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Abstract: Methods of calculating evapotranspiration are subject to uncertainty. It is important to evaluate their uncertainty. Using 54 years of data, this study evaluated the uncertainty values of monthly reference crop evapotranspiration calculated with the FAO-56 Penman-Monteith and Hargreaves-Samani methods. The objective of this study was to determine the range of variation in the results of each method. It was found that for both methods, the bandwidth uncertainty obtained with 95% confidence interval was more in warm months than in cold months, and the mean and variance by the Hargreaves-Samani method were always less than by the FAO-56 Penman-Monteith method. The uncertainty value of the FAO-56 Penman-Monteith method was more than of the Hargreaves-Samani method, because the number of parameters used in the FAO-56 method was more than in Hargreaves-Samani method which increased uncertainty resources.

Keywords: bootstrap; FAO-Penman-Monteith; Hargreaves-Samani; uncertainty.

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1 Introduction

Evapotranspiration (ET) is one of the most important components of the hydrologic cycle and its estimation is required for a range of studies, including water balance, design and management of irritation systems, simulation, planning and management of water resources (Allen et al., 1998). However, too many parameters involved in the calculation of ET on one hand, and the inability to measure some parameters on the other hand, have made it difficult to accurately estimate ET in some regions (Kouchakzade and Bahmani, 2005). ET is a complex nonlinear phenomenon and results of measurement methods with respect to climatic factors involve significant errors. Moreover, such methods often need numerous input data whose measurement is often difficult, time consuming and expensive (Shayannejad, 2006).

Reference evapotranspiration (ET_{ref} or ET_0), defined as the potential evapotranspiration of a hypothetical surface of actively growing and adequately watered green grass, is one of the most important hydrological variables (Gong et al., 2006). ET_{ref} represents a measure of the evaporative demand of the atmosphere independent of crop type, crop development and management practices. It is affected by only climatic factors (Gong et al., 2006; Wen et al., 2010) and consequently is a climatic parameter and can be computed from meteorological data (Gong et al., 2006).

Different methods have been applied to estimate potential evapotranspiration, including temperature and radiation based methods, mass transfer equations, combination and evaporation pan (Singh and Xu, 1997; Xu and Singh, 2001). The Penman-Monteith method is a combination method that has been widely used as a standard method (Gao, 2010). As this method requires numerous climatic data, and at many meteorological stations the measured data are limited to air temperature, FAO has introduced the Hargreaves-Samani method as an alternative due to its effectiveness and reasonable accuracy (Allen et al., 1998). Meteorological parameters are the key source of required data for measuring evapotranspiration and at the same time, they are the main sources of uncertainty. The key element in the calculation of water budget is the estimation of evapotranspiration that generally presents fundamental sources of uncertainty (Kingston et al., 2009). Beven (1993) proposed that uncertainty must enter into modelling activities.

Akhavan et al. (2009) investigated uncertainty in the values of blue water (sum of surface runoff and deep groundwater recharge), green water flow (real evapotranspiration), and green water supply (the water available in soil profile) calculated by the SWAT model in Hamadan – Bahar watershed using SUFI2 Software, and concluded that in general, the range of monthly mean uncertainty for blue water was greater than that of other elements. It was more significant in early months of spring. They attributed this big value of uncertainty to the inability of SWAT in simulating snow melting in mountainous regions at the end of winter and in early spring. Contrary to blue water, the range of uncertainty in monthly mean of green water flow (real evapotranspiration) is smaller than in other elements. The reason is that green water supply is controlled only by a single factor, i.e., soil evaporation compensation factor. In other words, this element is sensitive to less number of parameters. While all calibration parameters control blue water, the range of uncertainty related to green water supply (soil moisture) is smaller than of blue water and bigger than of green water flow.

In another study, Rostamian et al. (2008) simulated runoff discharge and sediment concentration in Behesht Abad basin (Sub-Basin of North Karoon River) using the SWAP model and reported that this model would yield good estimation of runoff, and the more uncertainty of input data, the more uncertainty of output would be.

Westerhoff (2015) used uncertainty of Penman and Penman-Monteith methods in combined satellite and ground-based evapotranspiration estimates. The results uncertainty analisis showed that: ET_0 is sensitive to temperature, solar radiation, relative humidity, and cloudiness ratio respectively and calculated uncertainty values were between 10% and 40% of ET_0, and it was depended on the ET_0 value.

Badgley et al. (2015) studied on uncertainty in global terrestrial evapotranspiration estimates from choice of input forcing datasets. In this research Priestly-Taylor JPL (PT-JPL) method was run with 19 different combinations of forcing data. The results showed that choice of net radiation dataset is main source of disagreement between input forcing results also showed that ISCCP data is widely different from the other radiation products examined and caused to dramatically different estimates of global terrestrial ET.

As mentioned above the accuracy of calculated ET_0 is depended on calculation methods and sensitivity of the method to each parameter and uncertainties of calculated ET_0 should be considered. Finally, we hope to highlight the importance of accounting uncertainty in calculation of ET in irrigation networks design and water resource management.

1.1 Materials and methods

The FAO56-Penman-Monteith equation is:

$$ET_0 = \frac{0.408\Delta(Rn - G) + \gamma(900(Tmean + 273))U_2(es - e)}{\Delta + \gamma(1 + 0.34U2)} \quad (1)$$

$$\Delta = \lambda.es/\left(Rv\ Tmean^2\right) \quad (2)$$

$$\gamma = cp.P(\varepsilon.\lambda) \quad (3)$$

$$es = 2.53 \times 10^8.\exp(-5,420/(Tmean + 273)) \quad (4)$$

$$e = UR.es \quad (5)$$

where ET_0 is the reference evapotranspiration (mm.day–1); D is the slope of the vapour pressure curve (kPa.ºC-1); Rn is the net radiation at the crop surface (MJ. m-2 day-1); G is the soil heat flux density (MJ. m-2 day-1); Tmean is the daily mean air temperature at 2 m height (°C); U2 is the wind speed at 2 m height (m.s-1); es is the saturation vapour pressure (kPa); e is the actual vapour pressure (kPa); UR is the relative humidity; (es – e) is the saturation vapour pressure deficit (kPa); γ is the psychrometric constant (kPa.ºC-1); λ is the heat required to vaporise free water (2,450 kJ.m-2.day-1); cp is the specific heat at constant pressure (1.01 kJ.kg-1.K-1); P is the atmospheric pressure (kPa); ε is the ratio molecular weight of water vapour/dry air, which is equal to 0.622. (Fernandes et al., 2012)

The Hargreaves-Samani equation is:

$$ET_0 = 0.0023(Tmean + 17.8).(Tmax - Tmin)0.5.Ra$$

where Tmax is the daily maximum temperature (ºC); Tmin is the daily minimum temperature (ºC) (Fernandes et al., 2012).

Figure 1 Isfahan Synptic station location in Iran map (see online version for colours)

The study area was the synoptic station in Isfahan classified as steppe in Koppen climate classification system. The characteristics of this station are summarised in Table 1. Monthly meteorological data for a period of 55 years (1951–2005), that included maximum temperature (Tmax), minimum temperature (Tmin), wind speed at 2 metres' height (U), maximum relative humidity (RHmax), minimum relative humidity (RHmin) and sunlight duration, were collected from Iran meteorological organisation, based on Gregorian calendar, and were qualitatively controlled. The variations of mentioned parameters during 55 years were separated by different months, as illustrated in Figures 2 to 5.

Table 1 Characteristics of Isfahan synoptic station

Longitude (East)	*Latitude (North)*	*Elevation (M)*	*Max temp (°C)*	*Min temp (°C)*	*Mean relative humidity (%)*	*Wind speed (m/s)*
51/4	32/37	1,550/4	23/41	9/06	41/47	2/08

Figure 2 Temperature variations in different months of the year

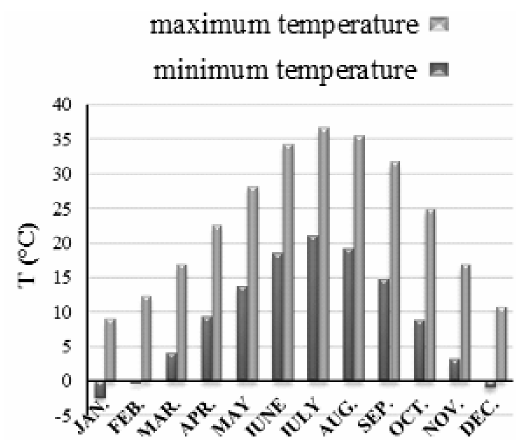


Figure 3 Relative humidity variation in different months of the year

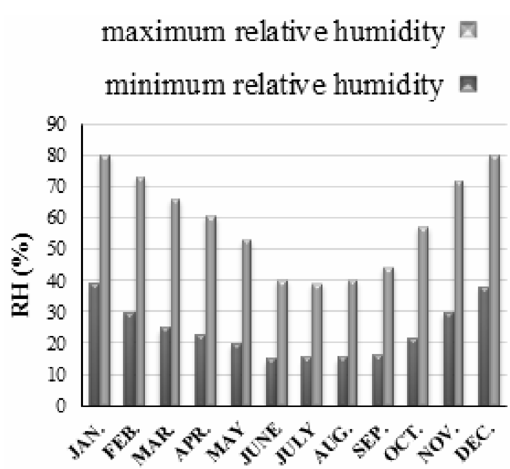


Figure 4 Sunlight duration variations in different months of the year

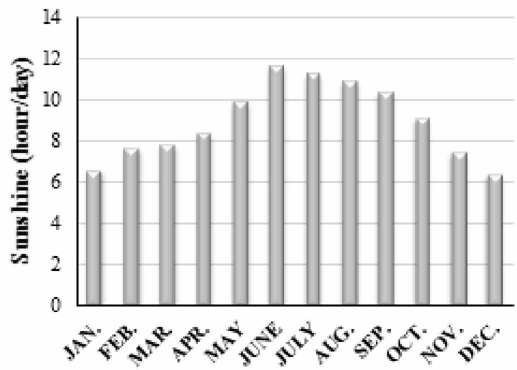


Figure 5 Wind speed variations in different months of the year

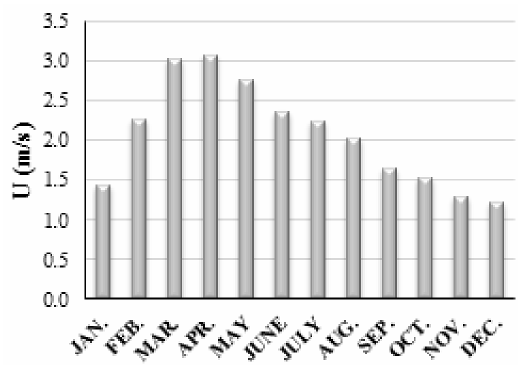
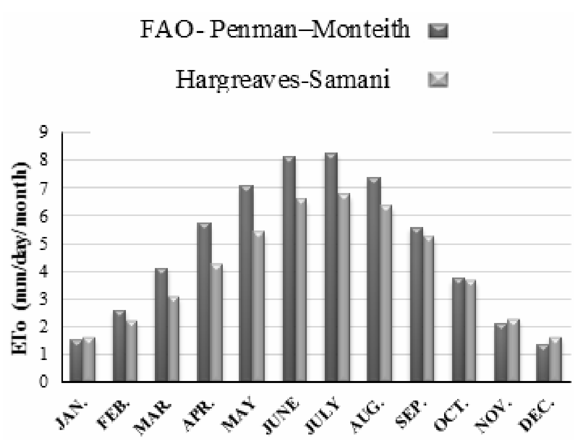


Figure 6 ET_{ref} variations calculated in different months of the year



Daily reference evapotranspiration in each month (mm/day/month) was calculated using calculator ET_0 software developed based on FAO-Penman-Monteith equation (Raes et al., 2009), with accuracy of one decimal degree (Figure 6). This software is able to calculate ET_{ref} with minimum number of data (maximum and minimum temperature) using the Hargreaves-Samani equation.

Errors in measurement of climatic parameters, as well as in the theoretical – empirical methods used for the estimation of reference evapotranspiration, are sources of uncertainty in the calculated values. It should be noted that the aim of this study was not to validate and compare results with observations, but to calculate and analysed the variation intervals for the results of each method. Confidence intervals provide information about the uncertainty in estimation of mean and variance.

In the present study, bootstrap, the most popular non-parametrical method to find mean confidence intervals, was used. This method was published by Efron in 1979 to evaluate sample accuracy and distribution. The basic idea of bootstrap consists of resampling a large number of new data set by replacing with original data set. This method starts with a sample of size 'n' and its algorithm is as follows:

1 Create a sample of size 'n' by replacing real sample.

2 Calculate mean or variance of new sample, m1,

3 Iterate 1,000 times steps 1 and 2 and calculate mean and variance of the i^{th} sample, mi.

4 Draw mean or variance distribution of 1,000 samples.

5 Create 95% confidence intervals for mean or variance finding 2.5% and 97.5% of the built distribution

To perform this analysis, the SPLUS2000 Software was used. in bootstrap test, having separated the calculated data based on Gregorian calendar months, these data were transferred to SPLUS environment and bootstrap test was run on data defining a code for each parameter. In this test, according to input data, a time series was created such that it would be homogenous.

2 Results and discussion

For monthly evapotranspiration of reference plant calculated by the two methods, i.e., FAO-Penman-Monteith and Hargreaves-Samani using SPLUS2000 software, the required statistics of bootstrapped mean and variance of data were computed. The mean values and upper/lower limits of bootstrapped mean of ET_0 calculated by FAO-Penman-Monteith and Hargreaves-Samani methods are presented in Table 2. It can be seen that the calculated values by the Hargreaves-Samani method were lower than the calculated values by the FAO-Penman-Monteith method except for January, October and November. The greatest difference between two methods was observed in warm months. The maximum value of evapotranspiration occurred in July for both methods, on 6/775 for the Hargreaves-Samani method and on 8/26 for the FAO-Penman-Monteith method, whereas the minimum value for the Hargreaves-Samani was 1/592 in January and for the FAO-Penman-Monteith was 1/373 in December.

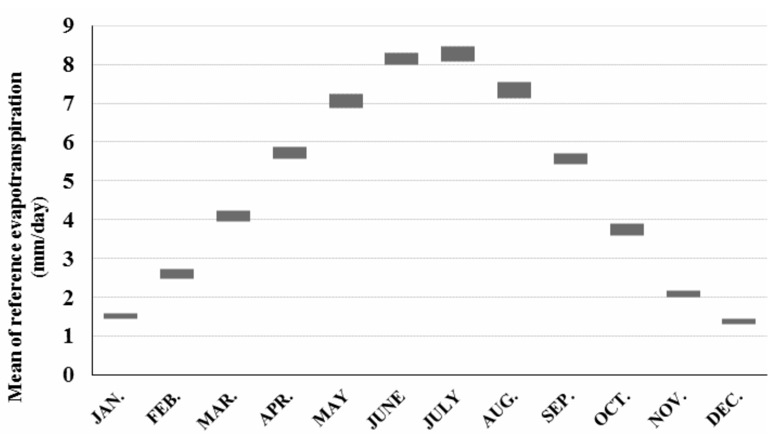
The range of calculated uncertainty for bootstrapped mean of ET_0 data for the FAO-Penman-Monteith method for different months of the year are presented in Figure 7. It started from 0.15 in January and continued to increase until July that reached the maximum value, i.e., 0.41. Then, it passed a uniform decreasing trend until December in which it reached to the minimum value, i.e., 0.12. In general, it can be concluded that results of computation in the warm months have lower uncertainty than in cold months.

The range of calculated uncertainty for the bootstrapped mean of ET_0 data in the Hargreaves-Samani method for different months of the year are presented in Figure 8. The variations of uncertainty in this method were more or less similar to those of the FAO-Penman-Monteith method. It started from 0.11 in January and continued to increase until May that reached the maximum value, i.e., 0.2, then followed a relatively uniform decreasing path until December in which it reached the minimum value, i.e., 0.09. Once again in this method, results of computations for warm months had higher uncertainty than for cold months. The sensitivity of the methods to temperature in the warm months of the year in Isfahan Station (Ahmadnejad et al., 2011) can explain the increased uncertainty in high temperatures.

Table 2 Mean values and upper/lower limits of bootstrapped mean of ET_0 calculated with 95% confidence interval

Month	*FAO-Penman-Monteith*			*Hargreaves-Samani*		
JAN.	2/5%	Mean	97/5%	2/5%	Mean	97/5%
FEB.	1/438	1/511	1/593	1/535	1/592	1/647
MAR.	2/489	2/606	2/722	2/142	2/204	2/266
APR.	3/956	4/097	4/235	2/980	3/049	3/116
MAY	5/562	5/712	5/865	4/154	4/240	7/333
JUN.	7/991	8/133	8/287	6/480	6/567	6/662
JUL.	8/062	8/260	8/476	6/678	6/775	6/875
AUG.	7/138	7/338	7/535	6/231	6/323	6/415
SEP.	5/416	5/565	5/718	5/135	5/214	5/295
OCT.	3/594	3/734	3/884	3/556	3/635	3/709
NOV.	2/005	2/091	2/180	2/215	2/274	2/333
DEC.	1/316	1/373	1/436	1/564	1/611	1/658

Figure 7 Range of calculated uncertainty for bootstrapped mean of ET_0 data for the FAO-Penman-Monteith method



Comparison of uncertainty for the means in two methods revealed that the calculated uncertainty for the Hargreaves-Samani method was lower than for the FAO-Penman-Monteith method, except for December. However, it should be noted that the calculated range of uncertainty was trivial compared to the value of mean evapotranspiration, in the Hargreaves-Samani method, this uncertainty was at most 6% and in the FAO-Penman-Monteith method was at most 10% of the mean value.

Figure 8 Range of calculated uncertainty for bootstrapped mean of ET_0 data for the Hargreaves-Samani method

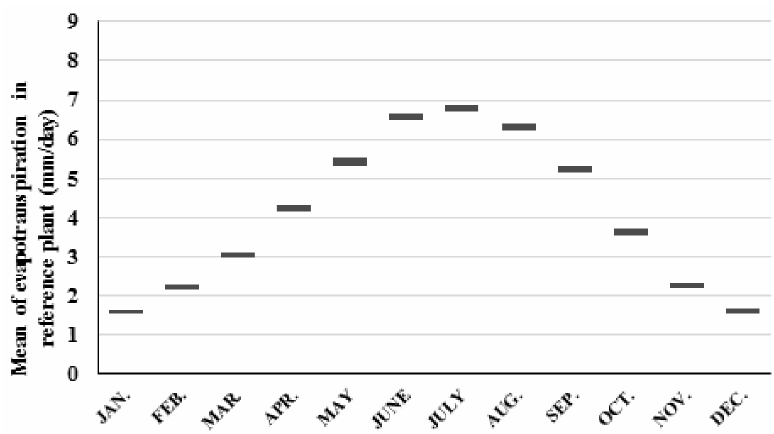


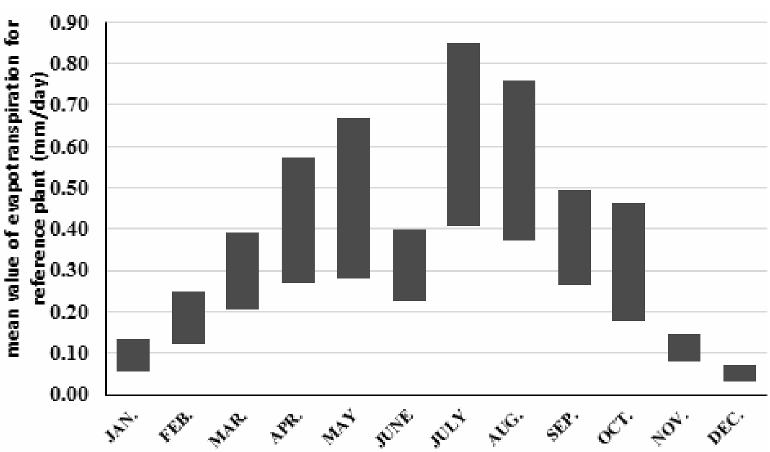
Table 3 Mean values and upper/lower limits of bootstrapped variances of ET_0 calculated with 95% confidence interval

Month	*FAO-Penman-Monteith*			*Hargreaves-Samani*		
	2/5%	*Mean*	*97/5%*	*2/5%*	*Mean*	*97/5%*
JAN.	0/057	0/094	0/135	0/031	0/045	0/060
FEB.	0/123	0/181	0/250	0/037	0/056	0/079
MAR.	0/204	0/293	0/393	0/046	0/065	0/088
APR.	0/268	0/409	0/572	0/079	0/119	0/162
MAY	0/282	0/461	0/667	0/079	0/128	0/184
JUN.	0/224	0/313	0/401	0/071	0/109	0/149
JUL.	0/409	0/620	0/848	0/076	0/117	0/158
AUG.	0/371	0/556	0/760	0/094	0/131	0/174
SEP.	0/264	0/372	0/495	0/058	0/090	0/126
OCT.	0/179	0/308	0/461	0/051	0/078	0/110
NOV.	0/080	0/114	0/148	0/034	0/049	0/065
DEC.	0/033	0/052	0/073	0/019	0/031	0/044

Results obtained from the uncertainty of variances differed with the uncertainty of mean values. Mean values and upper/lower limits of bootstrapped variances of ET_0 calculated by the two methods, i.e., FAO-Penman-Monteith and Hargreaves-Samani, with 95% confidence interval are presented in Table 3. The values of mean, upper limit, and lower limit calculated for the bootstrapped variance of ET_0 through the Hargreaves-Samani method was always lower than for the FAO-Penman-Monteith method. The mean values calculated for variances for warm months were higher than the calculated values for cold months. But the variation of this parameter did not follow a regular trend. The maximum value calculated for the variance of evapotranspiration occurred in August; it was 0.13 and 0.56 for the Hargreaves-Samani method and the FAO-Penman-Monteith method, respectively. The minimum value calculated for this parameter was observed in December, i.e., 0.03 and 0.05 for the Hargreaves-Samani method and the FAO-Penman-Monteith method, respectively.

The range of calculated uncertainty for the bootstrapped variance of ET_0 data for the FAO-Penman-Monteith method for different months of the year are presented in Figure 9. It started from 0.077 in January and continued to increase until in July when it reached the maximum value, i.e., 0.44, then it decreased and in December reached the minimum value of the year, i.e., 0.04. In this method, the variance of computational results in warm months of the year had higher uncertainty than in cold months.

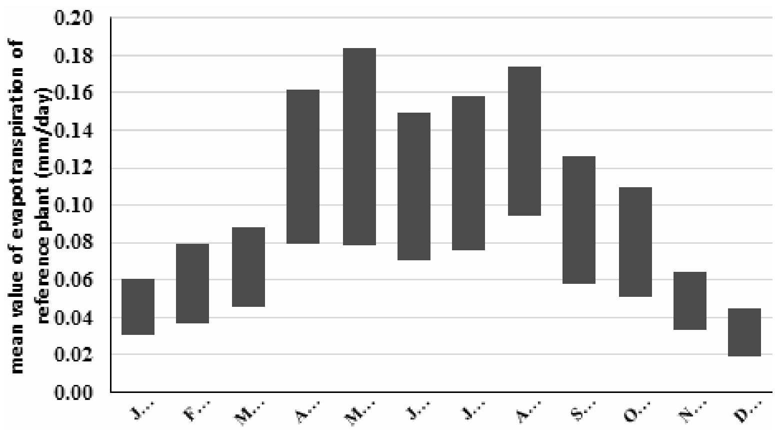
Figure 9 Range of uncertainty calculated for bootstrapped variance of ET_0 data by the FAO-Penman-Monteith method



The range of calculated uncertainty for bootstrapped variance of ET_0 data for the Hargreaves-Samani method for different months of the year are presented in Figure 10. It started from 0.03 in January and continued to increase until in May when it reached the maximum value, i.e., 0.2, then it decreased through a non-uniform trend and in December reached to the minimum value of the year, i.e., 0.025. For this method, it can be concluded that computational results in warm months had higher uncertainty compared to cold months. Once again, it is resulted from the sensitivity of the methods to variations in high temperature.

Compared to FAO-Penman-Monteith method, the uncertainty calculated by the Hargreaves-Samani method had lower values. It is worthwhile that despite the results obtained from variance analysis, the range calculated for variances was significant compared to values of evapotranspiration variance. For the Hargreaves-Samani method, this value was maximum 82% and for the FAO-Penman-Monteith method, it was at most 84% of the resulting variance. As in most of the projects and plans in which the FAO-Penman-Monteith and Hargreaves-Samani equations are used to calculate evapotranspiration, the goal is the calculation of mean evapotranspiration, then high values for variance of uncertainty interval will not be problematic, but if in a specific case the value of variance of evapotranspiration is considered, then the resulting values for this parameter should be used with caution.

Figure 10 Range of uncertainty calculated for bootstrapped variance of ET_0 data by the Hargreaves-Samani method



3 Conclusions

There have been numerous studies associated with comparison of calculated ET_0 with observed values and their results confirm the superiority of the FAO-Penman-Monteith to other methods. Therefore, the present study aimed to determine the interval that should be considered in results of each method.

Results suggest that in both methods, the range of uncertainty calculated with 95% confidence interval for mean and variance is higher in warm months than in cold months, and it was generally lower for the Hargreaves-Samani method than for the FAO-Penman-Monteith method. For the Hargreaves-Samani method the maximum and minimum values of uncertainty for mean were 0.094 and 0.203 and the minimum and maximum values of uncertainty for variance were 0.025 and 0.105 in December and May. Moreover, for the FAO-Penman-Monteith, these values were 0.12 and 0.414 for the range of mean uncertainty, and 0.039 and 0.440 for the range of variance uncertainty in December and July. The reason for higher uncertainty of the FAO-Penman-Monteith method compared to the Hargreaves-Samani could be attributed to larger number of parameters used in this method and thus the more source of uncertainty. The increased uncertainty in warm months may be due to increased sensitivity of these methods to variations in high temperature.

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