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Modifying Hargreaves-Samani Equation for Estimating Reference Evapotranspiration in Dryland Regions of Amudarya River Basin

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Abstract

Reference evapotranspiration (ETo) is a key factor in determining the amount of water needed for crops, which is crucial to correct irrigation planning. FAO Penman-Monteith (EToPM) is among the most popular method to estimate ETo. Apparently sometimes it is difficult to compute ETo using Penman-Monteith due to challenges on data availability. FAO Penman-Monteith method requires many parameters (solar radiation, air temperature, wind speed and humidity), while Hargreaves-Samani method calculates ETo based on air temperature. Because Central Asia is a data limited region with weather stations unable to provide all required parameters for the PM method, this study aimed to estimate ETo using the Hargreaves and Samani (HS) method in Karshi Steppe, in Kashkadarya province, in southern Uzbekistan, based on data from 2011 to 2017. Reference evapotranspiration calculated by non-modified HS method is underestimated during the summer months. The reason for this underestimation might be higher air temperature and wind speed during these months. Therefore, the HS method in its original form cannot be used in our study area to estimate ETo. Modification of the EToHS, through application of a bias correction factor, had better performance and allowed improving the accuracy of the ETo calculation for this region. The calculated ETo values can inform decision making and management practices regarding water allocation, irrigation scheduling and crop selection in dry land regions of Amudarya river basin and the greater Central Asia area.

Keywords

Reference Evapotranspiration, Hargreaves-Samani, Penman-Monteith, Amudarya

River Basin

1. Introduction

The population of Central Asia is expected to increase from 60.7 million to around 81 million between 2010 and 2050 [1]. This growth will lead to an increase in food demand, which means that farmers in Central Asia will need to increase crop production either by increasing the amount of agricultural land to grow crops or by improving productivity on existing agricultural lands through irrigation and fertilizer and adopting more innovative methods. The expansion of farming land in Karshi steppe of the Amudarya river Basin is limited by available water resources already fully allocated between users. Climate change is affecting both the water demand and the availability of water resources in the steppe. Over the last 50 years, air temperature in the Amudarya basin has increased by 0.1˚C - 0.2˚C each decade [2]. According to the Centre of Hydrometeorological Service of the Republic of Uzbekistan (UZHYDROMET), mean annual discharge of the Amudarya River will decrease by 6 - 10 percent from now to 2050, with an increased frequency of extreme flows [3] [4] [5]. Increasing temperatures and reduced water availability in the Karshi steppe are expected to increase the pressure on already scarce irrigation water with possible negative impacts on agricultural production. To mitigate these negative impacts, there is a need to develop an optimal approach to better understand the hydrological cycle and changes in evapotranspiration rates. Global warming causes accelerated depletion of glaciers and snow melting, altering streamflow discharge in Central Asia [6] [7]. Rising air temperature and changing precipitation patterns may affect soil water storage, availability of water resources and thus, crop evapotranspiration rates. Therefore, growing water scarcity will require new methodologies and adaptation strategies in the region. However, currently, optimal solutions and methodologies of evapotranspiration analysis in Central Asia are poorly understood and quantified, and adaptation and calibration of widely used approaches applicable to the region still require strong development.

Evapotranspiration (ET) is one of the main geophysical parameters, and its reliable assessment is vital in irrigation water management, water resource planning, distribution and conservation [8]. The quantification of this can lead to the more information and impact on crop yields, etc. Traditionally ET is estimated by multiplying the weather based reference evapotranspiration (ETo) by crop coefficients determined by crop types and the crop growth stage [9]. ET quantification often must be followed by the determination of ETo [10].

There are many methods available for estimation of ET. The selection and applicability of a particular ETo estimation method varies with climatic conditions and accessibility of meteorological information, and the data prerequisites change from method to method [11]. Testing the accuracy of the methods under a new set of conditions is laborious, time consuming and costly, and yet ET data are frequently needed on short notice for project planning or irrigation scheduling design. Some of the ETo estimation methods, such as those suggested by Blaney and Criddle (1950) [12], Makkink (1957) [13], and Priestley and Taylor (1972) [14] required only solar radiation, and that proposed by Hargreaves and Samani (HS) (1985) [15] required only air temperature. Caprio (CP), Irmak, McGuinness-Bordne (MGB), Ritchie (RT), Jensen-Haise (JH), Turc, Thornwaite (TH) and Baier-Robertson (BR) methods (or their modified versions) have also been used to calculate ET in various studies [16]. The FAO Penman-Monteith (EToPM) method [17], the standard method to estimate ETo, considers many parameters related to the evapotranspiration process: net radiation, air temperature, vapor pressure deficit and wind speed; and it has presented very good results when compared to data from lysimeters populated with short grass or alfalfa [18].

However, there are a limited number of meteorological stations where all climate parameters are observed in the region. This is especially true in developing countries where consistent collection of wind speed, humidity and radiation is limited [19]. As mentioned above, HS developed a substitute approach to estimate ETo where only mean maximum and mean minimum air temperature and extraterrestrial radiation are required. Because extraterrestrial radiation can be calculated for a certain day and location, only minimum and maximum temperatures are the parameters that require observation [18]. The HS method is usually chosen with respective to other more complicated equations since it provides reasonably adequate results and requires only maximum and minimum air temperatures [20]. The HS method has been successfully compared with the EToPM using full datasets, or with grass lysimeter data, indicating that the HS method performs well in most climatic regions, with the exception of humid areas where it tends to overestimate ETo [21]. Almorox and Grieser (2015) [22], Cobaner *et al.* (2017) [23], Ferreira *et al.* (2018) [24], Heydari and Heydari (2013) [25], Lima *et al.* (2013) [26], and Morales-Salinas *et al.* (2017) [27] have successfully used calibrated versions of the HS method to calculate ETo for various regions around the world.

According to Lima *et al.* (2013) [26], the Hargreaves-Samani method (EToHSc) calibrated using data of 2011 and 2012, demonstrated better performance (RMSE = 0.52 mm·d^{-1}) and suitability for predicting ETo in sub-humid region of north-eastern Brazil. The utilization of these calibrated ETo equations is recommended in the absence of data of any of the meteorological parameters necessary for the application of EToPM [28].

Therefore, the objective of this study was to evaluate the performance of the HS method to estimate ETo and calibrate HS method to standard EToPM using daily weather datasets for main irrigated zones of Kashkadarya region of Uzbekistan in the Amudarya River Basin.

2. Materials and Methods

2.1. Experimental Site and Field Measurements

The study site is located in the Karshi steppe of Kashkadarya province in southern part of Uzbekistan (located between 37˚59'55"N to 39˚32'47"N latitude and 64˚18'21"E to 67˚42'54"E longitude; see **Figure 1**). Kashkadarya province borders Bukhara, Samarkand and Surkhandarya provinces, and is close to the border with Turkmenistan. The study area has a total population of 491,300 as of 2016 [29]. Geographically, the Karshi steppe is surrounded by mountains on the east and a desert on the west. Climatically, the study area is continental and dry, with precipitation mainly occurring during the winter period. On average, the study area receives about 236 mm of rainfall per year (see **Figure 2**). The area has high summer temperatures (ranges from 27˚C to 35˚C during June, July and August). During the winter, temperatures drop to as low as −2˚C. Due to high summer temperatures and low rainfall, evaporation exceeds precipitation during the period from May to September (see **Figure 2**).

The study period is from 2011 to 2017. The weather data was obtained from the state Karshi weather station installed and operated by UZHYDROMET. The meteo station was established in 1966, and its elevation is 376 meters (Latitude 38.8˚, Longitude 65.717˚; see **Figure 1**). Meteo station tracks and records air temperature, precipitation, wind speed, relative humidity, dew point and sun duration. The measurements are collected at 2.0 meter above the top of the vegetation.

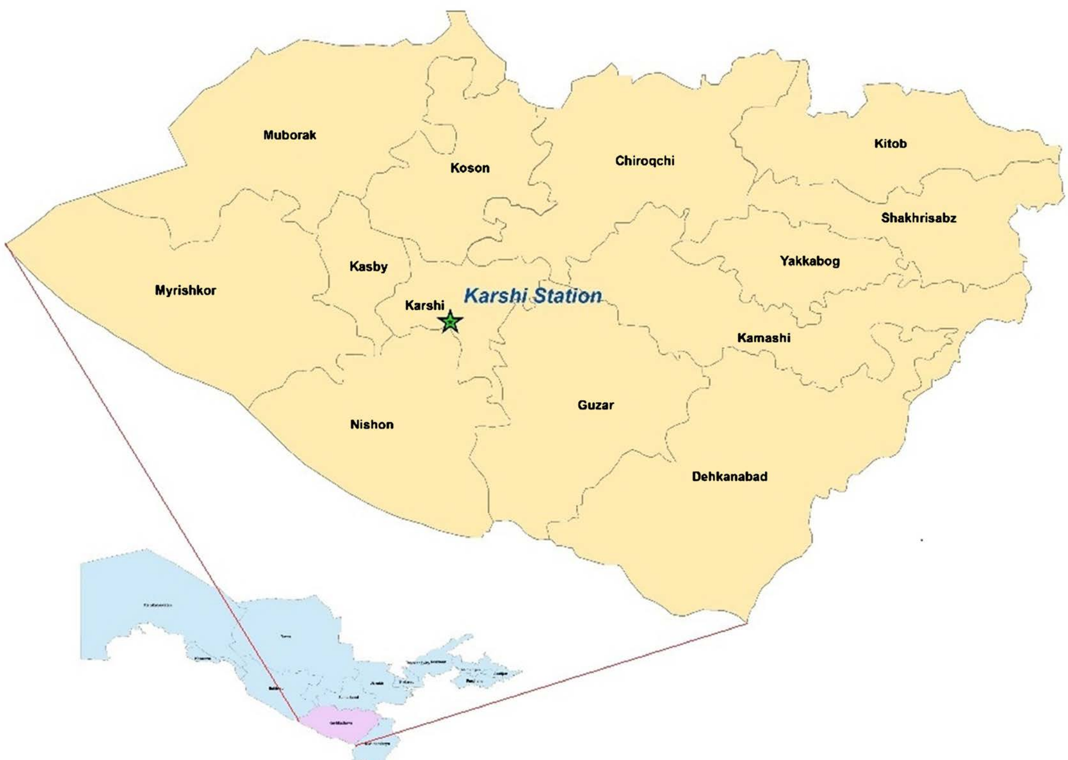

Figure 1. Study area map.

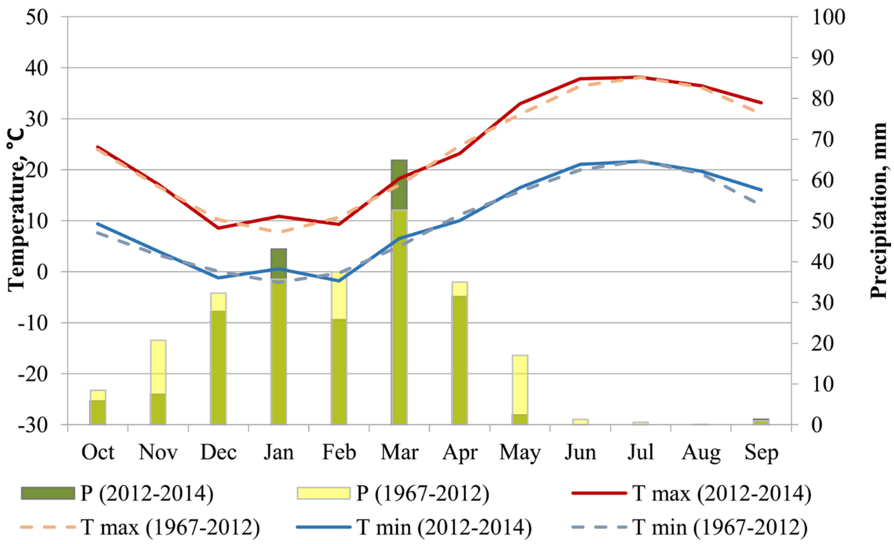

Figure 2. Monthly temperature ranges and monthly precipitation at Karshi site, comparing the long-term data and measurements from the study period.

2.2. Evapotranspiration Estimation Methods

The FAO Penman-Monteith (PM) equation for calculating ETo can be expressed as [30]:

$$\mathrm{ET_0PM} = \frac{0.408 \cdot (Rn - G) + \gamma \dfrac{900}{T_a + 273} U_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 U_2)} \quad (1)$$

where EToPM is reference evapotranspiration (mm day^{-1}), Rn is net radiation at the crop surface (MJ·m^{-2}·day^{-1}), G is soil heat flux density (MJ·m^{-2}·day^{-1}), T_a is mean daily air temperature at 2 meter height (˚C), U_2 is wind speed at 2 meter height (m·s^{-1}), e_s is saturation vapour pressure (kPa), e_a is actual vapour pressure (kPa), Δ is slope vapour pressure curve (kPa ˚C^{-1}), γ is psychrometric constant (kPa·˚C^{-1}).

The Hargreaves-Samani (HS) equation [31] requires less observations, with only $T_{\max}$ (˚C) and $T_{\min}$ (˚C) needed for calculation of reference evapotranspiration:

$$\mathrm{ET_0HS} = 0.0135 \times k_{Rs} \times R_a \sqrt{T_{\max} - T_{\min}} \times (T_a + 17.8) \quad (2)$$

where 0.0135 is a factor for conversion from American to the International system of units, k_{Rs} is the radiation adjustment coefficient (the common value k_{Rs} = 0.17 is used), and T_a is average temperature of day.

2.3. Modification and Validation

To modify the HS equation, we calculated the bias correction factor using the formula suggested by Teutschbeina and Seiberta (2012) [32]. The formula calculates the bias correction factor divides mean monthly evapotranspiration obtained from the PM equation by mean monthly evapotranspiration obtained from the HS equation:

$$\text{Bias Correction Factor}\left(\text{BC}\right) = \text{MMCV}_{\text{PM}} / \text{MMCV}_{\text{HS}} \quad (3)$$

where MMCV is mean monthly climate variable. Weather data from 2011 to 2015 were used for calibration and weather data from 2016 and 2017 were used for validation of the model. Afterwards, the identified bias correction factors for each month were considered in estimation of ETo in HS method for 2016 and 2017. Consequently, statistical performance between the non-calibrated EToHS and EToHSm was checked.

2.4. Evaluation Criteria

For evaluating the results of HS and corrected HS methods, the root mean square error (RMSE), the relative error percentage (REP), coefficients of determination (R^2) and index of agreement (d) [33] were used. The formulas of RMSE and index d are as follows:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}\left(P_i - O_i\right)^2}{n}} \quad (4)$$

$$d = 1 - \frac{\sum_{i=1}^{n}\left(P_i - O_i\right)^2}{\sum_{i=1}^{n}\left(\left|P_i - O\right|\right) + \left|P_i - O\right|)^2} \quad (5)$$

where P_i is predicted values, O_i is observed values, O is average of O_i and n is the total number of data.

3. Results and Discussion

Figure 3 illustrates comparisons of estimated mean monthly ETo values using EToPM and EToHS methods during the years from 2011 to 2017. According to the results, the tendency and majority monthly mean values match up pretty well, with only the non-calibrated HS method underestimating ETo mainly in June, July and August, which contradicts outcomes by Lima *et al.* (2013) [26], who found overestimates of ETo in HS method comparing to PM method in sub-humid regions of Brazil. In particular, research PM method indicates similar values of ETo in other months of compared years, when compared to PM method. The mean relative error percentage between EToPM and EToHS during the estimated years were 10%, 17% and 11% in June, July and August, respectively. In Karshi the estimated annual ETo for 2016 was 1573 mm with maximum (8.87 mm/day) and minimum (1.25 mm/day). A similar trend in ETo for the same period for northern part of Uzbekistan, Khorezm province was observed by Awan *et al.* (2011) [34], where PM method provided slightly lower (1375 mm) long-term (1987-2005) annual ETo with maximum (7.36 mm/day) observed in July and minimum (0.64 mm/day) observed in January.

The relationship between daily EToPM and EToHS values from 2011 to 2017 (2016 and 2017 none calibrated) is demonstrated in **Figure 4**. According to estimations, the correlation between daily EToPM and EToHS is high with the

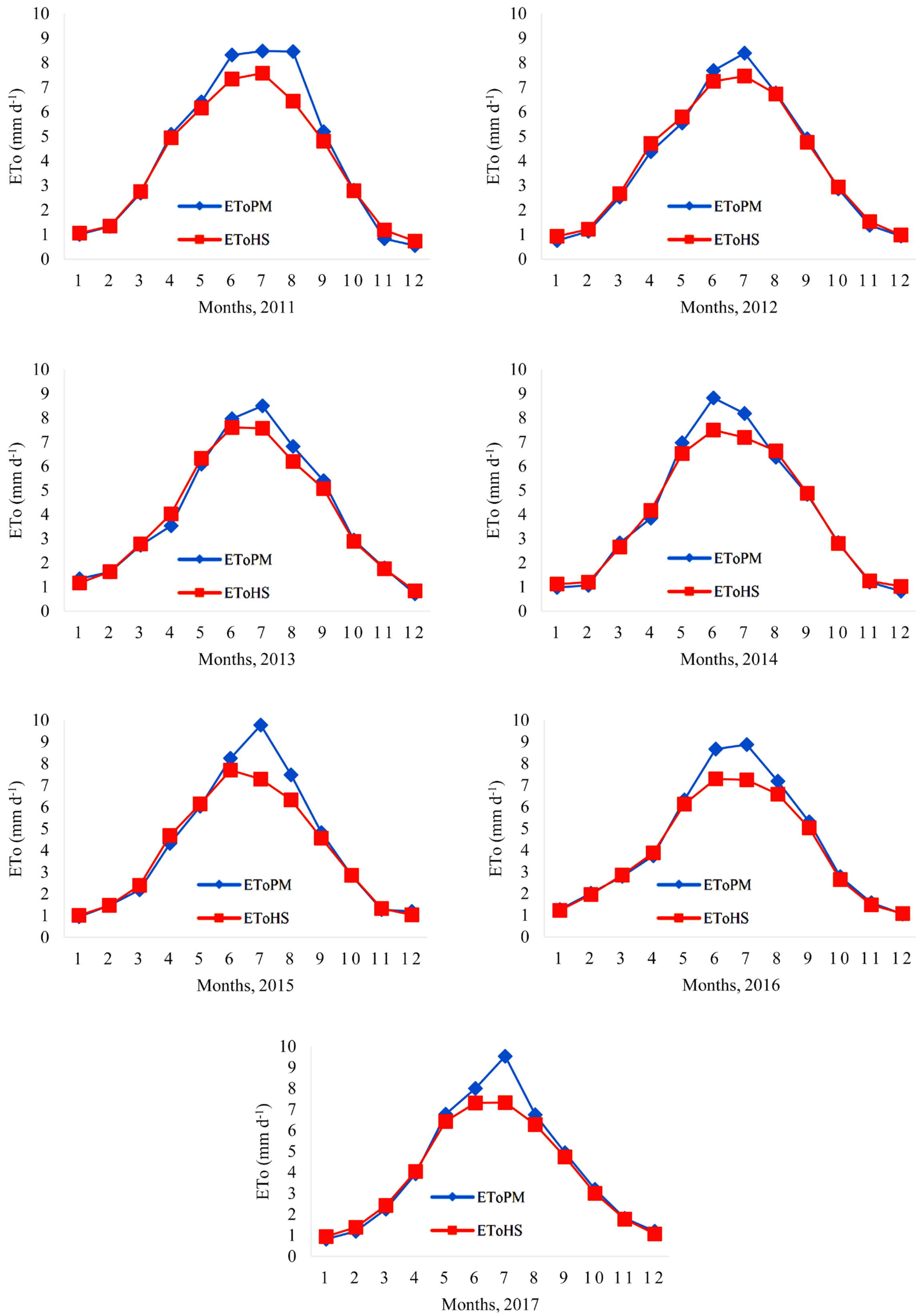

Figure 3. Comparison of the mean monthly EToPM and EToHS methods in Karshi steppe, Kashkadarya province, Uzbekistan during the years from 2011-2016.

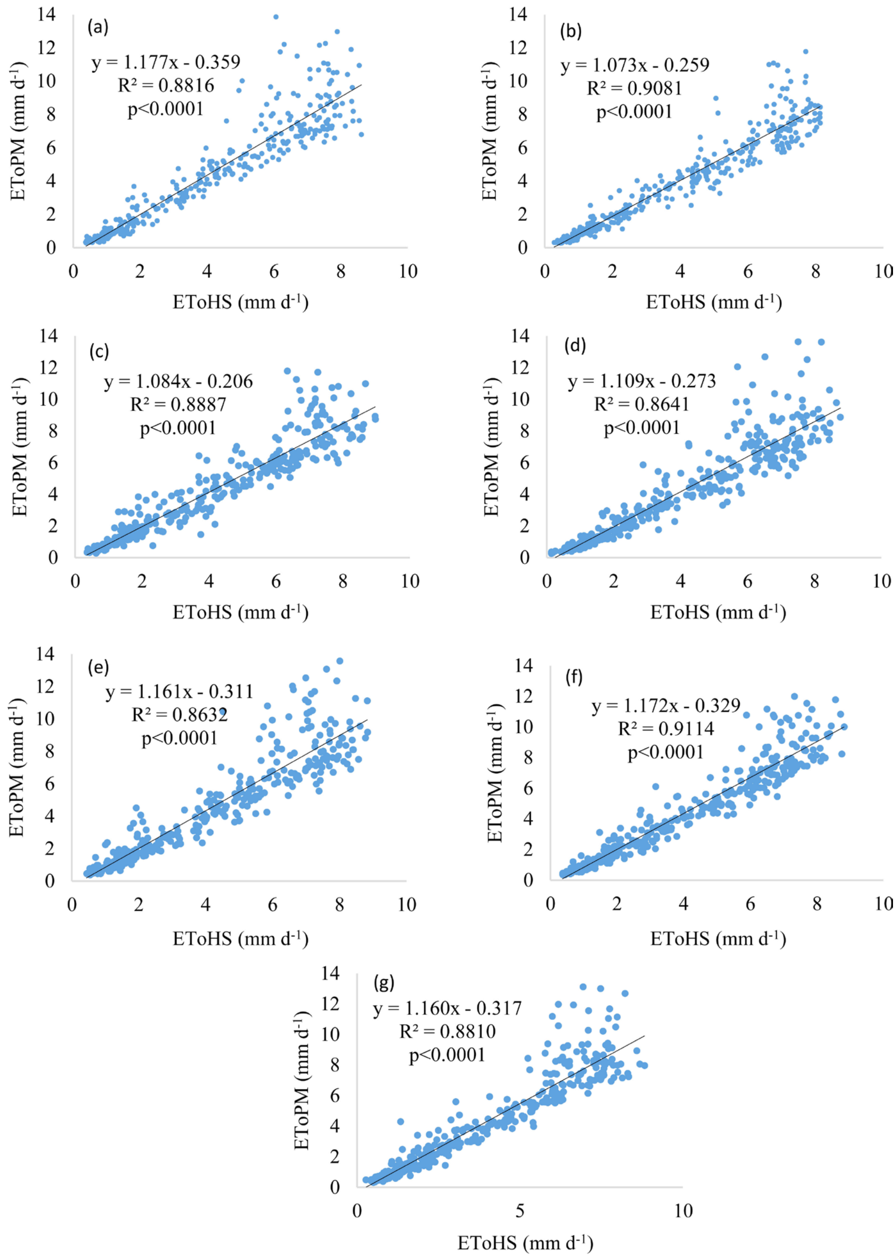

Figure 4. Correlation between daily EToPM and EToHS methods in Karshi steppe, Kashkadarya province, Uzbekistan during the years for 2011 (a), 2012 (b), 2013 (c), 2014 (d), 2015 (e), 2016 (f), 2017 (g).

coefficients of determination (R^2) of 0.88 in 2011, 0.91 in 2012, 0.89 in 2013, 0.86 in 2014 and 2015, 0.91 in 2016 and 0.88 in 2017, and p-values are less than 0.0001 which means the results are statistically significant. However, the method of HS underestimates the ETo value during the period from June to August in every year of observation, which can be seen in **Figure 3**. A similar trend for the same period were observed by Moeletsi *et al.* (2013) [35], where PM and HS were compared in different environmental conditions in South Africa.

Table 1 demonstrates the results of statistical analyses of EToHS and

EToHSm versus EToPM for estimating daily ETo during the years between 2011 and 2017. According to the results, the coefficient of determination and index of agreement between the variable is high in each year. However, the percentage of relative root mean square error is high and not acceptable.

Table 2 demonstrates the results of statistical analyses of EToHS and EToHSm versus EToPM for estimating monthly ETo during the years between 2011 and 2017. According to the results, the coefficient of determination and index of agreement between the variable is high (close to 1.0) in each year, which represents a high correlation between the variables. According to Stöckle *et al.* (2004) [36], most obtained indexes of agreement and coefficients of determination exhibit good performance, which are in the range of 6 to 20 percent. Moreover, relative error percentage of yearly sum ETo during the observation period varies from 0.65 to 8.88 percent. Furthermore, from Table 1 and Table 2, it should be noted that the values of relative root mean square error in monthly

Table 1. Statistical performance of the EToHS and EToHSm versus EToPM for estimating daily ETo during 2011 and 2017 in Karshi steppe, Kashkadarya province, Uzbekistan.

	R^2	d	RMSE (mm d^{-1})	RRSME (%)
HS 2011	0.88	0.95	1.25	29%
HS 2012	0.91	0.97	0.86	22%
HS 2013	0.89	0.97	0.99	24%
HS 2014	0.86	0.96	1.16	28%
HS 2015	0.86	0.95	1.29	30%
HS 2016	0.91	0.96	1.05	24%
HSm 2016	0.92	0.96	0.87	20%
HS 2017	0.88	0.95	1.16	28%
HSm 2017	0.89	1.00	1.00	24%

Table 2. Statistical performance of the EToHS and EToHSm versus EToPM for estimating monthly ETo during 2011 and 2017 in Karshi steppe, Kashkadarya province, Uzbekistan.

	R^2	d	RMSE	RRSME	REP
HS 2011	0.981	0.994	22.20	17%	8.57%
HS 2012	0.990	0.999	10.32	9%	0.65%
HS 2013	0.986	0.998	12.03	10%	3.37%
HS 2014	0.982	0.997	15.81	13%	3.95%
HS 2015	0.957	0.992	25.38	20%	8.20%
HS 2016	0.984	0.984	19.95	15%	8.88%
HSm 2016	0.996	0.998	7.74	6%	3.94%
HS 2017	0.975	0.982	21.61	17%	7.90%
HSm 2017	0.990	0.999	10.16	8%	2.98%

ETo is much lower than those of daily base.

Because of the high values of RMSE and RRSME, EToHS method cannot be used in our study area to estimate ETo. However, according to Teutschbeina and Seiberta (2012) [32], it is possible to improve the accuracy of climatic parameters by modifying the parameters to local conditions through identifying and application of a bias correction factor. The bias correction factor was calculated for every month using data from 2011 to 2015 (calibration period), and afterwards the identified bias correction factors were used for the data of 2016 and 2017 to validate the HS method (EToHSm) in daily base. The received bias correction factors for each month are shown in **Table 3**.

In the months from June to August, the bias correction factor is higher as expected and ranged from 1.10 to 1.17. The HS method has a lower sensitivity to air temperature during the summer months in comparison to the PM method. That is why the values of bias correction factors are higher during June, July and August. Moreover, it also notable that statistical parameters of the monthly modified EToHSm is more desirable than daily modified EToHSm. After modification of the EToHS, all statistical indicators improved in positive direction. Modification of the EToHS allowed improving the accuracy of the ETo calculation. Also, the application of the bias correction factor reduced the relative root mean square and relative error percentage in monthly base ETo by twofold. The relative root mean square errors of EToHS were 15% and 17% in 2016 and 2017, respectively. The calibration process reduced these values to 6% in 2016 and 8% in 2017. As a result of the calibration process, the statistical performance of the relative root mean square errors and index of agreement changed from "good" to "very good" in the terms of the statistics according to adopted similar standards in validation of ETo estimation Stöckle *et al.* (2004) [36].

Table 3. The bias correction factor Hargreaves-Samani equation for each month using data from 2011 to 2015 for Karshi steppe, Kashkadarya province, Uzbekistan.

Months	Bias Correction Factor
January	0.94
February	0.96
March	0.98
April	0.94
May	1.00
June	1.10
July	1.17
August	1.11
September	1.04
October	1.00
November	0.91
December	0.90

4. Conclusions

Based on the results, the modified EToHS equation is suitable for predicting ETo in arid continental climate of Karshi region in southern Uzbekistan. When data on solar radiation, humidity and wind speed is missing because of technical capacity and financial limitations of weather stations, it is possible to modify the HS methods and more accurately calculate ETo. Measuring evapotranspiration is highly important for understanding and ultimately intervening into the water cycle of natural systems, especially in the water balance of different critical users of water, like large scale irrigated areas. This is particularly true in the field of water management, where water resources have to be managed very clearly from the water basin to the irrigated fields, eventually reaching to smaller areas and users. If reliable and consistent information regarding evapotranspiration can be accessed with less time, temporal estimation and at low cost, it can be used to analyze the performance of irrigation systems and devise better management alternatives. The macro-level analysis of information can not only help understand the patterns and implications of the existing management strategies on the overall water use, it can also indicate the necessary changes required to manage water more beneficially and minimize the negative impacts. If ET based irrigation is widely adopted by the WUAs, it can result in larger water savings, which then can be diverted to expand agriculture for other purposes and improve ecological situation in the region. Additionally, the findings suggest that the methods used in this paper can be applied in data limited regions to calculate ETo, as well as to estimate future ETo values using global climate models, to inform decision making and develop more effective agricultural practices on water management, irrigation scheduling and crop production.

This research is a first attempt to implement the bias correction factor to calibrate the HS method for conditions along the Amudarya basin in Central Asia. The application of the bias correction factor to adjust the HS to PM method in order to estimate ETo was proved by statistical analyses. According to the analyses (see **Figure 5**), the majority of the variations between EToPM and EToHS methods are happening during the summer period (June to August), while ETo values of both methods in other months are statistically acceptable, which implies that the HS method can be implemented without correction during the other months. This paper did not investigate the reasons for the higher bias correction factors during the summer period in the particular climatic and territorial region; therefore it could be a subject of research in future studies. It should also be noted that the identified and verified bias correction method can be applied to the ETo values estimated from the downscaled global circulation models for the particular climate region and properly forecast future ETo values by the HS method, as some of those models are not adequate for ETo calculation using the PM method due to data limitations.

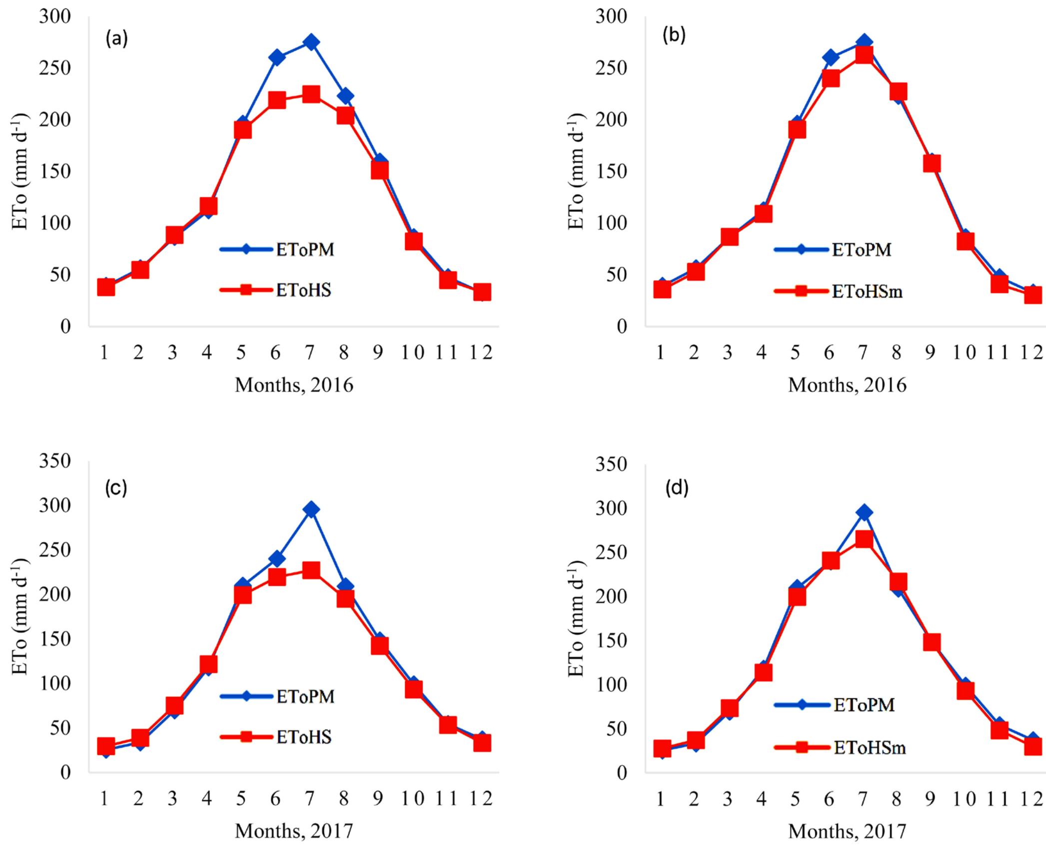

Figure 5. Comparison of the monthly EToHS (a) (c) and EToHSm (b) (d) in Karshi steppe, Kashkadarya province, Uzbekistan during 2016 and 2017.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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