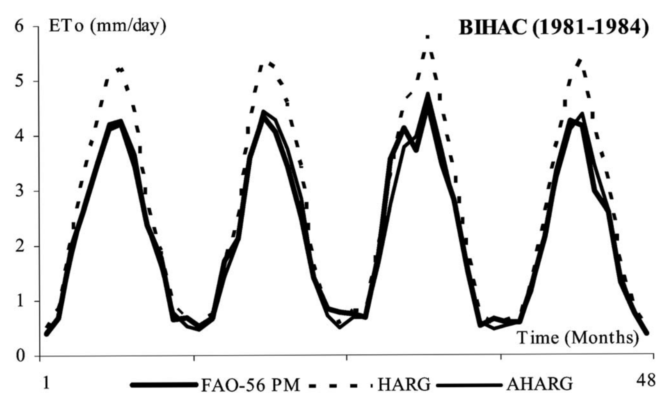


**Fig. 1.** Comparison of monthly $ET_0$ computed for four years at Bihac, Bosnia, and Hercegovina using FAO-56 Penman-Monteith (FAO-56 PM), Hargreaves (HARG), and adjusted Hargreaves (AHARG) methods

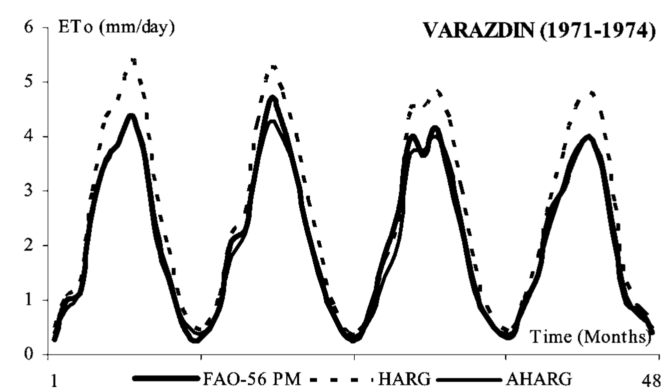


**Fig. 2.** Comparison of monthly $ET_0$ computed for four years at Varazdin, Croatia using FAO-56 Penman-Monteith (FAO-56 PM), Hargreaves (HARG), and adjusted Hargreaves (AHARG) methods

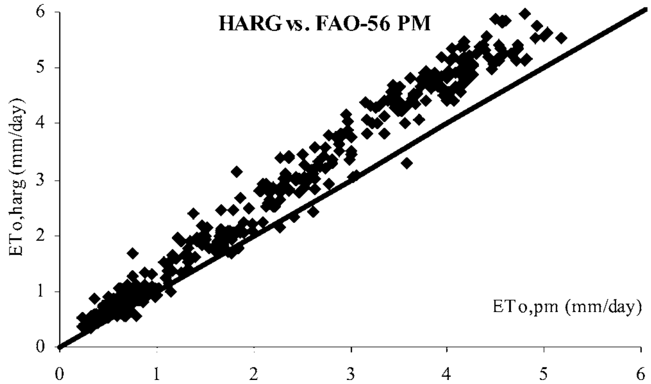


**Fig. 3.** Hargreaves (HARG) versus FAO-56 Penman-Monteith (FAO-56 PM) $ET_0$ estimates

underestimated these values at Novi Sad, Negotin, and Vranje. Comparison of monthly $ET_0$ computed for four years at Bihac and Varazdin using FAO-56 Penman-Monteith (FAO-56 PM), Hargreaves (HARG), and adjusted Hargreaves (AHARG) methods are shown in Figs. 1 and 2.

The mean daily values of $ET_0$ estimated by HARG and AHARG are plotted in Figs. 3 and 4 against FAO-56 PM estimates for all 384 months. An indication of the potential for overestimation by the HARG is shown in Fig. 3. The average overestimation was about 22%. It is interesting to note that the estimates by AHARG provide values of $ET_0$ which were near FAO-56 PM estimates. The average overestimation was about 1%.

## Summary and Conclusions

The FAO-56 PM equation is recommended as the standard for computing reference evapotranspiration. The use of this method is limited due to the availability of data in areas where meteorological information is scarce, as, for example, in the Western Balkans region.

In such circumstances, the Hargreaves equation based on the maximum and minimum air temperature is often used to estimate $ET_0$. However, this equation generally overestimates the $ET_0$ for the humid locations. In this study, the Hargreaves equation overestimated $ET_0$ and average differences varied from 15 to 29%. These results indicate that a calibration of this equation is necessary. A value of 0.424 is proposed instead of the original 0.5 and it should be used in the adjusted Hargreaves equation for the Western Balkan locations.

Estimates by AHARG are compared to FAO-56 PM values. The differences are generally low and the average overestimation was about 1%. The results recommended this equation for estimating reference evapotranspiration at humid Western Balkan locations.

Further research is required in order to assess the adjusted Hargreaves equation that is proposed in this paper in other humid areas. The approach presented in this study could be applied in other regions for obtaining the suitable regional calibrations of this equation.

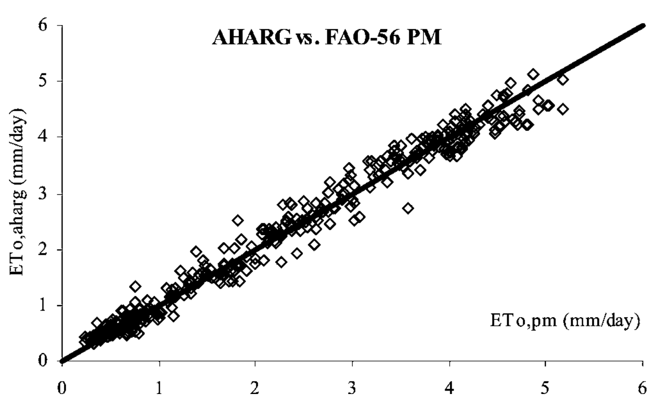


**Fig. 4.** Adjusted Hargreaves (AHARG) versus FAO-56 Penman-Monteith (FAO-56 PM) $ET_0$ estimates


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## Notation

*The following symbols are used in this paper:*

$ET_{0,AHarg}$ = $ET_0$ estimated by adjusted Hargreaves equation;
$ET_{0,Harg}$ = $ET_0$ estimated by Hargreaves equation;
$ET_{0,PM}$ = $ET_0$ estimated by PM method;
$(e_a\text{-}e_d)$ = vapor pressure deficit;
$G$ = soil heat flux density;
HC = empirical Hargreaves coefficient (HC=0.0023);
HE = empirical Hargreaves exponent (HE=0.5);
HT = empirical temperature coefficient (HT=17.8);
$pET_{0,PM}$ = $ET_0$ estimated by PM method for peak month;
$R_a$ = extraterrestrial radiation;
$R_n$ = net radiation;
$T$ = mean air temperature;
$T_{max}$ = maximum air temperature;
$T_{min}$ = minimum air temperature;
$U_2$ = average 24-h wind speed at 2 m height;
$\Delta$ = slope of saturation vapor pressure function; and
$\gamma$ = psychometric constant.

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