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Article

Comparative study of two equations with respect to FAO56 Penman-Monteith in Guanajuato

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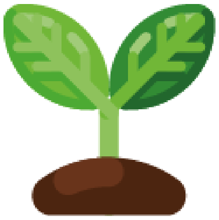
Abstract

The estimation of reference evapotranspiration (ET_0) has been widely used in irrigation engineering to calculate crop water requirements. The correct estimation of ET_0 represents a key step in planning and managing water resources. Experts recommend the FAO56 Penman-Monteith method as a standard method for estimating ET_0, with the disadvantage that it requires a lot of data on meteorological variables for its execution. This study aimed to estimate the daily reference evapotranspiration by the Hargreaves-Samani and Priestley-Taylor methods during the 2001-2006 period for five automatic weather stations in the state of Guanajuato; the results were compared with those of the FAO56 Penman-Monteith (FAO56 P-M) method to select the most accurate alternative method and determine the distance from any station at which the ET_0 data estimated with each of the methods were considered valid. The root means square error (RMSE) and the coefficient of determination (R2) were used to evaluate the performance of the methods compared to the FAO56 P-M. As a result, it was found that Hargreaves-Samani is the best alternative method to estimate ET_0 in the five stations in the state of Guanajuato. The distances determined from a station where the data of a method are valid are 93.02, 124.65, and 36.44 km for Hargreaves-Samani, Priestley-Taylor, and FAO56 Penman-Monteith, respectively.

Keywords:

Hargreaves-Samani, Priestley-Taylor, reference evapotranspiration.



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Introduction

Currently, the pressure on water resources is increasing day by day, and the demand for water for agriculture is the leading cause in many countries (Calera *et al*., 2017); Mexico is no exception, the largest volume concessioned for consumptive uses is agriculture, with 76%, where irrigation monopolizes most of it (CONAGUA, 2018), hence the need to calculate the water requirements of crops in an accurate way for good planning and management of water resources, especially in arid and semi-arid regions where water consumption by crops is higher and savings of a small percentage can generate greater availability (Berengena and Gavilán, 2005).

In agricultural production, measuring evapotranspiration (ET) is essential to determining crop water demand (Bakhtiari *et al*., 2011), irrigation scheduling and design (Lujano *et al*., 2023). ET is the combination of two processes that transfer large volumes of water to the atmosphere: evaporation of water from the soil and plant transpiration (Niaghi *et al*., 2021). Quantification of ET is usually based on the determination of reference evapotranspiration (ET_0) (Bakhtiari *et al*., 2011).

ET_0 is considered to be the maximum water loss resulting from evapotranspiration in a field covered by a reference crop; for example, grass without water restrictions (Babakos *et al*., 2020). ET_0 can be estimated by a wide variety of methods, including those that are practically empirical and based on statistical correlations between ET_0 and one or more climatic variables (Berengena and Gavilán, 2005).

Of the various empirical equations that exist to estimate ET_0, the FAO56 Penman-Monteith equation is the one that is widely used today and is accepted as a standard method (Lum *et al*., 2017); various studies have shown that the Penman-Monteith equation provides very accurate estimates of ET_0 in different environments (Berengena and Gavilán, 2005). The main disadvantage of the FAO56 Penman-Monteith application is the high demand for data, as the method requires data on air temperature, wind speed, relative humidity, and solar radiation.

Unfortunately, around the world, there are few weather stations where all these parameters are observed (Droogers and Allen, 2002); this restriction is due, among other things, to the fact that in underdeveloped regions or countries, there is little infrastructure and few resources to continuously monitor the data, also due to the differences in policies related to the subject between different countries or regions; therefore, it is difficult to find a common platform for data exchange, so some existing observations are not available (Du and Sun, 2012).

In the case of Mexico, most stations only record air temperature data. Therefore, there is an imminent need to evaluate simpler ET_0 equations with similar precision regarding the FAO56 Penman-Monteith equation. Given this, the objective of this study was to evaluate the performance to estimate ET_0 with Hargreaves-Samani (Hargreaves and Samani, 1985) and Priestley-Taylor (Priestley and Taylor, 1972) and to compare them with the FAO56 Penman-Monteith method (whose results are established as standard estimated values) to obtain an alternative method for the state of Guanajuato and determine the distance from a specific meteorological station where the values of a method are considered valid.

Materials and methods

Location of automatic stations under study

This study was carried out with data from five automatic weather stations located in the state of Guanajuato, the stations are shown in Figure 1.

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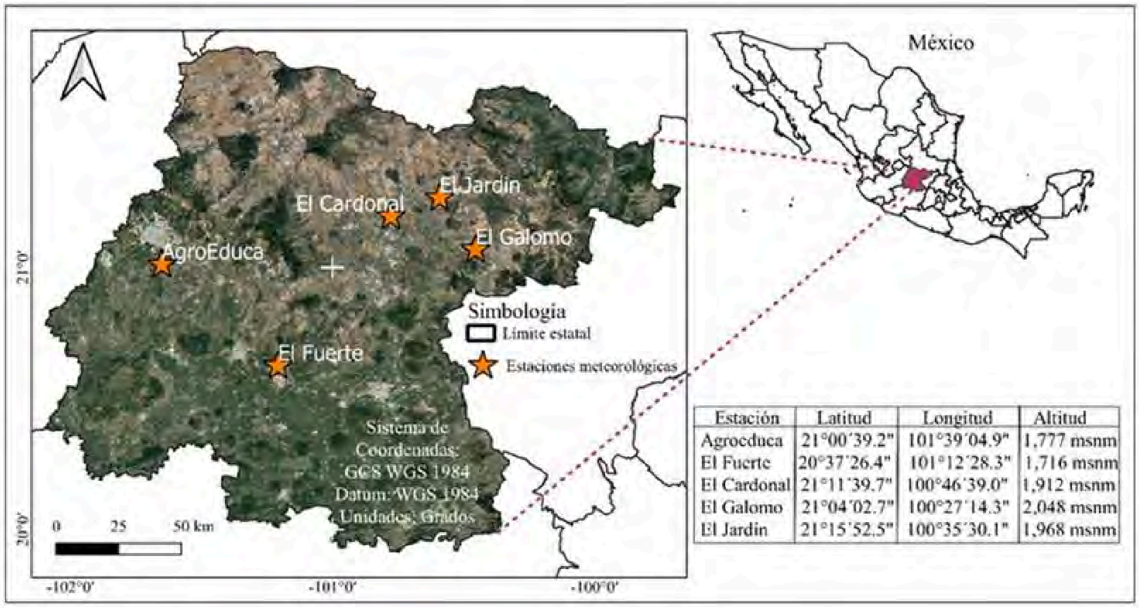
Figure 1. Location of automatic stations in the state of Guanajuato.



Estación	Latitud	Longitud	Altitud
Agroeduca	21°00´39.2"	101°39´04.9"	1,777 msnm
El Fuerte	20°37´26.4"	101°12´28.3"	1,716 msnm
El Cardonal	21°11´39.7"	100°46´39.0"	1,912 msnm
El Galomo	21°04´02.7"	100°27´14.3"	2,048 msnm
El Jardin	21°15´52.5"	100°35´30.1"	1,968 msnm

Weather information

The study period is from 2001 to 2006 since it is common for the five stations where the following hourly data are available: air temperature (°C), relative humidity (%), wind speed (m s-1), and solar radiation (MJ m-2). All meteorological variables are measured at a height of 2 m.

The quality of the data of the temporal meteorological series of each station was assessed visually, determining that the behavior of each of the variables used was correct, for example, that the temperature showed its maximum or minimum values in the corresponding months. One way to determine data quality would be to compare it with data from conventional stations, which would be the subject of another paper.

FAO56 Penman-Monteith (FAO56 P-M) method

In May 1990, a panel of experts and researchers in irrigation was organized by the Food and Agriculture Organization of the United Nations (FAO) in cooperation with the International Commission on Irrigation and Drainage (ICID) and the World Meteorological Organization (WMO) to review the methodologies for calculating crop water requirements previously proposed by FAO and based on this, make recommendations and updates thereof (Allen *et al*., 2006).

The FAO56 Penman-Monteith (FAO56 P-M) method is recommended as the only standard method for estimating reference evapotranspiration with climatic parameters and its equation is:

$$ET_0=\frac{0.408\Delta(R_n-G)+\gamma\frac{900}{T+273}u_2(e_s-e_a)}{\Delta+\gamma(1+0.34u_2)}$$

Where: ET_0 is the reference evapotranspiration in mm day-1; Δ is the slope of the vapor pressure curve in kPa °C-1; R_n is the net radiation on the crop surface in MJ m-2 day-1; G is the soil heat flux in MJ m-2 day-1; γ symbolizes the psychometric constant (kPa °C-1); T represents the average air temperature at 2 m altitude in °C; u_2 is the wind speed at 2 m high in m s-1; e_a indicates the actual vapor pressure in kPa; e_s stands for the saturation vapor pressure in kPa, and e_s-e_a symbolizes the vapor pressure deficit in kPa.

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Hargreaves-Samani (H-S) method

The model developed by Hargreaves and Samani (1985) only requires data on maximum and minimum air temperature and extraterrestrial radiation. The Hargreaves-Samani 1985 (H-S) equation is as follows:

$$ET_0=0.0023R_a(TC+17.8)TD^{0.5}$$

Where: ET_0 is the reference evapotranspiration in mm day-1; R_a represents extraterrestrial solar radiation in mm day-1; TC indicates the average daily temperature in °C and TD is the difference between the daily maximum temperature and the daily minimum temperature in °C.

Priestley-Taylor (P-T) method

The Priestley-Taylor (1972) (P-T) method is a formula that only uses radiation and temperature for the calculation of ET_0; it calculates the ET_0 component as a result directly from radiation, and augments it with a coefficient, which can be calibrated according to local conditions (values 1.12 or 1.26 are usually used) (Sheikh and Mohammadi, 2013):

$$ET_0=\propto\frac{\Delta}{\Delta+\gamma}(R_n-G)$$

Where: ET_0 is the reference evapotranspiration in mm day-1; α is an empirically derived (dimensionless) constant; ∆ symbolizes the slope of the saturated vapor pressure curve at the average air temperature in kPa °C-1; γ represents the psychometric constant in kPa °C-1; R_n is the net radiation, and G is the soil heat flux, both variables in mm day-1.

Comparison between methods

A first comparison was made to evaluate the Hargreaves-Samani and Priestley-Taylor methods with respect to the FAO56 Penman-Monteith method to select the best method in each station. Then, for each station, six comparisons were made, first each method against itself and then each method against the remaining two, so the combination of the comparisons was as follows: FAO56 Penman-Monteith vs FAO56 Penman-Monteith, FAO56 Penman-Monteith vs Hargreaves-Samani, FAO56 Penman-Monteith vs Priestley-Taylor, Hargreaves-Samani vs Hargreaves-Samani, Hargreaves-Samani vs Priestley-Taylor, and Priestley-Taylor vs Priestley-Taylor; the above was to determine the distance from a station where the estimated data of a method can be considered as valid.

Statistics and evaluation of methods

The root mean square error (RMSE) (Willmott, 1982) was used as it assesses how closely predictions match observations. Values can range from 0 (perfect fit) to +∞ (no fit) depending on the relative range of the data:

$$RMSE=\sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i-O_i)^2}$$

Where: n is the number of observations; O_i is observed or measured values; and P_i are predicted or estimated values.

The coefficient of determination (R2) (Tomás-Burguera *et al*., 2017) denotes the proportional amount of variation in the response variable (y), explained by the independent variable (x) in the linear regression model, ranging from 0 to 1, a value of 0 indicates that (x) does not explain the variations of (y), while a value of 1 suggests that (x) explains the total variations of (y). The higher the R2, the greater the variability explained by the linear regression model, so the use of this statistic was proposed:

$$R^2 = \left(\frac{\sum_{i=1}^{n} (O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n} (O_i - \bar{O})^2} \sqrt{\sum_{i=1}^{n} (P_i - \bar{P})^2}} \right)^2$$

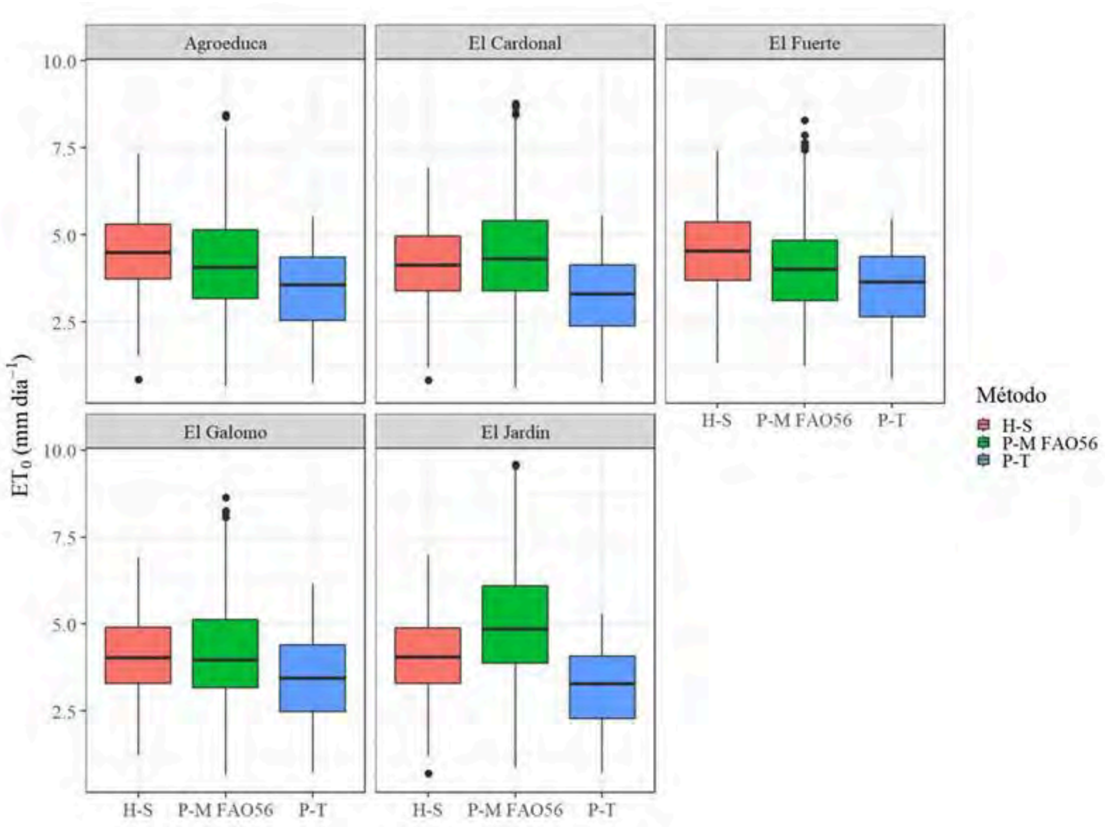
The meaning of the variables used in the coefficient of determination is the same as those of the RMSE.

Results and discussion

Statistical summary

Figure 2 shows the distribution and behavior of the ET_0 values estimated for each of the methods in each station. For the five stations, the FAO56 P-M method presented greater variation in the distribution of the values since the interquartile range or size of the box is larger; it is also observed that this method has a greater presence of outliers, especially maximum values, which was more noticeable in the El Cardonal, El Fuerte, and El Galomo stations; on the other hand, the H-S method was the one that showed the least variation in the distribution of ET_0 values for all stations.

Figure 2. Behavior of ET_0 values for each of the methods and each station.



According to the value of the mean, the median, and the position of the interquartile range, the highest values were yielded by the H-S method at the Agroeduca (4.57 and 4.5 mm day-1) and El Fuerte (4.56 and 4.53 mm day-1) stations, while at the El Cardonal (4.44 and 4.32 mm day-1), El Galomo (4.16 and 3.99 mm day-1) and El Jardín (5.03 and 4.87 mm day-1) stations, it was the FAO56 P-M method; in contrast, the lowest values were shown by the P-T method for the five stations (3.46 and 3.58 mm day-1 for Agroeduca, 3.28 and 3.31 mm day-1 for El Cardonal, 3.5 and 3.66 mm day-1 for El Fuerte, 3.45 and 3.45 mm day-1 for El Galomo, 3.22 and 3.29 mm day-1 for El Jardín) (Figure 2).

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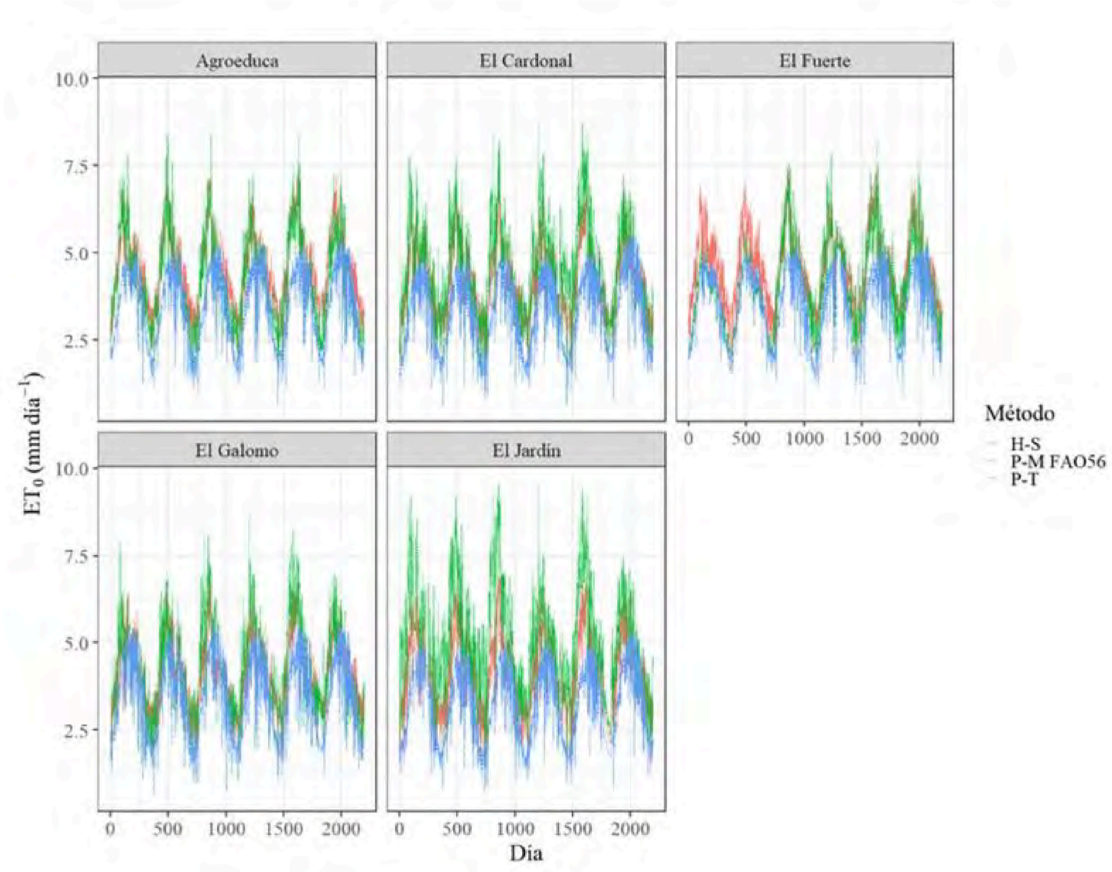
ET_0 temporal distribution

The temporal distribution of daily ET_0 estimated with each of the methods is shown in Figure 3. At the Agroeduca and El Fuerte stations, it is seen that the curves of the results of the FAO56 P-M (green line) and H-S (red line), as well as their distributions, are similar; at the El Cardonal, El Galomo and El Jardín stations, the curve of FAO56 P-M has the highest values, followed by the curve of H-S, the difference is more marked at the El Jardín station, where the presence of very high values (≈9 mm day-1) was observed throughout the period. On the other hand, the lowest values for the five stations are shown by P-T (blue line).

Figure 3. Temporal distribution of daily ET0 in the five stations.

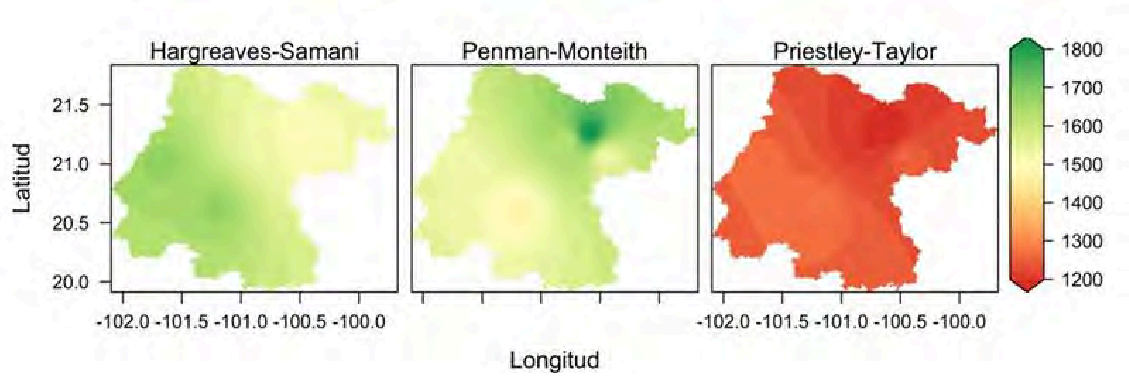


In general, the three methods show the same trend during the 2 191 days that correspond to the study period (2001-2006); likewise, the annual behavior of the results of each method was analyzed; that is, the values at the beginning of each year are low and, as the days go by, they increase until they reach the maximum value located approximately in the middle of the year to begin to decrease and end up with low values at the end of the year, very similar to those at the beginning of the year.

Spatial distribution of ET_0

Figure 4 shows the spatial distribution of average annual ET_0 in the state of Guanajuato, which was obtained as an average of the accumulated annual values of the six years of study. FAO56 P-M showed the highest values with a range from 1 521 to 1 841 mm year-1; the lowest values were found in the area of influence of the Agroeduca station (light color zone), while the highest are visualized in the part corresponding to El Jardín (green zone).

Figure 4. Spatial distribution of annual ET_0 in the state of Guanajuato with the different methods.



FAO56 P-M is followed by H-S, with a range of values between 1 503 and 1 669 mm year-1; the highest values of this method are concentrated in the middle of the state (green color), the lowest (light color) are influenced by the El Cardonal, El Jardín, and El Galomo stations. Finally, P-T showed the lowest values (1 176-1 281 mm year-1) compared to the other methods; the high values of P-T were present in most of the state (light color) as this part is influenced by three stations (Agroeduca, El Fuerte, and El Galomo); on the other hand, the low values were observed at the El Jardín station, mainly where the Agroeduca and El Fuerte stations are located.

FAO56 Penman-Monteith vs H-S and P-T

The H-S and P-T methods were evaluated with the RMSE and R2 values (Table 1). At the Agroeduca and El Fuerte stations, H-S stood out in its performance since it obtained an RMSE value of 0.68 mm day-1 and R2 of 0.82 and RMSE of 0.8 mm day-1 and R2 of 0.75, respectively; although in the latter station, the values of the P-T method were very similar (RMSE= 0.81 mm day-1 and R2= 0.74).

In El Cardonal, H-S presented the best performance, with values of 0.72 mm day-1 and 0.78 for RMSE and R2, respectively. In the remaining two stations, the H-S method also stands out compared to P-T; in the El Galomo station, H-S obtained an RMSE of 0.7 mm day-1 and an R2 of 0.72; in El Jardín, the RMSE was 1.25 mm day-1 and R2 of 0.75.

Table 1. Statistical analysis for the comparison of the empirical methods of H-S and P-T to estimate daily ET_0 in relation to the standard method of FAO56 P-M for the five stations.

Station	Method	RMSE (mm day^{-1})	R^2
Agroeduca	Hargreaves-Samani	0.68	0.82
	Priestley-Taylor	1.02	0.7
El Fuerte	Hargreaves-Samani	0.8	0.75
	Priestley-Taylor	0.81	0.74
El Cardonal	Hargreaves-Samani	0.72	0.78
	Priestley-Taylor	1.46	0.6
El Galomo	Hargreaves-Samani	0.7	0.72
	Priestley-Taylor	1.03	0.68
El Jardín	Hargreaves-Samani	1.25	0.75
	Priestley-Taylor	2.14	0.48

RMSE= root mean square error; R2= coefficient of determination (dimensionless).

In the five stations, the H-S method showed better performance compared to the standard method of FAO56 P-M; similar results were recorded by several authors who have evaluated empirical methods with the FAO56 P-M method: Tabari (2010) indicates that H-S (R2= 0.93 and RMSE= 1.26 mm day-1 average) is a better ET_0 estimator than P-T (R2= 0.92 and RMSE= 1.8 mm day-1) in different climates in Iran; Sabziparvar and Tabari (2010) point out that H-S (R2= 0.96 and RMSE= 20.19 mm month-1 average) performs better than P-T (R2= 0.94 and RMSE= 58.46 mm month-1) in the estimation of ET_0 in the arid and semi-arid regions of eastern Iran; Sheikh and Mohammadi (2013) found that H-S obtained a smaller difference than P-T when compared to FAO56 P-M; Bourletsikas *et al*. (2017) determined that H-S exhibited better performance than P-T in a Mediterranean forest in Greece; for their part, Lang *et al*. (2017) pointed out that H-S was better than P-T in estimating ET_0 in southwestern China.

Comparison between methods

To determine the distance from a station at which a method can be considered valid, the values of RMSE and R2 were evaluated; Ventura *et al*. (1999) point out that an RMSE value less than 50 W m-2 (1.76 mm day-1) is acceptable for practical purposes; in the case of R2, those cases where R2# 0.8 were accepted, according to Lang *et al*. (2017).

A comparison was made between the same methods, resulting in ten combinations (Table 2). When comparing FAO56 P-M vs FAO56 P-M, the best fit resulted from the confrontation of the El Cardonal and El Galomo stations, with the lowest RMSE value (0.6 mm day-1) and the highest R2 value (0.86), so it meets the acceptance condition and a distance of 36.44 km is considered; Figure 5a shows that this comparison is close to a 1:1 line.

Table 2. Statistical analysis for comparison between the same methods.

Station 1	Station 2	Distance (km)	P-M vs P-M				H-S vs H-S	P-T vs P-T
			RMSE	R^2	RMSE	R^2	RMSE	R^2
Agroeduca	El Fuerte	62.99	0.69	0.73	0.36	0.89	0.35	0.88
Agroeduca	El Cardonal	93.06	0.76	0.74	0.52	0.89	0.45	0.85
Agroeduca	El Galomo	124.65	0.72	0.72	0.61	0.86	0.47	0.81
Agroeduca	El Jardín	113.63	1.23	0.68	0.65	0.83	0.49	0.84
El Fuerte	El Cardonal	77.43	0.97	0.61	0.57	0.84	0.48	0.83
El Fuerte	El Galomo	92.58	0.8	0.65	0.65	0.82	0.48	0.81
El Fuerte	El Jardín	95.62	1.51	0.5	0.68	0.79	0.52	0.82
El Cardonal	El Galomo	36.44	0.6	0.86	0.24	0.95	0.43	0.87
El Cardonal	El Jardín	20.8	0.9	0.82	0.28	0.94	0.33	0.9
El Galomo	El Jardín	26.11	1.14	0.79	0.3	0.92	0.43	0.89

P-M= FAO56 Penman-Monteith; H-S= Hargreaves-Samani; P-T= Priestley-Taylor; RMSE= root mean square error (mm day-1); R2= coefficient of determination (dimensionless).

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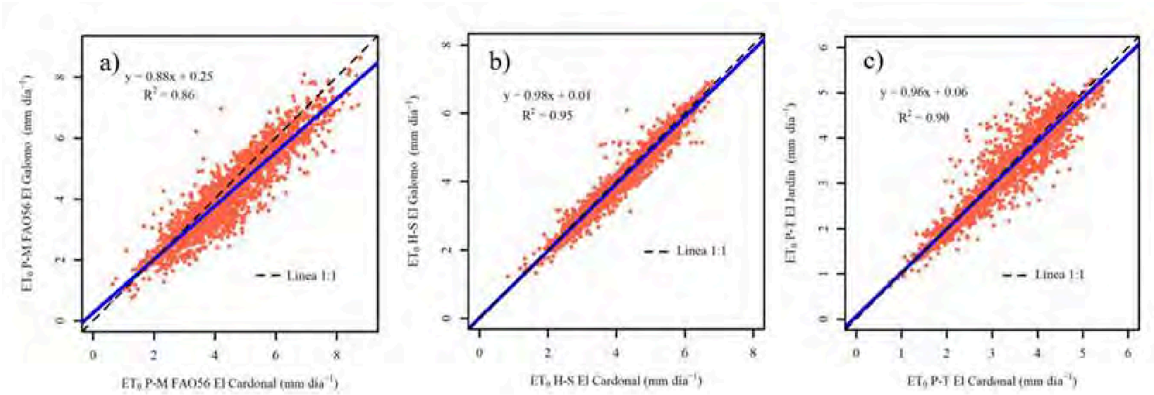
Figure 5. Linear regression between ET_0 values: a) El Cardonal (FAO56 P-M) vs El Galomo (FAO56 P-M); b) El Cardonal (H-S) vs El Galomo (H-S); and c) El Cardonal (P-T) vs El Jardín (P-T).



In the H-S vs H-S comparison, the best performance was obtained between El Cardonal and El Galomo; the almost perfect fit can be seen in Figure 5b, where it was seen that the fit model almost coincides with the 1:1 line; all combinations satisfy the condition mentioned above, except for El Fuerte and El Jardín, so the distance less than the distance between them (95.62 km) is taken; thus a distance of 93.06 km is defined.

In the third comparison (P-T vs P-T), when contrasting the El Cardonal and El Jardín stations, the lowest value of RMSE (0.33 mm day-1) was found, with an R2 of 0.9; this fit is seen in Figure 5c, where all combinations satisfy the acceptance condition, so all distances are valid and the largest (124.65 km) is taken.

Regarding the comparisons between different methods, 25 combinations were obtained for each (Table 3). Only one combination met the acceptance conditions and was Agroeduca (FAO56 P-M) with Agroeduca (H-S), but, as the distance between stations was 0 km, it was not considered valid.

Table 3. Statistical analysis for comparison between different methods.

Station 1	Station 2	Distance (km)	P-M vs H-S				P-M vs P-T	P-T vs P-T
			RMSE	R^2	RMSE	R^2	RMSE	R^2
Agroeduca	Agroeduca	0	0.68	0.82	1.02	0.7	1.26	0.7
Agroeduca	El Fuerte	62.99	0.74	0.76	1.03	0.65	1.22	0.69
Agroeduca	El Cardonal	93.06	0.73	0.68	1.21	0.62	1.42	0.7
Agroeduca	El Galomo	124.65	0.76	0.66	1.06	0.65	1.28	0.69
Agroeduca	El Jardín	113.63	0.78	0.64	1.26	0.61	1.49	0.67
El Fuerte	Agroeduca	62.99	0.83	0.72	0.91	0.66	1.26	0.69
El Fuerte	El Fuerte	0	0.8	0.75	0.81	0.74	1.18	0.77
El Fuerte	El Cardonal	77.43	0.79	0.59	1.04	0.65	1.42	0.68
El Fuerte	El Galomo	92.58	0.8	0.58	0.92	0.65	1.27	0.69
El Fuerte	El Jardín	95.62	0.83	0.55	1.09	0.63	1.49	0.66
El Cardonal	Agroeduca	93.06	0.71	0.76	1.4	0.49	0.98	0.64
El Cardonal	El Fuerte	77.43	0.77	0.7	1.37	0.49	0.93	0.65
El Cardonal	El Cardonal	0	0.72	0.78	1.46	0.6	1.09	0.7
El Cardonal	El Galomo	36.44	0.78	0.75	1.33	0.6	0.97	0.68
El Cardonal	El Jardín	20.8	0.79	0.74	1.54	0.54	1.17	0.65
El Galomo	Agroeduca	124.65	0.82	0.71	1.18	0.48	0.95	0.61
El Galomo	El Fuerte	92.58	0.85	0.68	1.14	0.5	0.9	0.62

Station 1	Station 2	Distance (km)	P-M vs H-S				P-M vs P-T	P-T vs P-T
			RMSE	R^2	RMSE	R^2	RMSE	R^2
El Galomo	El Cardonal	36.44	0.73	0.7	1.24	0.57	1.05	0.66
El Galomo	El Galomo	0	0.70	0.72	1.03	0.68	0.92	0.67
El Galomo	El Jardín	26.11	0.75	0.68	1.28	0.56	1.12	0.63
El Jardín	Agroeduca	113.63	1.03	0.69	2	0.39	0.98	0.59
El Jardín	El Fuerte	95.62	1.08	0.64	1.94	0.42	0.93	0.61
El Jardín	El Cardonal	20.8	1.23	0.71	2.11	0.46	1.07	0.64
El Jardín	El Galomo	26.11	1.29	0.71	1.93	0.51	0.96	0.63
El Jardín	El Jardín	0	1.25	0.75	2.14	0.48	1.13	0.62

P-M= FAO56 Penman-Monteith; H-S= Hargreaves-Samani; P-T= Priestley-Taylor; RMSE= root mean square error (mm day-1); R2= coefficient of determination (dimensionless).

Conclusions

Reference evapotranspiration (ET_0) was estimated with the FAO56 Penman-Monteith (FAO56 P-M), Hargreaves-Samani (H-S), and Priestley-Taylor (P-T) methods for five automatic stations in the state of Guanajuato for daily periods; it was found that the FAO56 P-M method presented a greater variation in the distribution of the estimated ET_0 values in all stations, while H-S is the one that had the slightest variation.

After comparing the data estimated with H-S and P-T against FAO56 P-M, it is pointed out that the H-S method is the best alternative method to estimate ET_0 in the five stations since its values are the closest to those estimated with FAO56 P-M; therefore, the H-S method can be adopted as an alternative method to estimate ET_0 in the state of Guanajuato. In the comparison between methods, for P-T vs P-T, a distance of 124.65 km was defined from any station where the data estimated with P-T can be considered valid; for H-S vs H-S, a distance of 93.02 km was specified, and for FAO56 P-M vs FAO56 P-M, the distance was 36.44 km.

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