Estimating reference evapotranspiration using the Hargreaves - Samani formula for end-user applications

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Abstract. Reference evapotranspiration is one of the main geophysical parameters, the reliable assessment of which is important in irrigation water management, planning, distribution and regulation of water resources. The Food and Agriculture Organization of the United Nations recommends using the Penman-Monteith formula to estimate ETo. However, its' application by end-users is limited since the formula requires several parameters which are often missing. In such cases, it recommends the Hagreaves-Samani formula. In this study, the reference evapotranspiration is estimated as the case study for Uzbekistan applying both, the Penman - Monteith and the Hargreaves - Samani methods. Data used is taken from 13 state climate stations of Uzbekistan. The results of the study indicate that under data-scarce conditions, the Hargreaves – Samani formula, can be recommended for end-user applications, after the adjustment to local conditions, in order to determine the water requirements of crops and irrigation scheduling.

1. Introduction

The population of Central Asia is expected to increase from 60.7 million (2010) to 81 million by 2050 [1]. This growth will lead to an increase in demand for food, which means that farmers will need to increase the area of agricultural land for growing food crops and the productivity of existing land through application timely irrigation [2]. This in turn may increase the demand for irrigation water. When growing crops, the water consumption is equal to evaporation from the soil surface and crop transpiration, or evapotranspiration (ETc). However, direct determining ETc values is an expensive and time-consuming task, especially at large spatial scales [3]. The Food and Agriculture Organization of the United Nations (FAO) proposes a three-step calculation of ETc (FAO-56), with the first step estimating only climate-dependent reference evapotranspiration (ETo). ETo is one of the key variables for optimal design and planning of agricultural water management tasks such as efficient irrigation scheduling, regional water management, drought monitoring and estimating crop water requirements [4]. FAO recommends the Penman-Monteith (PM) formula for estimating ETo [5]. The PM method requires several meteorological variables to calculate ETo. In many cases, in the absence of the meteorological variables to calculate EToPM, simpler models based on less data were tested [6].

For example, in the countries of Central Asia, N.N. Ivanov's formula, which takes into account relative humidity and average temperature, was widely used until recent years. The Hargreaves-Samani formula (EToHS) gets wide application in many parts of the world. In several countries, the estimation of ETo using the Hagreaves-Samani formula has shown good results [7]. Studies in the Ebro Valley in northern Spain showed that the Hargreaves-Samani (HS) equation is the most suitable for estimating ETo in warm, humid and semi-arid conditions [8,9]. Estimation of ETo using the HS formula for different regions and subregions having different climatic conditions, including Canada [10], Iran [11-13], China [14], and Poland [15] showed the need to verify the ETo coefficients in relation to local conditions.

This study aims to determine a potential of using the Hargreaves- Samani formula for estimating the reference evapotranspiration for end-user needs in crop production, in conditions where climate information is limited only by air temperature (minimum, average and maximum).

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Study area. The territory of Uzbekistan is unique in its natural conditions. These are the richest alpine meadows and glaciers in high mountains, forests and orchards in the middle zone of the mountains, magnificent spring-autumn pastures on low mountains and foothills, the fertile irrigated lands in river valleys, and hilly plains of the foothills, endless steppes gradually merging with deserts. The main features of the climate are abundance of solar radiation, low air humidity, long hot dry summers and short warm winters, contributing to high evaporation. Within the desert zone, average temperatures and the duration of the frost-free period increase from north to south. The number of months with positive average temperatures in the south is 11-12, in the northern belt of deserts is 8-12. Precipitation falls mainly in the winter-spring period and its amount varies from 90-450 mm/year on the lowlands, including low foothills, to 1000 mm/year in the mountains. According to long-term average data, the rainiest period is March-April and the driest month is June-August. The total number of days with precipitation on the lowlands varies from 30 to 70 per year. The summer period is characterized by extreme dry air - relative air humidity in the range of 27-35%. In other seasons it is higher - within 40-65% during the daytime, and 70-90% at night. High temperatures and a lack of humidity cause high evaporation—the evapotranspiration of crops significantly exceeds the amount of precipitation, thereby cultivating crops on 95% of the agricultural land requires irrigation [16].

2. Materials and Methods

The study area covers the agricultural land of Uzbekistan, located approximately between 37°13′N–42°27′N latitude and 59°36′–72°21′ E. longitude. To estimate ETo, the study uses daily climate data for 2019–2022 from the Center for Hydrometeorological Service of the Republic of Uzbekistan (UZHYDROMET). Among 95 climate stations, currently operating in Uzbekistan, several stations were selected that have sufficient data to apply the Penman-Monteith formula.

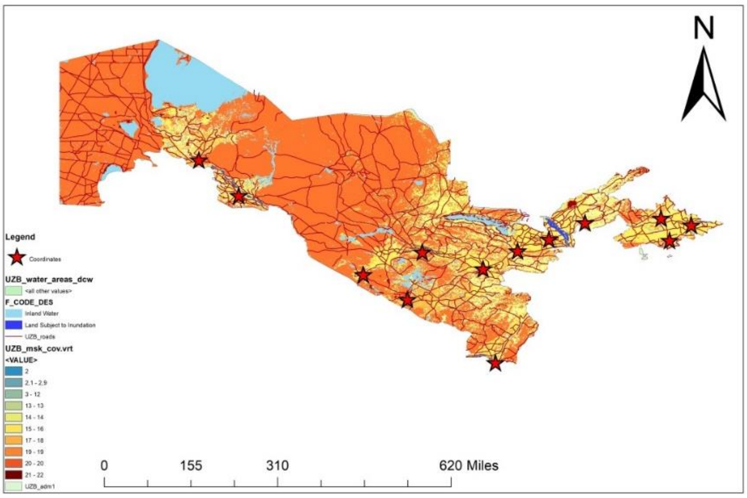

Fig. 1. Geographical location of selected hydrometeorological stations

2.1 Estimation of reference evapotranspiration

Determining reference evapotranspiration on irrigated areas is important for end-user needs. After each irrigation, water storages in soil equal to the field capacity. On average, 55% of this amount of water can be absorbed by crops, resulting in a depletion of soil water reserves and a demand for next irrigation. The crop transpiration (T) and the amount of water evaporated from the soil during this period (E) constitute crop evapotranspiration (ETc), which depends on climatic conditions and crop type (Allen et al., 1998):

$$ETc = kt \cdot кс \cdot ETo$$

where, kt – coefficient that takes into account the influence of factors leading to a decrease in crop transpiration (for example, soil salinization, water shortage), кс – crop coefficient (FAO 56, 2015), ETo – reference evapotranspiration.

Reference evapotranspiration depends only on climatic conditions and is determined in conditions where the crop has a height of 10...12 cm and completely covers the soil surface. Three step approach is applied in this study. In the first step, ETo is estimated using the Penman Monteith formula (EToPM) (FAO 56).

The Penman Monteith formula is as follows [17]:

$$ETоPM = \frac{0.408\Delta\,(Rn - G) + \gamma\,\frac{900}{T+273}\,\mathrm{u2}\,(\mathrm{es} - \mathrm{ea})}{\Delta + \gamma(1 + 0.34u2)}$$

where:

Rn - net radiation on the surface of the crop [MF m $^{-2}$ days $^{-1}$],
G - soil heat flux density [MF m $^{-2}$ days $^{-1}$],
T – average daily air temperature at a height of 2 m [°C],
u2 – wind speed at a height of 2 m [ms $^{-1}$],
es - saturated steam pressure [kPa],
ea - actual steam pressure [kPa],
es - ea - saturation vapor pressure deficit [kPa],
Δ - slope of the steam pressure curve [kPa °C $^{-1}$],
γ-psychrometric constant [kPa °C $^{-1}$],
EToPM – reference evapotranspiration estimated based on the Penman-Monteith formula [mm/day].

In this study, reference evapotranspiration is estimated using the FAO “ETo-calculator”, the software based on the Penman Monteith formula. Climatic parameters require measurements at a height of 2 m (or recalculated to this height) to ensure the reliability of the calculations. The fact that this formula includes relative humidity, temperature, wind speed, sunshine duration and other parameters makes it difficult to use by end-users.
In the second step, the Hargreaves-Samani formula has been tested that requires a minimum of parameters to estimate ETo (EToHS). EToHS depends only from air temperature and many studies indicate, that under many environments, it produces results close to EToPM. The Hargreaves-Samani formula for determining reference evapotranspiration is as follows:

$$EToHS = 0{,}0023\ (Tmax - Tmin)^{0,5} (\ Td + 17{,}8\ )\ Ra$$

where: Tmax = maximum, Tmin = minimum, Td = average daily temperature, Ra = extraterrestrial radiation, (mm•day $^{-1}$).

Extraterrestrial radiation is calculated based on the coordinates of climate stations (latitude) and the day of the year. (Hargreaves and Samani, 1985).

$$Ra = 37{,}6.\ G_{SC}.\ d_r.\ (\omega S.\ sin(\varphi)\ .\ sin(\delta).\ con(\delta).\ cos(s).\ sin(\omega_S))$$

where: GSC = solar constant (0.0820 MF•m^{-2} •min^{-1}), φ = latitude (radian), latitude is converted from degrees to radians (radian = degree (π/180)).

Depending on the calendar day of the year, the remaining factors are calculated using the following equation [18].

$$d_r = 1{+}0{,}33.\ cos\ (2\pi/365J)$$

where, dr = the number opposite the relative distance from the Earth to the Sun, and J - the calendar day of the year [19].

$$\delta = 0{,}409.\ sin\ (2\pi/365J{-}1{,}39)$$

where, δ = the height of the sun at midday (radians) and J - the calendar day of the year [20].

$$\omega_s = arccos\ ({-}\ tan\ \varphi.\ tan\ \delta)$$

where, ωs = sunset angle (radians) and J - the calendar day of the year.

The Excel-based tool was developed and used in this study to estimate EToHS.

In the third step, to assess the reliability of the calculation of reference evapotranspiration, determined by the Hargreaves-Samani formula, the value of the coefficient r^2 of the regression model was calculated using the formula:

$$r^2 = (n(\Sigma x_i y_i) - (\Sigma x_i)(\Sigma y_i)) / \sqrt{((n\Sigma x_i^2 - (\Sigma x_i)^2 * (n\Sigma y_i^2 - (\Sigma y_i)^2)}$$

where

y = EToPM, ETo calculated using the Penman Monteith formula, x = EToHS, ETo calculated using the Hargreaves–Samani formula.

3. Results and Discussion

To justify the possibility of using the Hargreaves-Samani formula by end-users, EToHS and EToPM were calculated and the results were compared based on data from 2019..2022, monitored at the climate stations (c.s.) located in Uzbekistan, including one in the Republic of Karakalpakstan and the other 12 in the provinces. The results (average values for 2019-2022) of the estimates EToPM and EToHS values are given in Figure 2 for three selected stations, representing northern (Urgench c.s.), central (Jizah c.s.) and southern climatic zone (Termez c.s.).

Figure 2 shows that the absolute error of the estimates using the Hargreaves-Samani formula vary in the different climatic conditions, which indicates the need of calibration to local conditions. Figure 2 demonstrates that the Hargeaves-Samani formula underestimates the reference evapotranspiration under arid climate (Urgench and Termez climate stations) and provides good convergences in semi-arid climate conditions (Jizzah climate station). The results of the estimates of the reference evapotranspiration using by the Hagreaves-Samani formula and its calibration in respect to those estimated by the Penman-Monteith equation for selected stations of Uzbekistan are given in Figure 3.

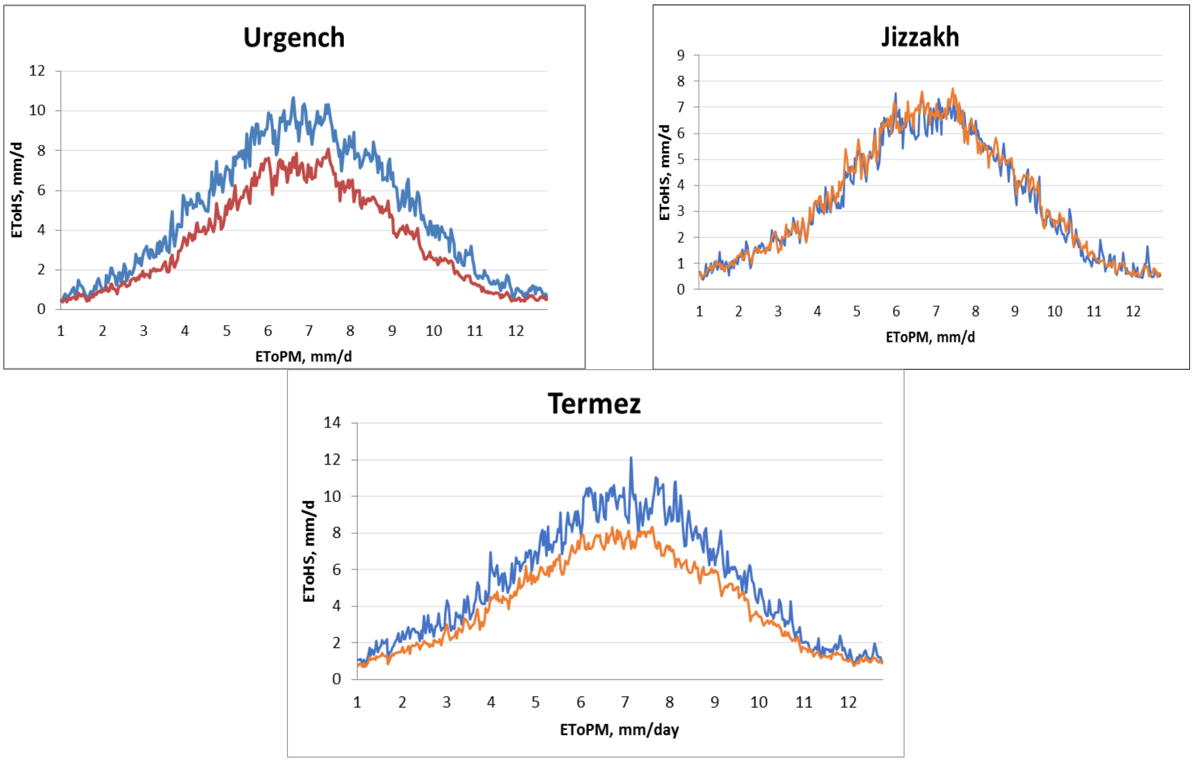

Fig. 2. EToHS and EToPM estimated for three selected climate stations, namely Urganch, Jizzakh and Termez.

The calibration parameters obtained by the linear regression between ETo values calculated using the Penman-Monteith and Hagreaves-Samani formulas is given in Table 1.

The calculation results show a good correlation between the ETo values calculated using the Hargreaves- Samani and Penman-Monteith formulas, which indicates the possibility of using the Hargreaves-Samani formula by end-users after taking into consideration local conditions by using the coefficients a and b given in Table 1. The results of the study demonstrate that the reference evapotranspiration is highly depends on the air temperature and in many cases an impact of other climatic factors can be ignored. In spite of close values obtained between EToHS and EToPM for the most of the climate stations, there are few stations which requires further analyses. These stations (Navoi, Korakol and Termez) are located in the southern climatic zone, where in addition to the air temperature, the impact of other climatic factors is to be taken into consideration to improve the accuracy of the ETo estimates under date scarce conditions.

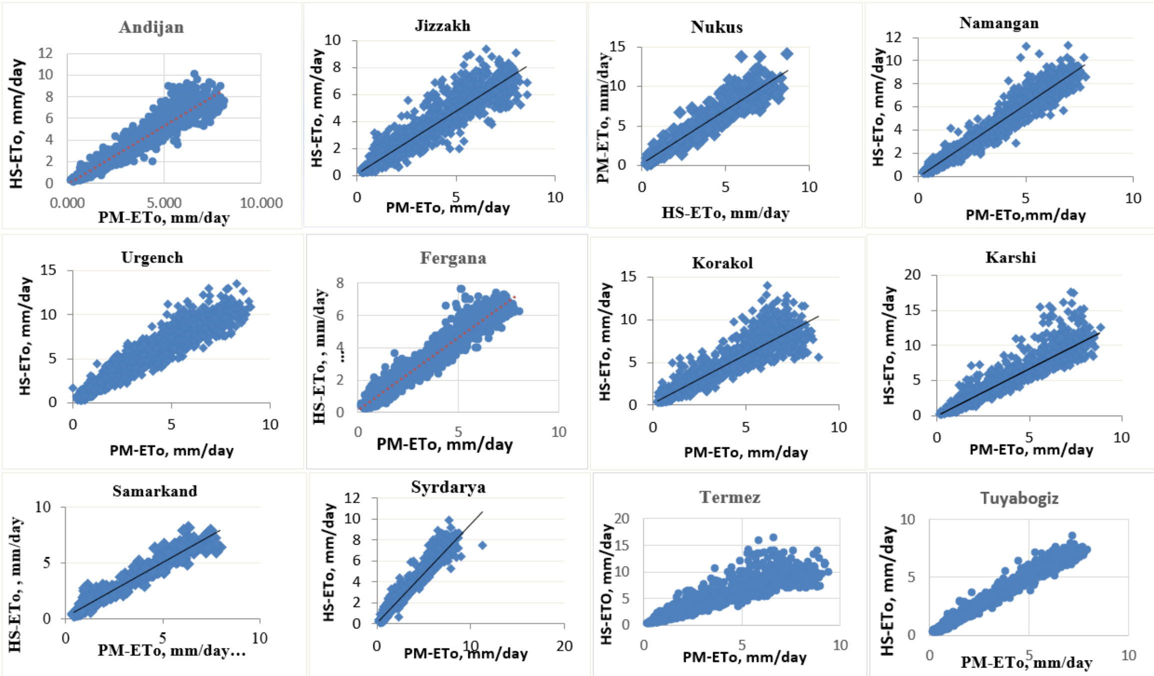

Fig. 3. Reference evapotranspiration values estimated by the Hagreaves-Samani equation and its calibration in respect to those estimated by the Penman-Monteith equation for selected stations of Uzbekistan.

Table 1. The result of assessing the correlation between reference evapotranspiration calculated using the Penman-Monteith and Hargreaves-Samani formulas

Station	r^2	a	b
Samarkand	0.9389	0.153	0.9716
Urgench	0.9176	0.4274	1.2722
Jizzakh	0.8864	0.1557	0.9254
Fergana	0.9453	0.1463	0.8982
Karshi	0.8723	0.0046	1.341
Termez	0.8226	0.3847	1.1915
Tuyabogiz	0.9744	0.0223	0.9914
Andijan	0.924	0.1294	1.0787
Korakol	0.8373	0.2483	1.141
Namangan	0.9494	0.0251	1.2454
Nukus	0.9007	0.1848	1.3685
Syr Darya	0.9583	0.1016	0.9447
Navoi	0.7932	0.191	1.2211

4. Conclusions

Estimation of reference evapotranspiration based on the Hargreaves-Samani formula showed close results to the FAO Penman-Monteith formula ($r2 > 0.80$). At the same time, research results show that under the high-temperature climate in the southern provinces (Navoi, Korakol and Termez climate stations), other climatic factors (in addition to air temperature) should be taken into account. This indicates the need for further studies.

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