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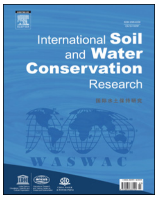

Validation and calibration of various reference evapotranspiration alternative methods under the climate conditions of Bosnia and Herzegovina

Sabrija Čadro [a,*], Mirza Uzunović [a], Jasminka Žurovec [a], Ognjen Žurovec [b]

[a] *Faculty of Agriculture and Food Sciences (PPF), University of Sarajevo (UNSA), Bosnia and Herzegovina*
[b] *Norwegian University of Life Sciences (NMBU), Norway*

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ABSTRACT

In Bosnia and Herzegovina (BiH), the number of weather stations (WS) that are monitoring all climatic parameters required for FAO-56 Penman-Monteith (FAO-PM) equation is limited. In fact, it is of great need and importance to achieve the possibility of calculating reference evapotranspiration (ET_0) for every WS in BiH (around 150), regardless of the number of climate parameters which they collect. Solving this problem is possible by using alternative equations that require less climatological data for reliable estimation of daily and monthly ET_0. The main objective of this study was to validate and determine, compared to the FAO-PM method, a suitable and reliable alternative ET_0 equations that are requiring less input data and have a simple calculation procedure, with a special focus on Thornthwaite and Turc as methods previously often used in BiH. To fulfill this objective, 12 alternative ET_0 calculation methods and 21 locally adjusted versions of same equations were validated against FAO-PM ET_0 method. Daily climatic data, recorded at sixteen WS, including mean maximum and minimum air temperature (°C), precipitation (mm), minimum and maximum relative humidity (%), wind speed ($m\,s^{-1}$) and sunshine hours (h) for the period 1961–2015 (55 years) were collected and averaged over each month. Several types of statistical indicators: the determination coefficient (R^2), mean bias error (MBE), the variance of the distribution of differences ($s_d{}^2$), the root mean square difference (RMSD) and the mean absolute error (MAE) were used to assess alternative ET_0 equation performance. The results, confirmed by various statistical indicators, shows that the most suitable and reliable alternative equation for monthly ET_0 calculation in BiH is the locally adjusted Trajkovic method. Adjusted Hargreaves-Samani method was the second best performing method. The two most frequently used ET_0 calculation methods in BiH until now, Thornthwaite and Turc, were ranked low.

1. Introduction

Agriculture is one of the most sensitive sectors to the negative impact of climate variations (Dos Santos & Sentelhas, 2012; INCBH, 2009; Žurovec et al., 2015), and it is of great importance that measures within agricultural activities, such as soil amelioration and water management, are designed to accept the concept of sustainable agriculture (Pretty, 2007). The main goal of such activities should be total utilization of the plant potential with a minimal use of non-renewable natural resources, especially soil and water. Reference Evapotranspiration (ET_0), in addition to soil and plant characteristics, represents a major input to each soil water balance, thus the hydro-melioration project (Žurovec, 2012). Irrigation water requirement must be adjusted to the atmospheric demand, which is closely related to the climatic conditions (Jabloun & Sahli, 2008). Properly managed, improved estimates of crop water requirements based upon weather and climatic data can result in significant improvements in the use of agricultural water (Hargreaves & Samani, 1985). The precise estimation of ET_0 is crucial for determination of the net irrigation requirement, flood risk assessment, regional water management decision-making, drought analyses, environmental studies, and to model the climate change impacts (Pandey, Dabral, & Pandey, 2016; Pereira, Allen, Smith, & Raes, 2015).

Among the different components of the hydrological cycle and soil water balance, a precise approximation of evapotranspiration in daily, decade, or monthly level is perhaps most difficult due to

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[*] Corresponding author.
E-mail address: s.cadro@hotmail.com (S. Čadro).

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its complex interactions with the soil–plant–atmosphere system (Pandey et al., 2016). Evapotranspiration is a major component of the land surface water balance, allowing the transference of water and energy to the atmosphere (Fernandes, Paiva, & Filho, 2012). The direct approach to quantify ET_0 is using lysimetric measurements (Bogawski & Bednorz, 2014; Xu, Peng, Ding, Wei, & Yu, 2013). Lysimetric measurements were carried out in four-year period (1975–1978) in the Mediterranean climate region (*Csa sx””*) of Bosnia and Herzegovina (BiH), at the lysimetric station Buna near Mostar (Vlahinić, 1982, 2004). At this location, sequence order of correlation relationship intensity between lysimetric measured evapotranspiration of the three tested crops (sorghum, grass mixtures and alfalfa) and calculated evapotranspiration by Thornthwaite (1948), Turc (1961) and Penman (1963) was as follows: Thornthwaite > Turc > Penman. At the same research location, Čustović and Žurovec (2010, 2011) found that the correlation between lysimetric measured apple and maize evapotranspiration and potential evapotranspiration (*PET*) calculated by Thornthwaite (1948), Turc (1961) and Penman (1963), shows that Turc and Penman's calculation method cannot be reliably used for apple ($R = 0.542$ and $R = 0.435$, respectively), whereas the Thornthwaite's method is slightly more reliable ($R = 0.725$). Turk's method was more reliable ($R = 0.803$) than Penman's ($R = 0.796$) and Thornthwaite's ($R = 0.736$) in case of maize.

The Committee on Irrigation Water Requirements of the American Society of Civil Engineers (ASCE) analyzed the properties of twenty different equations against carefully selected lysimeter data from eleven stations located worldwide in different climates (Jensen, Burman, & Allen, 1990). The Penman-Monteith equation ranked as the best equation for estimating daily and monthly ET_0 in every climate. The Turc equation ranked second in humid areas, and 18th in arid, while the Thornthwaite's ranked 13th in humid and last in arid locations. Compared to lysimetric measurements, many authors worldwide reported that FAO-56 Penman-Monteith (Allen, Pereira, Raes, & Smith, 1998) equation provides best results (Allen et al., 2005; Irmak et al., 2008; Irmak, Irmak, Allen, & Jones, 2003; Jensen et al., 1990; Ventura, Spano, Duce, & Snyder, 1999; ; Gavilan, Berengena, & Allen, 2007; Lopez-Urrea Olalla, Fabeiro, & Moratalla, 2006; Pereira & Pruitt, 2004; Pereira et al., 2015).

The FAO Irrigation & Drainage Paper No. 56, (Allen et al., 1998), and ASCE Task Committee on Standardized Evapotranspiration Calculations (ASCE-EWRI, 2005) accepted and solely recommended the FAO-56 Penman-Monteith method (FAO-PM) as a standard equation to calculate ET_0. The FAO-PM method is the most suitable indirect approach for accurate estimation of ET_0 and evaluation of other empirical models. The main shortcoming of this method is that it requires the detailed climatological data, which are not always available for many locations, especially in developing countries (Djaman, Irmak, & Futakuchi, 2016; Jabloun & Sahli, 2008; Popova, Kercheva, & Pereira, 2006; Trajkovic & Kolakovic, 2009a). According to Čadro, Žurovec, Mrkulić et al. (2016), the most frequently used methods for potential (*PET*) or reference evapotranspiration (ET_0) calculation in BiH are methods by Thornthwaite (1948), Penman (1948, 1963) and Turk (1961). Only recently, researchers started using the FAO-PM method in this region (Čadro, Žurovec, & Radović, 2016; Čadro, Žurovec, Mrkulić et al., 2016; Žurovec & Čadro, 2010, 2011). By examining the hydrological yearbooks of the hydrometeorological institutes in BiH, we found that about 158 public weather stations (WS) in BiH were operational between 1945 and 2015. Among these, only 24 WS, so-called "main stations", have been monitoring all major climatic parameters, such as temperature, precipitation, wind, insolation and air humidity. However, none of these main stations have been working continuously, so the number of WS who have long-term continuous datasets (> 30 years) is only 16. Such a small number of WS in the area of 51 million hectares (total area of BiH), means that each main station covers a horizontally projected area of 320,000 ha, which in terms of terrain complexity, diverse agro-ecological conditions and climatic heterogeneity in BiH is certainly not enough. However, the situation is not much better globally. The number of WS where all major climatic parameters are observed is limited in many areas worldwide, especially those where reliable data for all parameters exist (Shahidian et al., 2012). For example, there is one such WS for every three million hectares in Africa (Jagtap, 1991), or every 40,000 ha of irrigated land in Texas, USA (Henggler, Samani, Flynn, & Zeitler, 1996). Based on the World Meteorological Organization (WMO) horizontal distribution criteria for inclusion of the WS in the Regional Basic Synoptic Network (RBSN) for Europe, stations are accepted if the horizontal distance from one another is no more than 90 km (WMO, 2011).

It is of great need and importance to achieve the possibility of calculating ET_0 for every WS in Bosnia and Herzegovina (around 150), regardless of the number of climate parameters which they collect. Solving this problem is possible by using alternative equations that require less climatological data for reliable estimation of daily and monthly ET_0. There is a clear need to be able to have a precise estimation of ET_0 for locations and regions where the full range of reliable climatological data are not available. Performance assessment of the different ET_0 estimation methods is a challenging task (Pandey et al., 2016) and in order to be used, these alternative equations are requiring local validation and if necessary, calibration. Validation can be performed against either lysimetric measurements or the FAO-PM standard model (Tabari, Grismer, & Trajkovic, 2011). This can be done for WS with full datasets by comparing ET_0 calculated with full and limited datasets (Allen et al., 1998).

Any computation procedure for estimating ET_0 should provide consistent and reliable results and require a minimum of data and computations (Hargreaves & Samani, 1985). The most important parameters in estimating ET_0 are temperature and solar radiation (Samani, 2000). According to Jensen (1985), at least 80% of ET_0 can be explained by temperature and solar radiation. Temperature based methods of estimating ET_0 are widely used because the air temperature data are more readily available for most of the WS compared to other data. This is also true for BiH, where all 158 WS have been collecting or still collect maximum and minimum air temperature and precipitation data, while the other data, such as relative humidity, sunshine hours and wind speed is regularly collected at only 24 of them.

Numerous studies under different climate conditions proposed that regional calibration of temperature and radiation based models can improve their performance (Allen, 1995; Bogawski & Bednorz, 2014; Pandey et al., 2016; Samani, 2000; Todorovic, Karic, & Pereira, 2013; Trajkovic, 2005; Xu & Singh, 2001, 2002.). Many such studies were performed for humid conditions, including countries such as USA (Irmak Irmak, Allen, & Jones, 2003), Bulgaria (Popova et al., 2006), Italy (Berti, Tardivo, Chiaudani, Rech, & Borin, 2014), Poland (Bogawski & Bednorz, 2014), India (Pandey et al., 2016; Pandey, Pandey, & Mahanta, 2014), China (Xu, Peng, Yang, Luo, & Wang, 2012), Iran (Tabari et al., 2011), Serbia (Trajkovic & Kolakovic, 2009a, 2009b; Trajkovic, 2005, 2007), but none of them for the humid climate conditions of BiH.

The main objective of this study was to validate and determine, compared to the FAO-PM method, a suitable and reliable alternative ET_0 equations, which require less input data and have a simple calculation procedure, with a special focus on Thornthwaite (1948) and Turc (1961) as methods previously often used in BiH. The secondary objective was to categorize regions in BiH by creating groups of WS with similar ET_0 ranking results. The main importance of this study is that the identified alternative equations could be used for monthly ET_0 calculations at WS, which are collecting only basic climatic data. The obtained ET_0 results could be further used in more precise agricultural and urban planning, irrigation planning and management, regional water balance studies, climate change studies, and agro-climatological zoning.

2. Materials and methods

2.1. Study area

According to the United Nation Environment Programme (UNEP) aridity Index (UNEP, 1992), most of the area of BiH belongs to humid climate region (Čustović, Ljuša, & Sitaula, 2015; Todorovic et al., 2013).

Three main climatic classes: *C*, *D* and *E*, have been defined in BiH according to Köppen–Geiger (Geiger, 1961) Climatic Classification (Kottek, Grieser, Back, Rudolf, & Rubel, 2006; Peel, Finlayson, & McMahon, 2007). Based on the climate regionalization by Drešković and Mirić (2013), *Cf* - temperate warm and humid climate has a dominant surface share (64.62%), followed by *Df* - humid boreal (24.53%), and Mediterranean climates (10.71%). Within the same study, it was found that the average annual temperature for the entire country is about 10.9 °C, which ranges from 9.7 °C in the northern temperate climate zone to 12.1 °C in the Mediterranean climate zone. The average annual precipitation is about 1255 mm and characterized with the high variation in spatial distribution, which ranges between 706 mm to 3259 mm (Drešković & Mirić, 2013).

2.2. Data availability

To evaluate the performance of monthly ET_0 estimates from limited climatic data, daily data recorded at sixteen WS were used to evaluate the performance of monthly ET_0 estimates from limited climatic data. We selected weather stations in BiH which fulfill the requirements of WMO horizontal distribution criteria for inclusion in RBSN (WMO, 2011). The locations of the selected WS (Fig. 1) along with climate characteristics and observation periods are given in Table 1. All used WS are situated in "interior" locations of the country.

Daily climatic data, including mean maximum and minimum air temperature (°C), precipitation (mm), minimum and maximum relative humidity (%), wind speed (m s^{-1}) and sunshine hours (h) for the period 1961–2015 (55 years) were collected and averaged over each month. All the months that did not have complete climate data set required for FAO-PM calculation were removed from calculation procedure. The quality check and integrity of different data was performed as recommended by Allen et al. (1998).

Monthly values of FAO-PM ET_0 were calculated using REF-ET: Reference Evapotranspiration Calculator (Allen & Zhenguli, 2016). For other used methods (not included in "REF-ET") Microsoft Excel was used. We used MATLAB 2015a for statistical computations, while ESRI ArcGIS was used for the graphical representation.

2.3. Methodology

Reference evapotranspiration (ET_0) was calculated using FAO-56 Penman-Monteith equation (Eq. 1) that is closely resembling the evaporation of an extension surface of green grass of uniform height (0.12 m), actively growing with enough water, given as (Allen et al., 1998):

$$ET_0 = \frac{0.408\Delta\left(R_n - G\right) + \gamma\frac{900}{T_{mean}+273}u_2\left(e_s - e_a\right)}{\Delta+\gamma\left(1 + 0.34u_2\right)} \tag{1}$$

where ET_o is the reference evapotranspiration (mm day^{-1}), R_n the net radiation at the crop surface (MJ m^{-2} day^{-1}), G the soil heat flux density (MJ m^{-2} day^{-1}), T_{mean} the mean daily air temperature at 2 m height (°C), u_2 the wind speed at 2 m height (m s^{-1}), e_s the saturation vapor pressure (kPa), e_a the actual vapor pressure (kPa), e_s - e_a the saturation vapor pressure deficit (kPa), Δ the slope of the vapor pressure curve (kPa °C^{-1}) and γ is the psychrometric constant (kPa °C^{-1}).

For all the equations that are requiring it, solar radiation (R_s) was calculated from measured sunshine hours (The Campbell–Stokes sunshine recorder) by using the Ångström equation (Allen et al., 1998):

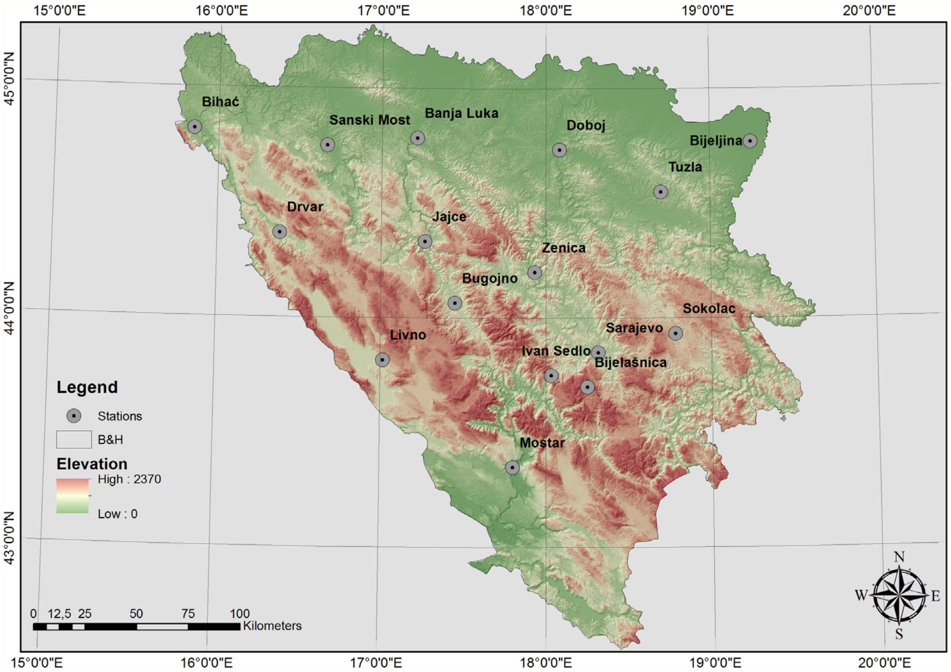

Fig. 1. Geographical location of analyzed weather stations in Bosnia and Herzegovina.

Table 1
Location, climate characteristics and observation periods of 16 used weather stations in BiH.

Weather station (WS)	A (m)	°E	°N	P (mm)	T_{mean} (°C)	Köppen–Geiger	Observ. period	Patterns
Mostar (MO)	99	17°47'	43°20'	1493	15.0	*Csa sx“*	1961–2015	547
Bijeljina (BIJ)	90	19°15'	44°46'	754	11.3	*Cfa x“s*	1961–2010	360
Banja Luka (BL)	153	17°13'	44°47'	1045	11.1	*Cfb x“s*	1961–2010	552
Doboj (DO)	146	18°05'	44°44'	928	10.9	*Cfb x“s*	1961–2010	530
Sanski Most (SM)	158	16°40'	44°46'	1039	10.5	*Cfb x“s*	1961–2015	414
Jajce (JA)	430	17°16'	44°20'	911	10.2	*Cfb x“s*	1961–2015	384
Zenica (ZE)	344	17°54'	44°12'	807	10.6	*Cfb x“s*	1961–2015	543
Tuzla (TU)	305	18°41'	44°32'	906	10.4	*Cfb x“s*	1961–2015	534
Sarajevo (SA)	630	18°25'	43°52'	940	9.9	*Cfb x“s*	1961–2015	624
Bugojno (BU)	562	17°27'	44°03'	833	9.3	*Cfb x“s*	1961–2015	411
Bihać (BI)	246	15°51'	44°48'	1341	11.0	*Cfb x“s*	1961–2015	529
Livno (LI)	724	17°00'	43°49'	1151	9.4	*Cfb x“s*	1963–2015	402
Drvar (DR)	485	16°22'	44°22'	1133	9.5	*Cfc x“w*	1964–1992	296
Sokolac (SO)	872	18°47'	43°56'	851	6.9	*Dfb x“w*	1964–2015	468
Ivan Sedlo (IS)	967	18°02'	43°45'	1476	7.5	*Cfc x“w*	1961–2000	240
Bjelašnica (BJ)	2067	18°15'	43°42'	1163	1.4	*ET fx“*	1961–2015	511

Note: A – altitude; °E – longitude; P – precipitation; °N – latitude; T_{mean} – mean air temperature; *Csa sx“* - mediterranean climate; *Cfa x“s*, *Cfb x“s*, *Cfc x“w* - temperate warm and humid climates; *Dfb x“w* - snow-forest climate; *ET fx“* - tundra climate.

$$R_s = \left(a_s + b_s\frac{n}{N}\right)R_a \tag{2}$$

where R_a is the extraterrestrial radiation (MJ m^{-2} day^{-1}) calculated for each day of the year and for different latitudes, from the solar constant ($G_{sc} = 0.0820$ MJ m^{-2} min^{-1}), the solar declination (δ) and the time of the year (J) and then by selecting the R_a for 15th day of each month converted to monthly values, n is the actual duration of sunshine (h), N is the maximum possible duration of sunshine or daylight hours (h), a_s is the regression constant, expressing the fraction of extraterrestrial radiation reaching the earth on overcast days ($n = 0$) and $a_s + b_s$ is the fraction of extraterrestrial radiation reaching the earth on clear days ($n = N$). In the absence of actual solar radiation (R_s) measurements and calibration for improved a_s and b_s parameters, the values $a_s = 0.25$ and $b_s = 0.5$ were used as suggested by Allen et al. (1998).

Actual vapor pressure (e_a) was derived from relative humidity data (Allen et al., 1998) as:

$$e_a = \frac{e^0(T_{min})\frac{RH_{max}}{100} + e^0(T_{max})\frac{RH_{min}}{100}}{2} \tag{3}$$

where e_a is actual vapor pressure (kPa), $e°(T_{min})$ saturation vapor pressure at daily minimum temperature (kPa), $e°(T_{max})$ saturation vapor pressure at daily maximum temperature (kPa), RH_{max} maximum relative humidity (%), RH_{min} minimum relative humidity (%).

2.3.1. *Combination methods*

The following combination and temperature based alternative methods for estimating ET_0 have been chosen for this study. The selection of methods was based on their wide acceptance, simple calculation procedure and applicability in BiH conditions.

Classic form of Penman equation (Penman, 1948, 1963) as:

$$ET_{0Penman} = \left(\frac{\Delta}{\Delta+\gamma}(R_n - G) + 6.43\frac{\gamma}{\Delta+\gamma}(a_w + b_w u_2)(e_s - e_a)\right)/\lambda \tag{4}$$

where a_w and b_w are empirical wind coefficients, λ latent heat of vaporization (MJ kg^{-1}), all other terms are the same as those used for the Penman-Monteith equation (Eq. 1).

The Makkink (1957) method frequently used in Western Europe in this study is calculated as:

$$ET_{0Makkink} = 0.61\frac{\Delta}{\Delta+\gamma} \times \frac{R_s}{2.45} - 0.12 \tag{5}$$

where R_s is solar radiation (MJ m^{-2} d^{-1}), and Δ and γ are as defined for the Eq. (1).

Turc (1961) developed an equation for general climatic conditions of Western Europe. According to Jensen et al. (1990), the Turc method is one of the most accurate empirical equations used to estimate ET_0 in humid conditions (Trajkovic & Kolakovic, 2009a). His method estimated ET_o based on measurements of maximum and minimum temperature and solar radiation using following equation:

$$ET_{0Turc} = a_T 0.013\frac{T_{mean}}{T_{mean}+15} \times \frac{23.8856R_s + 50}{\lambda} \tag{6}$$

where R_s is solar radiation (MJ m^{-2} d^{-1}), T_{mean} is mean daily air temperature (°C), and λ is latent heat of vaporization (MJ kg^{-1}). The coefficient a_T is defined as $a_T = 1$ for $RH_{mean} \geq 50\%$, where RH_{mean} is mean daily relative humidity (%). When $RH_{mean} < 50\%$, then $a_T = 1 + (50 - RH_{mean})/70$.

The Priestley and Taylor (1972) equation was developed as simplification of the FAO-56 P.M. method, and it has form:

$$ET_{0Priestley-Taylor} = 1.26\frac{\Delta}{\Delta+\gamma} \times \frac{R_n - G}{\lambda} \tag{7}$$

where R_n is net radiation (MJ m^{-2} d^{-1}), G is soil heat flux density (MJ m^{-2} d^{-1}), λ is latent heat of vaporization (MJ kg^{-1}), and Δ and γ are as defined for the Penman-Monteith equation (Eq. 1).

The method by Caprio (1974) is expressed as:

$$ET_{0Caprio} = (0.01092708T_{mean} + 0.0060706)R_s \tag{8}$$

The original equation by Hargreaves (1975), is expressed as:

$$ET_{0Hargreaves} = 0.0135 \times 0.408 \times R_s \times (T_{mean} + 17.8) \tag{9}$$

The method by Irmak et al. (2003), developed using multiple linear regressions, is expressed as:

$$ET_{0Irmak} = -0.611 + 0.149 \times R_s + 0.079 \times T_{mean} \tag{10}$$

Tabari et al. (2011) developed two modified Irmak's equations:

$$ET_{0Tab1} = -0.642 + 0.174 \times R_s + 0.0353 \times T_{mean} \tag{11}$$

$$ET_{0Tab2} = -0.478 + 0.156 \times R_s - 0.0112 \times T_{max} + 0.0733 \times T_{min} \tag{12}$$

2.3.2. *Temperature-based methods*

The Thornthwaite (1948) method is the most commonly used method for ET_0 (PET) estimation in BiH (Čadro, Žurovec, Mrkulić et al., 2016; Čengić, 2010; Čustović & Žurovec, 2010, 2011; Čustović, Vlahinić, & Žurovec, 2012; Jakisic, Sekularac, Djuric, & Stojiljkovic, 2012; Jakisic, Sekularac, Mojevic, Govedarica, & Jugovic, 2013; Vlahinić, 1982, 2000, 2004; Žurovec J, 2015) and according to some authors provides the best results on the regional level (Čustović & Vlahinić & Hakl, 1989; Vlahinić, 1982, 2004). In this study, it was calculated as:

$$ET_{0Thornthwaite} = 16\left(\frac{T_{mean}}{I}\right)^{a} \tag{13}$$

$$I = \sum_{n=1}^{12} \left(0.2T_a\right)^{1.514} \tag{14}$$

$$a = 6.75 \times 10^{-7} I^3 - 7.71 \times 10^{-5} I^2 + 1.7912 \times 10^{-2} I + 0.49239 \tag{15}$$

where T_{mean} is mean air temperature (°C), I is a thermal index imposed by the local normal climatic temperature regime, and the exponent "a" is a function of I.

The Baier and Robertson (1965) method has the following equation:

$$ET_{0Baier-Robertson} = 0.157T_{max} + 0.158TD + 0.109R_a - 5.39 \tag{16}$$

where T_{max} is maximum air temperature (°C), and TD is temperature difference between maximum (T_{max}) and minimum (T_{min}) air temperature (°C).

The method by Hargreaves and Samani (1985) requires only minimum (T_{min}) and maximum (T_{max}) air temperature and extraterrestrial radiation (R_a), and it is expressed as:

$$ET_{0HS} = 0.0023 \times 0.408R_a \times \left(T + 17.8\right) \times TD^{0.5} \tag{17}$$

The coefficient 0.0023 is an empirical coefficient including both the conversion from American to the International system of units (0.0135) and the kR_s factor, which in this case as explained by Samani (2004) has a value of 0.17. Based on this, R_s can be calculated as:

$$R_s = kR_s \times R_a \times TD^{0.5} \tag{18}$$

than Hargreaves and Samani (1985) equation has the following form:

$$ET_{0HS} = 0.0135 \times kR_s \times 0.408R_a \times \left(T + 17.8\right) \times TD^{0.5} \tag{19}$$

Hargreaves (1994) recommended using $kR_s = 0.162$ for "interior" regions and $kR_s = 0.19$ for "coastal" regions (Allen et al., 1998; Popova et al., 2006; Samani, 2000). Differently to recommendations by Hargreaves and Samani (1985) and Allen et al. (1998), many authors suggested use of local kR_s (Jabloun & Sahli, 2008; Ren, Qu, Martins, Parades, & Pereira, 2016; Todorovic et al., 2013). Based on this, by using local kR_s coefficient HS Eqs. 19, and 22 were adjusted for the local conditions. The following six other versions of HS equation were used in this study, in which: ET_o is the reference evapotranspiration (mm day^{-1}), TD is temperature difference between maximum (T_{max}) and minimum (T_{min}) air temperature (°C), R_a is extraterrestrial radiation (MJ m^{-2} day^{-1}), and T_{mean} the mean daily air temperature at 2 m height (°C).

Allen (1993) attempted to improve original Hargreaves-Samani equation, the result was the following form of the HS:

$$ET_{0HS\_Allen} = 0.0030 \times 0.408R_a \times \left(T_{mean}+20\right) \times TD^{0.4} \tag{20}$$

Droogers and Allen (2002) reported two other types of the Hargreaves-Samani (HS) equation, based on IWMI global Climate Atlas data grids:

$$ET_{0HS\_Global} = 0.0025 \times 0.408R_a \times \left(T_{mean} + 16.8\right) \times TD^{0.5} \tag{21}$$

and other that included precipitation:

$$ET_{0HS\_Prcp} = 0.0013 \times 0.408R_a \times \left(T_{mean} + 17\right) \times \left(TD - 0.0123P\right)^{0.76} \tag{22}$$

Trajkovic (2007) reported adjusted HS equation for the humid climate of western Balkans region as follows:

$$ET_{0HS\_Trajk} = 0.0023 \times 0.408R_a \times \left(T_{mean} + 17.8\right) \times TD^{0.424} \tag{23}$$

Bogawski and Bednorz (2014) adjusted HS equation for the humid climate of Poland as follows:

$$ET_{0HS\_Boga} = 0.001 \times 0.408R_a \times \left(T_{mean} + 17\right) \times TD^{0.724} \tag{24}$$

Dorji et al. (2016) developed new HS equation for the mountainous terrain of Bhutan as follows:

$$ET_{0HS\_Dorji} = 0.002 \times 0.408R_a \times \left(T_{mean} + 33.9\right) \times TD^{0.296} \tag{25}$$

In order to have a local adjustment of kR_s for Eq. (22), we combined Droogers and Allen (2002) form of HS equation that include the precipitation with Hargreaves and Samani (1985) equation (Eq. 19), thus creating the following equation:

$$ET_{0AHS\_Prcp} = 0.0135 \times 0.408R_a \times kR_s \times \left(T_{mean} + 17.8\right) \times \left(TD - 0.0123P\right)^{0.5} \tag{26}$$

2.3.3. *Local calibration procedure*

According to suggestion by Todorovic et al. (2013), in order to avoid a multiplicity of HS equations it is preferable to adjust kR_s (from 0.1 to 0.24) than to blindly change the coefficient 0.0023, or the exponent of the temperature difference, thus altering the estimation of R_s, or changing the term "$T_{mean} + b$" using an exponent or changing the mean air temperature offset, thus the scaling of ET relative to the temperature difference. Therefore, a local calibration of the Hargreaves and Samani (1985) equation and Eq. (26) (HS_Prcp), was carried out using trial and error procedure – TE (Raziei & Pereira, 2013; Ren et al., 2016) to adjust kR_s. For equations that don't include kR_s (Eqs. 23, 24 and 25), calibration was carried out by changing the value of b coefficient in term "$T_{mean} + b$".

Through this procedure following 12 locally adjusted (LA) equations was defined: LA Hargreaves-Samani (1985) equation (AHS), LA Irmak (2003) equation (AIrmak), LA modified Irmak Eqs. 1 and 2 (ATab1 and ATab2), LA Droogers and Allen (2002) equation (AHS_Prcp), LA Trajkovic (2007) equation (AHS_Trajk), LA Bogawski and Bednorz (2014) equation (AHS_Boga), and LA HS_Dorji (Dorji et al., 2016) equation (AHS_Dorji).

Additionally, curtain transformation of combination methods by Irmak et al. (2003) Eq. (10) and two Tabari et al. (2011) modified Irmak methods (Eqs. (11) and (12)), to temperature-based, was done by using estimated (Eq. (18)) instead of measured R_s.

Except with trial and error (TE) procedure, adjusting of kR_s value for HS equation (Eq. 19), was done by Allen (1997) and Samani (2000, 2004) method:

a. Allen (1997) method to estimate kR_s as a function of elevation

$$kR_s = kR_0 \times \left(\frac{P}{P_0}\right)^{0.5} \tag{27}$$

where P is mean monthly atmospheric pressure of the site, P_0 mean monthly atmospheric pressure at sea level, kR_0 depends of site location and for "interior" regions it is 0.17 and for "coastal" 0.20. Atmospheric pressure as suggested in by Allen et al. (1998), was calculated according to Burman, Jensen, and Allen (1987):

$$P = P_0\left(\frac{(273.16 + T) - \alpha_1(z - z_0)}{(273.16 + T)}\right)^{\frac{g}{\alpha_1 R}} \tag{28}$$

where P is atmospheric pressure at elevation z (kPa), P_o is atmospheric pressure at sea level = 101.3 (kPa), z is elevation (m), z_o is elevation at reference level (m), g is gravitational acceleration = 9.807 (m s^{-2}) R is specific gas constant = 287 (J kg^{-1} K^{-1}), a_1 is constant lapse rate moist air = 0.0065 (K m^{-1}), T is mean air temperature for the time period of calculation (°C). Than Hargreaves and Samani (1985) equation with Allen (1997) kR_s adjustment (HS_A) have the following form:

$$ET_{0HS\_A} = 0.0135 \times \left[kR_0 \times \left(\frac{P}{P_0}\right)^{0.5}\right] \times 0.408R_a \times TD^{0.5}(T + 17.8) \tag{29}$$

b. Samani (2000, 2004) method to calculate kR_s, as a function of temperature difference

$$kR_s = 0.00185(TD)^2 - 0.0433TD + 0.4023 \tag{30}$$

Then Hargreaves and Samani (1985) equation with Samani (2000, 2004) kR_s calibration (HS_S) can be expressed as:

$$ET_{0HS\_S} = 0.0135 \times \left(0.00185(TD)^2 - 0.0433TD + 0.4023\right) \times 0.408R_a \times TD^{0.5}(T + 17.8) \tag{31}$$

In total, 12 alternative ET_0 calculation methods and 21 transformed and adjusted versions of same equations were validated against FAO-PM ET_0 method.

2.4. Statistical analysis

Frequently used correlation analyses, such are the correlation coefficient (R), the determination coefficient (R^2) and tests of statistical significance in general, are often inappropriate or misleading when used to compare model predicted (P) and observed (O) variables (Efthimiou, Alexandris, Karavitis, & Mamassis, 2013; Fox, 1981; Willmott, 1981, 1982). Four types of measures recommended by Fox (1981): the mean bias error (MBE), the variance of the distribution of differences (s_d^2), the root mean square difference ($RMSD$) and the mean absolute error (MAE) were used to assess alternative ET_0 equation performance. In addition, widely used determination coefficient (R^2), was also calculated and used in this research. In statistical equations, observed values (O) are represented by ET_0 calculated with FAO-PM equation (ET_{PM}), while predicted values (P) are, ET_0 values calculated with other, alternative equations (ET_{EQ}).

Used statistical methods are expressed as:

$$MBE = \frac{\sum_{i=1}^{n}\left(ET_{PM,i} - ET_{EQ,i}\right)}{n} \tag{32}$$

$$s_d^2 = (n-1)^{-1}\sum_{i=1}^{n}\left(ET_{EQ,i} - ET_{PM,i} - MBE\right)^2 \tag{33}$$

$$RMSD = \sqrt{\frac{\sum_{i=1}^{n}\left(ET_{PM,i} - ET_{EQ,i}\right)^2}{n}} \tag{34}$$

$$MAE = \frac{\sum_{i=1}^{n}\left(\left|ET_{PM,i} - ET_{EQ,i}\right|\right)}{n} \tag{35}$$

$$R^2 = \left\{\frac{\sum_{i=1}^{n}\left(ET_{PM,i} - \bar{E}T_{PM}\right) \times \left(ET_{EQ,i} - \bar{E}T_{EQ}\right)}{\left[\sum_{i=1}^{n}\left(ET_{PM,i} - \bar{E}T_{PM}\right)^2\right]^{0.5} \times \left[\sum_{i=1}^{n}\left(ET_{EQ,i} - \bar{E}T_{EQ}\right)^2\right]^{0.5}}\right\}^2 \tag{36}$$

In the equations above, n - total number of observations (data points), $ET_{EQ,i}$ – ith predicted data (ET_0 estimated by the reduced-set approaches) mm day^{-1}, $ET_{PM,i}$ - ith observed – reference data (ET_0 estimated by the FAO-56 full set PM equation) mm day^{-1}, $\bar{E}T_{PM}$ – average value for $ET_{PM,i}$, with i = 1,2,…, $\bar{E}T_{EQ}$ - average value for $ET_{EQ,i}$.

Ranking of the tested alternative ET_0 methods was based on their statistical results (MAE, $RMSD$, S_d^2, MBE and R^2), after which, for purpose of comprehensible results display, WS are separated into groups with similar FAO-PM ET_0 daily average values and alternative ET_0 methods ranking results.

3. Results

3.1. Local calibration and adjustments

Local calibration of kR_s values was based on trial and error procedure (TE), Allen (1997) and Samani (2000) calculation methods (Eqs. (27), (30)). Fifteen values of kR_s (from 0.10 to 0.24) were tested using TE procedure. Obtained kR_s values mostly ranged from 0.12 to 0.16, except for the mediterranean (WS Mostar) and mountain location (WS Bjelašnica), where kR_s was 0.16–0.20 and 0.17–0.23, respectively (Table 2).

The obtained values of kR_s empirical coefficient calculated with Allen equation (Eq. (20)) are without significant variations. Average values are related to the climate type or the mean air temperature at the location of WS. For the stations with the annual average temperature from 15.0 to 10.0 °C, kR_s was 0.17, for the stations with lower annual temperatures, from 9.9 to 6.9 °C, kR_s was 0.16, while mountain WS Bjelašnica (1.4 °C), had kR_s value of 0.15.

Samani (Eq. (23)) kR_s calculation is based on maximum and minimum air temperatures only. In this method, values of kR_s are sensitive to the temperature difference, this resulted in high variation of the values between months and the locations. kR_s depending on season and region varied in wide range, from 0.14 to 0.36, with the highest values calculated for winter months (0.18–0.36).

Similar values of kR_s and other empirical coefficients ($T_{mean}+b$) for different WS in the same climate type indicate a possibility of using these adjusted equations for ET_0 calculation on nearby or other similar stations when only limited climate data are available.

3.2. ET_0 ranking results

Based on statistical analysis, for purpose of comprehensible results display, sixteen WS were divided into seven separate regions with similar ET_0 ranking results: Northern (Sanski Most, Banja Luka, Doboj and Bijeljina), Central (Bugojno, Zenica, Tuzla and Sarajevo), Western (Bihać, Drvar, Livno), Southern (Mostar), Eastern hilly (Sokolac), and Central mountainous (Bjelašnica). Stations within one region show similar ranking results for the all tested ET_0 calculation methods, similar values of the locally adjusted empirical coefficients (kR_s), similar average daily FAO-PM ET_0 and are primarily linked with geographic location, as well as

Table 2
Characteristic empirical calibration coefficients for the studied WS.

Region	WS	ET_0	Empirical Coefficients	kR_s					$T_{mean}+b$		
			Used for method (Eq. No.)	HS 19	Irmak 10	Tab1 11	Tab2 12	HS_Prcp 26	HS_Trajk 23	HS_Boga 24	HS_Dorji 25
Southern (S)	Mostar (MO)	3.43		0.16	0.18	0.19	0.20	0.17	23.5	19.0	34.0
Northern (N)	Bijeljina (BIJ)	2.37		0.12	0.12	0.13	0.15	0.13	13.6	16.0	30.0
	Banja Luka (BL)	2.56		0.13	0.13	0.14	0.16	0.14	15.5	17.7	32.7
	Doboj (DO)	2.36		0.12	0.12	0.13	0.15	0.13	13.8	16.2	29.5
	Sanski M. (SM)	2.41		0.12	0.12	0.13	0.15	0.13	14.2	16.0	30.0
	Jajce (JA)	2.36		0.13	0.13	0.14	0.16	0.13	15.5	17.7	32.7
Central (C)	Zenica (ZE)	2.48		0.12	0.13	0.13	0.15	0.13	14.2	16.0	31.0
	Tuzla (TU)	2.43		0.13	0.13	0.13	0.15	0.13	14.4	16.5	30.5
	Sarajevo (SA)	2.55		0.14	0.14	0.15	0.16	0.14	17.6	19.0	34.0
	Bugojno (BU)	2.35		0.13	0.13	0.13	0.15	0.13	14.8	16.2	30.5
Western (W)	Bihać (BI)	2.56		0.14	0.14	0.15	0.16	0.15	16.7	19.0	33.8
	Livno (LI)	2.65		0.14	0.14	0.14	0.17	0.15	18.1	19.0	34.0
	Drvar (DR)	2.47		0.13	0.13	0.13	0.15	0.13	15.4	16.6	31.5
Central hilly (CH)	Sokolac (SO)	2.25		0.13	0.13	0.14	0.16	0.14	15.0	17.7	32.7
Eastern hilly (EH)	Ivan Sedlo (IS)	2.16		0.15	0.13	0.14	0.16	0.16	15.4	17.7	32.7
Central mo. (CM)	Bjelašnica (BJ)	1.59		0.20	0.19	0.17	0.19	0.23	24.3	19.0	34.0

Note: ET_0 – Average daily FAO-PM ET_0 (mm day-1).

having a similar mean temperature and climate type in general (Tables 1 and 2).

Tables 3 and 4 show statistical summary for the *MAE*, S_d^2 and *RMSE* values, of reference evapotranspiration (ET_0) estimates for all tested alternative methods at sixteen locations (WS) in Bosnia and Herzegovina. Figs. 2–6 show the coefficient of determination (R^2) and the *MBE* for the best ranked combination and temperature methods for every region, represented with one representative WS as an example. The figures also contain the results using Thornthwaite method, due to its importance in the previous ET_0 measurements in BiH and comparison.

3.2.1. Southern region (S)

Southern region is represented with WS Mostar (MO). It is located within the mediterranean climate with the hot and dry summers (*Csa sx*''), with the annual mean air temperature of 15 °C, and 1493 mm of precipitation (Table 1). The best ranked alternative method for reliable monthly ET_0 estimation at this location is combination Priestley-Taylor ($RMSD = 0.294$ mm day^{-1}) method, followed by Hargreaves ($RMSD = 0.325$ mm day^{-1}) and Irmak methods ($RMSD = 0.343$ mm day^{-1}) (Table 3). The obtained determination coefficient (R^2) value between FAO-PM and combination Priestley-Taylor method is high ($R^2 = 0.962$). The *MBE* results showed that this method slightly underestimate the ET_0 values (*MBE* -0.107), as shown in Fig. 2. From temperature based methods, calibration proved to be important, so the methods HS_A ($RMSD = 0.382$ mm day^{-1} and $R^2 = 0.934$), AHS ($RMSD = 0.383$ mm day^{-1}) and AHS_Trajk ($RMSD = 0.386$ mm day^{-1}) provided the best results and were better than the original version of same equations (HS and HS_Trajk). HS_A method overestimated ($MBE = 0$–066) ET_0 values (Fig. 2). The Thornthwaite method that proved to be reliable in the lysimetric research at the nearby location (Vlahinić, 1982, 2004; Čustović & Žurovec, 2010, 2011), was ranked last out of all analyzed methods with *RMSD* values up to 1.308 mm day^{-1}, and *MBE* values of -1.189, showing high underestimation of monthly ET_0 values (Fig. 2).

3.2.2. Northern region (N)

Following WS are included in the Northern region: Bijeljina (BIJ), Banja Luka (BL), Doboj (DO), Sanski Most (SM) and Jajce (JA). The area in which these stations are located has a temperate warm and humid climate with warm summers and without dry periods (*Cfb sx*''), while the mean annual air temperature ranges from 10.2 to 11.3 °C and precipitation from 754 to 1045 mm. As a result of empirical coefficients adjustments (TE procedure), the temperature methods performed much better in this region compared to the combined methods that have much higher input data requirements. The best results (*RMSD* from 0.168 to 0.211 mm day^{-1}), were achieved with the locally adjusted Trajkovic at al. (2007) equation (AHS_Trajk) developed for humid conditions of Serbia.

In this equation (Eq. (23)) the value of empirical coefficient within term "$T_{mean}+b$", depending on WS, ranged from 13.6 to 15.5 (Table 2). The representative WS of this region (N) is Banja Luka (Fig. 3). For best ranked temperature method AHS_Trajk the coefficient of determination (R^2) was high ($R^2 = 0.977$), while *MBE* had very low value (0.001), as shown in Fig. 3. From combination methods, best results were achieved using Tab 1 method (Tabari et al., 2011), with high R^2 (0.969) and low *MBE* values ($MBE = -0.037$). The Thornthwaite method had low ranking results, with ET_0 underestimation and *RMSD* values higher than 0.745 mm day^{-1} (Fig. 3).

3.2.3. Central region (C)

Four analyzed WS belong to this region: Zenica (ZE), Tuzla (TU), Bugojno (BU) and Sarajevo (SA). These WS are located in the area with *Cfb sx*'' humid climate, same as stations in Northern region. Mean annual air temperature ranges from 9.3 to 10.6 °C, and precipitation from 807 to 940 mm (Table 1). Adjusted temperature methods provided better results than more complex combination methods in this region. Calibration of the empirical coefficients in the temperature methods resulted in significant improvements of the original equations, this particularly relates to AHS_Trajk, AHS_Prcp and AHS, where *RMSD* ranged from 0.164 to 0.232 mm day^{-1} (Tables 3, 4).

Central region can be represented with Sarajevo WS, where AHS_Trajk was ranked best, with low *RMSD* (0.173) and *MBE* (-0.005), and high R^2 values (0.977), as shown in Fig. 4. From combination methods, the Makkink method ($RMSD = 0.359$ mm day^{-1}), with low ET_0 underestimations ($MBE = -0.327$) showed the best performance. Within the all other analyzed methods and their variations, Turc and Thornthwaite methods were ranked 15th and 21st, respectively, with *RMSD* values from 0.585 and 0.896 mm day^{-1} (Tables 3, 4). In WS Sarajevo Thornthwaite method showed high underestimation of ET_0 values ($MBE = -0.794$) (Fig. 4).

Table 3

Statistical summary for ET_0 alternative methods - Southern, Northern and Central region of BiH.

		Combination methods									**Temperature methods**					
Station	Method	Penman	Makkink	Turc	Priestley-T.	Caprio	Hargreaves	Irmak	Tab1	Tab2	Thornthwaite	Baier-R.	HS	HS_Glob	HS_Prcp	HS_Trajk
MO	*MAE*	0.440	0.697	0.356	0.223	0.809	0.268	0.258	0.452	0.602	1.198	0.708	0.310	0.406	0.488	0.515
(S)	S_d^2	0.012	0.432	0.062	0.083	0.282	0.061	0.305	0.669	0.488	0.165	0.489	0.012	0.041	0.022	0.035
	RMSD	0.446	0.770	0.448	0.294	0.940	0.325	0.343	0.593	0.714	1.308	0.925	0.388	0.507	0.593	0.634
BIJ	*MAE*	0.277	0.217	0.427	0.433	0.704	0.331	0.297	0.164	0.239	0.625	1.168	0.903	1.091	0.924	0.368
(N)	S_d^2	0.009	0.005	0.325	0.037	0.649	0.188	0.250	0.071	0.020	0.186	5.794	0.707	0.953	1.374	0.161
	RMSD	0.292	0.251	0.620	0.480	0.797	0.423	0.338	0.212	0.288	0.708	1.290	1.016	1.224	1.124	0.426
BL	*MAE*	0.303	0.308	0.388	0.327	0.713	0.268	0.210	0.167	0.341	0.745	0.947	0.771	0.964	0.757	0.236
(N)	S_d^2	0.003	0.013	0.451	0.023	0.772	0.232	0.270	0.082	0.079	0.193	2.771	0.304	0.459	0.498	0.034
	RMSD	0.315	0.344	0.551	0.375	0.797	0.352	0.247	0.212	0.384	0.846	1.058	0.840	1.049	0.901	0.280
DO	*MAE*	0.278	0.231	0.408	0.419	0.666	0.304	0.289	0.175	0.232	0.671	1.090	0.881	1.068	0.839	0.353
(N)	S_d^2	0.006	0.024	0.410	0.042	0.713	0.247	0.335	0.122	0.118	0.238	3.103	0.395	0.552	0.594	0.070
	RMSD	0.293	0.281	0.573	0.467	0.767	0.396	0.328	0.230	0.287	0.757	1.214	0.986	1.189	1.010	0.421
SM	*MAE*	0.271	0.217	0.463	0.416	0.699	0.308	0.280	0.280	0.262	0.678	1.048	0.888	1.077	0.887	0.338
(N)	S_d^2	0.017	0.037	0.104	0.004	0.428	0.012	0.000	0.000	0.033	0.301	1.568	0.255	0.368	0.244	0.038
	RMSD	0.281	0.257	0.678	0.468	0.783	0.403	0.322	0.322	0.314	0.781	1.158	0.971	1.179	1.050	0.382
JA	*MAE*	0.279	0.265	0.462	0.375	0.674	0.255	0.236	0.164	0.320	0.671	1.059	0.813	0.994	0.810	0.297
(N)	S_d^2	0.012	0.017	0.225	0.003	0.407	0.027	0.025	0.009	0.008	0.269	2.854	0.361	0.503	0.421	0.061
	RMSD	0.288	0.308	0.679	0.426	0.757	0.326	0.280	0.211	0.368	0.772	1.185	0.921	1.121	0.997	0.361
ZE	*MAE*	0.301	0.346	0.400	0.296	1.599	1.599	1.347	1.427	0.967	0.708	1.172	0.913	1.081	0.966	0.332
(C)	S_d^2	0.023	0.007	0.208	0.000	3.336	1.734	1.143	0.879	0.433	0.072	7.196	0.800	1.075	1.308	0.152
	RMSD	0.312	0.391	0.585	0.337	2.072	1.894	1.472	1.515	1.058	0.813	1.294	1.030	1.221	1.170	0.400
TU	*MAE*	0.305	0.211	0.429	0.413	1.989	2.139	1.838	1.999	1.493	0.696	1.046	0.846	1.034	0.838	0.303
(C)	S_d^2	0.024	0.011	0.121	0.015	3.996	1.490	0.448	0.302	0.254	0.208	1.915	0.264	0.383	0.279	0.033
	RMSD	0.322	0.241	0.597	0.464	2.592	2.486	1.978	2.105	1.605	0.793	1.160	0.940	1.147	1.008	0.353

		Temperature methods																	
Station	Methodthe climate conditions of Bosnia and Herzegovina	HS_Boga	HS_Dorji	AHS	HS_A	HS_S	AIrmak	Irmak_A	Irmak_S	ATab1	Tab1_A	Tab1_S	ATab2	Tab2_A	Tab2_S	AHS_Prcp	AHS_Trajk	AHS_Boga	AHS_Dorji
MO	*MAE*	0.892	0.676	0.308	0.305	0.330	0.371	0.367	0.458	0.452	0.498	0.671	0.403	0.566	0.671	0.361	0.304	0.746	0.671
(S)	S_d^2	0.081	0.212	0.000	0.007	0.002	0.023	0.039	0.055	0.092	0.163	0.201	0.038	0.107	0.201	0.032	0.004	0.059	0.210
	RMSD	0.972	0.900	0.383	0.382	0.426	0.464	0.479	0.608	0.567	0.693	0.909	0.517	0.768	0.909	0.442	0.386	0.832	0.896
BIJ	*MAE*	0.211	0.261	0.159	0.895	0.722	0.216	0.780	0.654	0.296	0.730	0.627	0.229	0.406	0.353	0.182	0.150	0.200	0.261
(N)	S_d^2	0.166	0.002	0.034	0.676	0.072	0.133	0.586	0.013	0.041	0.331	0.035	0.065	0.175	0.070	0.109	0.055	0.131	0.002
	RMSD	0.269	0.311	0.213	1.002	0.849	0.270	0.853	0.724	0.375	0.808	0.718	0.284	0.478	0.422	0.237	0.193	0.251	0.311
BL	*MAE*	0.160	0.340	0.148	0.753	0.589	0.225	0.660	0.532	0.360	0.647	0.552	0.285	0.351	0.313	0.168	0.141	0.153	0.326
(N)	S_d^2	0.025	0.026	0.009	0.279	0.128	0.019	0.126	0.047	0.009	0.009	0.005	0.003	0.012	0.001	0.024	0.014	0.032	0.033
	RMSD	0.205	0.395	0.195	0.816	0.703	0.284	0.717	0.596	0.438	0.734	0.648	0.345	0.407	0.387	0.212	0.185	0.196	0.388
DO	*MAE*	0.184	0.354	0.169	0.865	0.664	0.215	0.780	0.631	0.298	0.730	0.599	0.235	0.428	0.343	0.172	0.157	0.182	0.259
(N)	S_d^2	0.047	0.004	0.004	0.358	0.109	0.030	0.191	0.039	0.003	0.034	0.009	0.010	0.038	0.003	0.018	0.022	0.037	0.019
	RMSD	0.245	0.405	0.229	0.962	0.753	0.281	0.849	0.686	0.385	0.812	0.692	0.303	0.494	0.413	0.233	0.211	0.237	0.325
SM	*MAE*	0.168	0.347	0.142	0.872	0.735	0.188	0.803	0.682	0.300	0.806	0.679	0.227	0.426	0.326	0.148	0.132	0.151	0.262
(N)	S_d^2	0.029	0.007	0.001	0.232	0.232	0.003	0.081	0.116	0.014	0.010	0.027	0.001	0.015	0.032	0.000	0.012	0.021	0.019
	RMSD	0.211	0.393	0.195	0.949	0.859	0.251	0.853	0.746	0.370	0.870	0.773	0.286	0.480	0.411	0.192	0.168	0.189	0.321
JA	*MAE*	0.178	0.317	0.155	0.747	0.649	0.225	0.689	0.614	0.360	0.686	0.610	0.285	0.342	0.295	0.155	0.141	0.153	0.326

(N)	S_d^2	0.053	0.003	0.028	0.297	0.133	0.019	0.189	0.062	0.009	0.051	0.000	0.003	0.040	0.000	0.004	0.014	0.032	0.033
	RMSD	0.227	0.366	0.210	0.845	0.781	0.284	0.754	0.677	0.438	0.751	0.701	0.345	0.405	0.375	0.201	0.185	0.196	0.388
ZE	*MAE*	0.205	0.333	0.171	0.837	0.795	0.241	2.438	2.393	0.272	2.703	2.650	0.228	2.110	2.063	0.165	0.170	0.196	0.264
(C)	S_d^2	0.199	0.000	0.028	0.706	0.078	0.248	3.254	0.329	0.073	3.226	0.129	0.069	2.038	0.019	0.049	0.049	0.153	0.007
	RMSD	0.260	0.380	0.232	0.948	0.977	0.295	2.537	2.494	0.373	2.778	2.740	0.308	2.180	2.142	0.215	0.219	0.240	0.334
TU	*MAE*	0.150	0.309	0.144	0.800	0.639	0.196	2.751	2.529	0.270	3.066	2.806	0.199	2.449	2.216	0.134	0.128	0.148	0.242
(C)	S_d^2	0.022	0.010	0.010	0.224	0.132	0.010	0.891	0.688	0.013	0.757	0.543	0.000	0.626	0.451	0.000	0.008	0.018	0.024
	RMSD	0.192	0.351	0.186	0.885	0.760	0.241	2.834	2.598	0.347	3.128	2.864	0.259	2.509	2.269	0.176	0.164	0.187	0.297

Note: Tab1 and Tab2 – Modified Irmak Eqs. 1 and 2 (Tabari et al., 2011); HS – Hargreaves-Samani (1985); HS_Glob – Droogers-Allen (2002); HS_Prcp - Droogers-Allen (2002) that included precipitation; HS_Trajk – Trajkovic (2007); HS_Boga – Bogawski and Bednorz (2014); HS_Dorji (Dorji et al., 2016); AHS – Locally adjusted Hargreaves-Samani (1985) equation; HS_A - Hargreaves-Samani (1985) with Allen (1997) *kRs*; HS_S - Hargreaves-Samani (1985) with Samani (2000, 2004) *kRs*; AIrmak – Locally adjusted Irmak (2003) equation; Irmak_A - Irmak (2003) with Allen (1997) *kRs*; Irmak_S - Irmak (2003) with Samani (2000, 2004) *kRs*; ATab1 and ATab2– Locally adjusted modified Irmak Eqs. 1 and 2 (Tabari et al., 2011); Tab1_A and Tab2_A – modified Irmak with Allen (1997) kRs; Tab1_S and Tab2_S – Modified Irmak (2003) with Samani (2000, 2004) *kRs*; AHS_Prcp - Locally adjusted Droogers-Allen (2002); AHS_Trajk - Locally adjusted Trajkovic (2007); AHS_Boga – Locally adjusted Bogawski and Bednorz (2014); AHS_Dorji – Locally adjusted HS_Dorji (Dorji et al., 2016).

3.2.4. *Western region (W)*

Western region includes three WS: Drvar (DR), Bihać (BI) and Livno (LI). According to Köppen–Geiger (Geiger, 1961) climate classification, Livno and Bihać are classified into *Cfb*, while Drvar WS belongs to *Cfc*, climate type (Drešković & Mirić, 2013). Nevertheless, these stations have similar average climate characteristics (Table 1) and obtained ET_0 methods ranking results (Table 4). Mean annual air temperature ranges from 9.4 to 11.0 °C, with relatively high values of annual precipitation ranging from 1133 to 1341 mm (Table 1). Of all the analyzed temperature-based methods in this region represented with Bihać WS, AHS_Trajk had the best performance (*RMSD* from 0.157 to 0.188 mm day^{-1} and R^2 = 0.979), followed by the AHS (*RMSD* from 0.168 to 0.236 mm day^{-1}) and the AHS_Boga (*RMSD* from 0.191 to 0.235 mm day^{-1}) methods (Table 4 and Fig. 5). From combination methods, Irmak and Tab 1 equations showed good results (*RMSD* from 0.216 to 0.303 mm day^{-1}), with high R^2 (0.968) and low *MBE* values (from −0.078).

The Thornthwaite method in this area was one of the lowest ranked methods for estimating monthly ET_0, with high *RMSD* (from 0.849 to 1.070 mm day^{-1}) and low *MBE* values (from −0.708) (Table 4 and Fig. 5).

3.2.5. *Central hilly region (CH)*

Central hilly region is represented with Ivan Sedlo (IS) WS. The area in which this station is located has temperate warm and humid climate with fresh summer and without dry periods (*Cfc x"w*). Mean annual air temperature is about 7.5 °C, and mean annual precipitation is 1476 mm (Table 1). Similar as for Northern, Central and Western regions, method with the best performance for this area is AHS_Trajk (*RMSD* = 0.185 mm day^{-1} and R^2 = 0.957) followed by the AHS (*RMSD* = 0.193 mm day^{-1}) method (Table 4 and Fig. 6).

From combination methods, the Tab 1 showed best performance, with *RMSD* values of 0.214 mm day^{-1}, R^2 values of 0.957, and low ET_0 overestimation (*MBE* = 0.075) (Fig. 6). The Turc and the Thornthwaite methods, together with the Caprio and the Baier-Robertson were ranked lowest (Table 4).

3.2.6. *Eastern hilly region (EH)*

Eastern hilly region is represented with only one WS – Sokolac (SO). According to climate classification, this station is located in the snow-forest climate, with warm summer and without dry periods (*Dfb x"w*). Mean annual air temperature is about 7.5 °C, and mean annual precipitation is 1476 mm (Table 1). The most suitable option for ET_0 calculation with limited data is the AHS (*RMSD* = 0.160 mm day^{-1} and R^2 = 0.977) method (Table 4 and Fig. 6), followed by HS_Boga (*RMSD* = 0.167 mm day^{-1}) and AHS_Trajk (*RMSD* = 0.183 mm day^{-1}) methods. AHS had very low *MBE* value of −0001 (Fig. 6). From combination methods, Makkink equation had best results, with *RMSD* values of 0.231 mm day^{-1}, R^2 = 0.982, and *MBE* = −0.179. Thornthwaite method with *RMSD* value of 0.844, R^2 = 0.927, and *MBE* = −0.724 was one of the lowest ranked methods (Table 4 and Fig. 6).

3.2.7. *Central mountainous region (CM)*

Central mountain region is represented with WS Bjelašnica (BJ) located at 2067 m a.s.l. Based on Köppen–Geiger (Geiger, 1961) climate classification, this location has tundra climate (*ET fx"*). Average annual temperature is about 1.4 °C, with 1163 mm of annual precipitation. Similar to Southern region (Mostar), combination methods performed better than temperature methods. The most suitable alternative method for ET_0 calculation is Hargreaves (*RMSD* = 0.278 mm day^{-1} and R^2 = 0.948), followed by Makkink (*RMSD* = 0.302 mm day^{-1}) method (Table 4 and Fig. 6). Hargreaves method slightly overestimate ET_0 values (*MBE* = 0.146).

Table 4
Statistical summary for ET_0 alternative methods – Central, Western, Central hilly, Eastern hilly and Central mountain region of BiH.

		Combination methods									Temperature methods					
Station	Method	Penman	Makkink	Turc	Priestley-T.	Caprio	Hargreaves	Irmak	Tab1	Tab2	Thornthwaite	Baier-R.	HS	HS_Glob	HS_Prcp	HS_Trajk
SA	*MAE*	0.346	0.323	0.448	0.271	1.757	1.900	1.662	1.859	1.379	0.805	0.918	0.512	0.683	0.496	0.129
(C)	S_d^2	0.006	0.001	0.063	0.023	3.187	1.965	1.046	1.070	0.605	0.056	3.341	0.361	0.501	0.678	0.052
	RMSD	0.357	0.359	0.665	0.315	2.269	2.226	1.791	1.955	1.474	0.896	1.096	0.603	0.793	0.636	0.174
BU	*MAE*	0.288	0.273	0.541	0.322	1.590	1.788	1.658	1.879	1.317	0.723	1.085	0.797	0.977	0.874	0.279
(C)	S_d^2	0.016	0.004	0.496	0.000	3.711	1.902	1.245	0.942	0.590	0.085	5.884	0.557	0.773	0.884	0.102
	RMSD	0.297	0.315	0.862	0.365	2.017	2.086	1.783	1.970	1.411	0.831	1.217	0.919	1.120	1.102	0.339
BI	*MAE*	0.337	0.318	0.418	0.317	0.731	0.288	0.222	0.179	0.344	0.747	0.881	0.609	0.791	0.515	0.147
(W)	S_d^2	0.014	0.039	0.026	0.001	0.347	0.023	0.001	0.020	0.005	0.203	0.555	0.051	0.094	0.002	0.001
	RMSD	0.346	0.348	0.595	0.370	0.818	0.367	0.262	0.216	0.384	0.849	1.009	0.688	0.887	0.670	0.183
LI	*MAE*	0.351	0.243	0.516	0.323	0.746	0.233	0.183	0.187	0.332	0.982	0.814	0.506	0.683	0.578	0.145
(W)	S_d^2	0.049	0.092	0.073	0.001	0.285	0.001	0.051	0.195	0.024	0.273	0.034	0.001	0.009	0.068	0.018
	RMSD	0.364	0.286	0.751	0.369	0.863	0.306	0.224	0.241	0.384	1.070	0.931	0.593	0.786	0.753	0.191
DR	*MAE*	0.275	0.301	0.536	0.364	0.696	0.261	0.257	0.210	0.411	0.810	0.986	0.794	0.981	0.854	0.283
(W)	S_d^2	0.001	0.010	0.079	0.124	0.493	0.074	0.008	0.002	0.009	2.167	0.017	0.011	0.014	0.049	0.001
	RMSD	0.289	0.396	0.742	0.418	0.791	0.328	0.304	0.298	0.512	0.932	1.108	0.890	1.093	1.046	0.338
SO	*MAE*	0.260	0.192	0.741	0.393	0.728	0.199	0.239	0.184	0.364	0.755	0.929	0.671	0.834	0.732	0.203
(EH)	S_d^2	0.020	0.000	0.386	0.020	0.249	0.055	0.116	0.020	0.038	0.106	1.444	0.136	0.220	0.147	0.006
	RMSD	0.272	0.231	1.260	0.436	0.840	0.250	0.287	0.235	0.420	0.844	1.073	0.752	0.935	0.885	0.247
IS	*MAE*	0.364	0.187	0.625	0.413	0.684	0.190	0.232	0.174	0.213	0.676	0.948	0.282	0.412	0.293	0.160
(CH)	S_d^2	0.009	0.010	0.050	0.045	0.177	0.073	0.080	0.040	0.025	0.204	1.341	0.102	0.156	0.208	0.014
	RMSD	0.376	0.224	0.939	0.452	0.786	0.247	0.268	0.214	0.263	0.768	1.255	0.369	0.510	0.360	0.216
BJ	*MAE*	0.823	0.247	1.566	0.739	1.024	0.221	0.342	0.479	0.316	0.660	1.965	0.319	0.283	0.725	0.413
(CM)	S_d^2	0.075	0.143	0.027	0.461	0.321	0.190	0.136	0.112	0.117	1.306	1.394	0.253	0.283	0.044	0.207
	RMSD	0.852	0.302	2.282	0.792	1.118	0.278	0.402	0.564	0.383	0.765	2.114	0.436	0.384	0.857	0.553

		Temperature methods																
Station	Method	HS_Boga	HS_Dorji	AHS	HS_A	HS_S	AIrmak	Irmak_A	Irmak_S	ATab1	Tab1_A	Tab1_S	ATab2	Tab2_A	Tab2_S	AHS_Prcp	AHS_Trajk	AHS_Boga	AHS_Dorji
SA	*MAE*	0.317	0.258	0.128	0.417	0.324	0.176	2.244	2.187	0.259	2.539	2.472	0.200	1.988	1.928	0.173	0.128	0.190	0.258
(C)	S_d^2	0.057	0.002	0.072	0.278	0.000	0.096	1.844	0.087	0.084	2.033	0.034	0.036	1.275	0.000	0.061	0.049	0.104	0.002
	RMSD	0.354	0.327	0.173	0.494	0.387	0.231	2.330	2.212	0.320	2.602	2.493	0.274	2.048	1.947	0.219	0.173	0.237	0.326
BU	*MAE*	0.195	0.296	0.148	0.711	0.762	0.188	2.377	2.429	0.204	2.719	2.780	0.168	2.070	2.124	0.137	0.146	0.190	0.201
(C)	S_d^2	0.124	0.001	0.058	0.455	0.171	0.198	2.263	0.594	0.035	2.030	0.323	0.055	1.381	0.166	0.024	0.040	0.099	0.011
	RMSD	0.235	0.333	0.189	0.819	1.061	0.228	2.463	2.610	0.273	2.779	2.950	0.227	2.127	2.284	0.169	0.181	0.224	0.263
BI	*MAE*	0.248	0.280	0.134	0.576	0.441	0.181	0.477	0.383	0.293	0.438	0.399	0.213	0.211	0.272	0.168	0.121	0.153	0.279
(W)	S_d^2	0.009	0.061	0.001	0.038	0.038	0.012	0.008	0.023	0.068	0.005	0.000	0.019	0.000	0.003	0.014	0.002	0.004	0.062
	RMSD	0.287	0.336	0.168	0.647	0.529	0.226	0.534	0.436	0.354	0.506	0.486	0.276	0.265	0.332	0.212	0.157	0.191	0.336
LI	*MAE*	0.293	0.281	0.146	0.394	0.448	0.175	0.379	0.400	0.274	0.452	0.472	0.235	0.207	0.262	0.169	0.144	0.187	0.281
(W)	S_d^2	0.095	0.091	0.028	0.001	0.044	0.096	0.073	0.285	0.291	0.243	0.640	0.036	0.040	0.226	0.060	0.018	0.091	0.090
	RMSD	0.342	0.353	0.191	0.469	0.709	0.231	0.429	0.541	0.351	0.506	0.615	0.284	0.277	0.361	0.213	0.188	0.235	0.352
DR	*MAE*	0.180	0.336	0.171	0.718	0.814	0.213	0.693	0.734	0.296	0.754	0.794	0.240	0.351	0.359	0.173	0.173	0.179	0.295
(W)	S_d^2	0.000	0.012	0.000	0.006	0.096	0.023	0.048	0.000	0.111	0.168	0.026	0.038	0.053	0.000	0.005	0.003	0.000	0.010
	RMSD	0.236	0.411	0.236	0.806	1.097	0.296	0.743	0.868	0.401	0.803	0.933	0.350	0.419	0.509	0.244	0.243	0.233	0.389
SO	*MAE*	0.132	0.327	0.117	0.535	0.570	0.225	0.568	0.584	0.360	0.703	0.724	0.285	0.275	0.268	0.144	0.139	0.153	0.326
(EH)	S_d^2	0.001	0.031	0.000	0.079	0.160	0.019	0.045	0.136	0.009	0.000	0.030	0.003	0.004	0.051	0.000	0.000	0.032	0.033

	RMSD	0.167	0.374	0.160	0.601	0.746	0.284	0.624	0.678	0.438	0.764	0.814	0.345	0.331	0.368	0.185	0.183	0.196	0.388
IS	*MAE*	0.478	0.270	0.143	0.192	0.336	0.225	0.235	0.431	0.360	0.277	0.585	0.285	0.194	0.413	0.191	0.140	0.153	0.326
(CH)	S_d^2	0.001	0.000	0.034	0.066	0.003	0.019	0.074	0.002	0.009	0.035	0.006	0.003	0.022	0.008	0.099	0.014	0.032	0.033
	RMSD	0.526	0.326	0.193	0.260	0.392	0.284	0.292	0.490	0.438	0.329	0.675	0.345	0.258	0.485	0.237	0.185	0.196	0.388
BJ	*MAE*	0.787	0.368	0.255	0.425	0.406	0.292	0.496	0.585	0.358	0.417	0.931	0.300	0.506	0.647	0.273	0.302	0.707	0.369
(CM)	S_d^2	0.114	0.248	0.348	0.207	0.403	0.453	0.320	0.551	0.396	0.319	0.594	0.437	0.300	0.537	0.148	0.301	0.129	0.249
	RMSD	0.939	0.476	0.324	0.563	0.483	0.364	0.596	0.678	0.470	0.566	1.029	0.387	0.627	0.740	0.361	0.383	0.864	0.476

Note: Tab1 and Tab2 – Modified Irmak Eqs. (1 and 2) (Tabari et al., 2011); HS – Hargreaves-Samani (1985); HS_Glob – Droogers-Allen (2002); HS_Prcp - Droogers-Allen (2002) that included precipitation; HS_Trajk – Trajkovic (2007); HS_Boga – Bogawski and Bednorz (2014); HS_Dorji (Dorji et al., 2016); AHS – Locally adjusted Hargreaves-Samani (1985) equation; HS_A - Hargreaves-Samani (1985) with Allen (1997) *kRs*; HS_S - Hargreaves-Samani (1985) with Samani (2000, 2004) *kRs*; AIrmak – Locally adjusted Irmak (2003) equation; Irmak_A - Irmak (2003) with Allen (1997) *kRs*; Irmak_S - Irmak (2003) with Samani (2000, 2004) *kRs*; ATab1 and ATab2– Locally adjusted modified Irmak Eqs. 1 and 2 (Tabari et al., 2011); Tab1_A and Tab2_A – modified Irmak with Allen (1997) *kRs*; Tab1_S and Tab2_S – Modified Irmak (2003) with Samani (2000, 2004) *kRs*; AHS_Prcp - Locally adjusted Droogers-Allen (2002); AHS_Trajk - Locally adjusted Trajkovic (2007); AHS_Boga – Locally adjusted Bogawski and Bednorz (2014); AHS_Dorji – Locally adjusted HS_Dorji (Dorji et al., 2016).

From temperature methods, similar results were obtained for the AHS (*RMSD* = 0.324 mm day^{-1} and R^2 = 0.868) when calibrated kR_s value of 0.20 was used, and AHS_Prcp (*RMSD* = 0.361 mm day^{-1}) with $kR_s = 0.23$ (Tables 2, 4). HS_Dorji equation, which was originally developed for the mountain region of Bhutan (Dorji et al., 2016), could not achieve *RMSD* or *MAE* value under 0.368 mm day^{-1}, even after local calibration (Table 4).

4. Discussion

Overall, the most suitable and reliable alternative equation for monthly ET_0 calculation in BiH is the locally adjusted Trajkovic (Trajkovic, 2007) method (AHS_Trajk). Trajkovic (2007) modified this method for the humid area of Serbia by adjusting empirical coefficients in simple Hargraves-Samani (1985) equation. By modifying these same coefficients ($T_{mean} + 17.8$) for each analyzed location in BiH (Table 2), we developed the best performing alternative ET_0 equation (AHS_Trajk) in our study, with low *RMSD* (from 0.157 to 0.243 mm day^{-1}), *MAE* (from 0.121 to 0.173 mm day^{-1}), *MBE* (from −0.266 to 0.080) and high R^2 (from 0.952 to 0.980). Exceptions are mediterranean (Southern region) and mountain (Central mountainous region) locations, where AHS_Trajk was sixth performing equation with *RMSD* around 0.384 mm day^{-1}. The combination methods performed much better (Priestley-Taylor, Hargreaves and Makkink) in these cases. Beside the difference in most suitable alternative ET_0 methods, Southern and Central mountain region also differ in the possibility of precise ET_0 determination, compared to all other regions. Thus, the lowest *RMSD* and *MAE* values for S and CM region range from 0.221 to 2.940 mm day^{-1} as compared to 0.117–0.233 mm day^{-1}, for the other regions (Tables 3, 4). AHS was the second best performing method. When used with locally adjusted empirical coefficients (Table 2), this equation was ranked first to third for most WS.

In general, considering all used statistical methods of validation, ten best performing methods, have a following order: AHS_Trajk > AHS > AHS_Prcp > AHS_Boga > AIrmak > HS_Trajkovic > Makkink > ATab2 > HS_Boga > Penman. The first 5 methods were locally calibrated and adjusted, and only 2 from best 10 are combination methods.

All tested alternative methods that had the value of *MAE* and *RMSD* > 0.5 mm day^{-1}, could be rejected as not suitable and reliable, and we do not recommend their usage for ET_0 calculations in BiH. On a monthly basis, 0.5 mm day^{-1} would amount to 15 mm of ET_0, which means that the mistake will be 50% or more in the winter period (November – February) when the monthly ET_0 is mostly less than 30 mm. Based on our results, the following methods belong in this group: Baier and Robertson (1965), Caprio (1974), Thornthwaite (1948), and Turc (1961). It is interesting to notice that last two are mostly used methods in BiH until now.

The conversion of combination methods by Irmak (2003) and Tabari et al. (2011) to temperature methods using estimated (Eq. (18)) instead of measured R_s values, did not provide promising results. All transformed combination methods (AItmak, ATab1, ATab2) performed worse than locally adjusted HS equations (AHS_Trajk, AHS, AHS_Prcp). Modification of Droogers and Allen (2002) equation (Eq. (22)) that includes precipitation, resulted in reliable method (Eq. (26)), which was much better than the original form of equation (Eq. (22)) and in the case of one WS (Central region, WS Zenica) showed very good results (*RMSD* = 0.215 mm day^{-1}, *MBE* = 0.011 and R^2 = 0.965) based on which it was ranked as the best performing alternative ET_0 method.

Importance of calibration and local adjustment procedure was stressed by many researchers worldwide (Gavilan, Lorente, Tornero, & Berengena, 2006; Irmak et al., 2003; Xu & Singh, 2002; Gonzalez et al., 2009, Bautista, Bautista, & Delgado-Carranza,

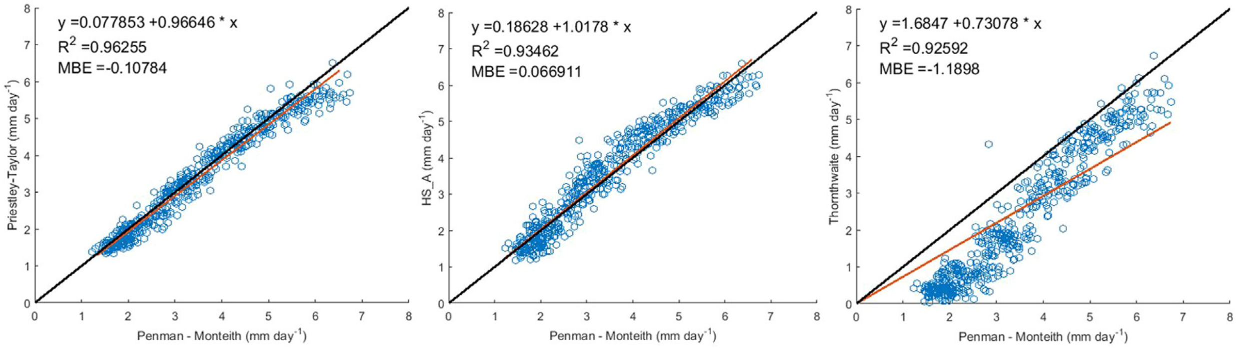

Fig. 2. Relationship between daily FAO-PM ET_0 values and estimates by Thornthwaite method, best combination method and best temperature method for the Southern region (Mostar).

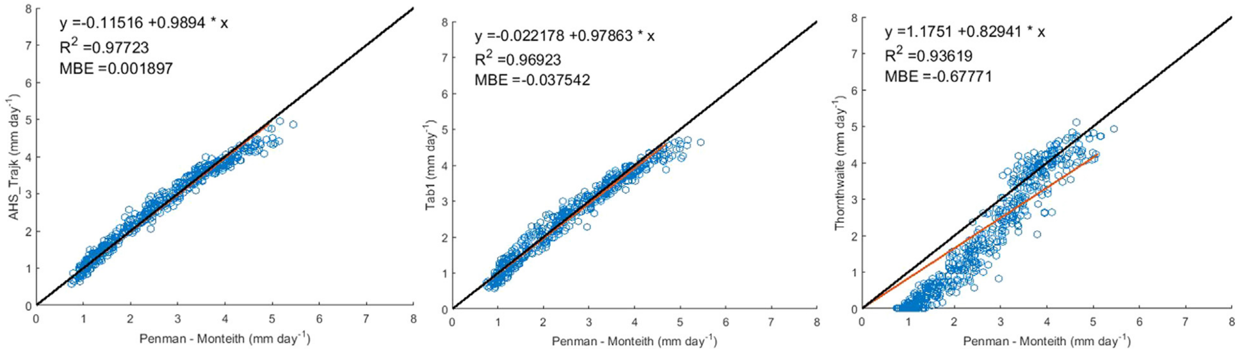

Fig. 3. Relationship between daily FAO-PM ET_0 values and estimates by Thornthwaite method, best combination method and best temperature method for the Northern region (Banja Luka).

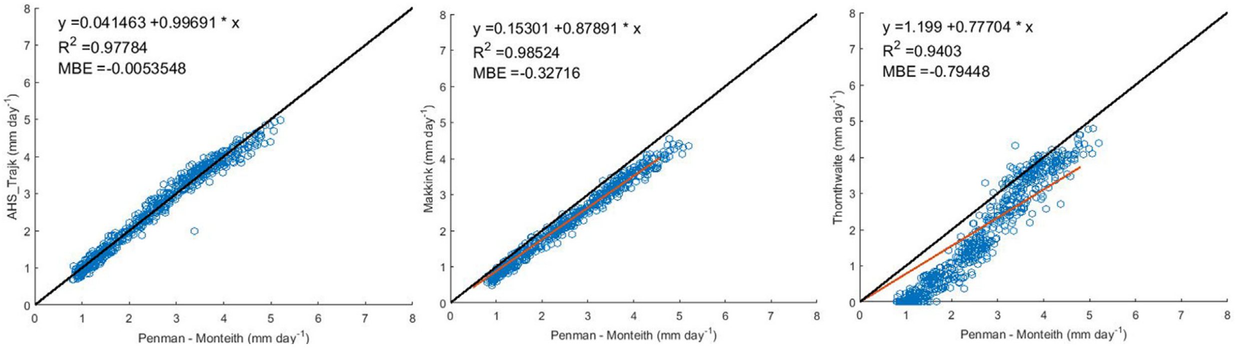

Fig. 4. Relationship between daily FAO-PM ET_0 values and estimates by Thornthwaite method, best combination method and best temperature method for Central region (Sarajevo).

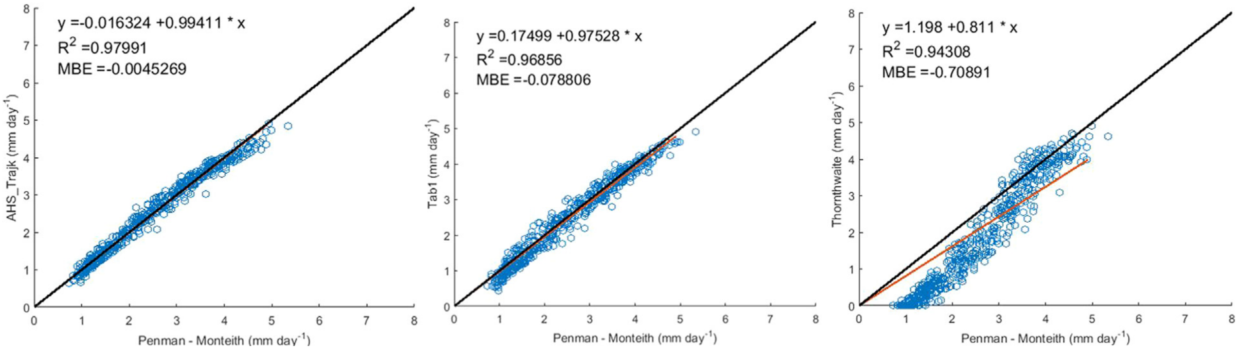

Fig. 5. Relationship between daily FAO-PM ET_0 values and estimates by Thornthwaite method, best combination method and best temperature method for Western region (Bihać).

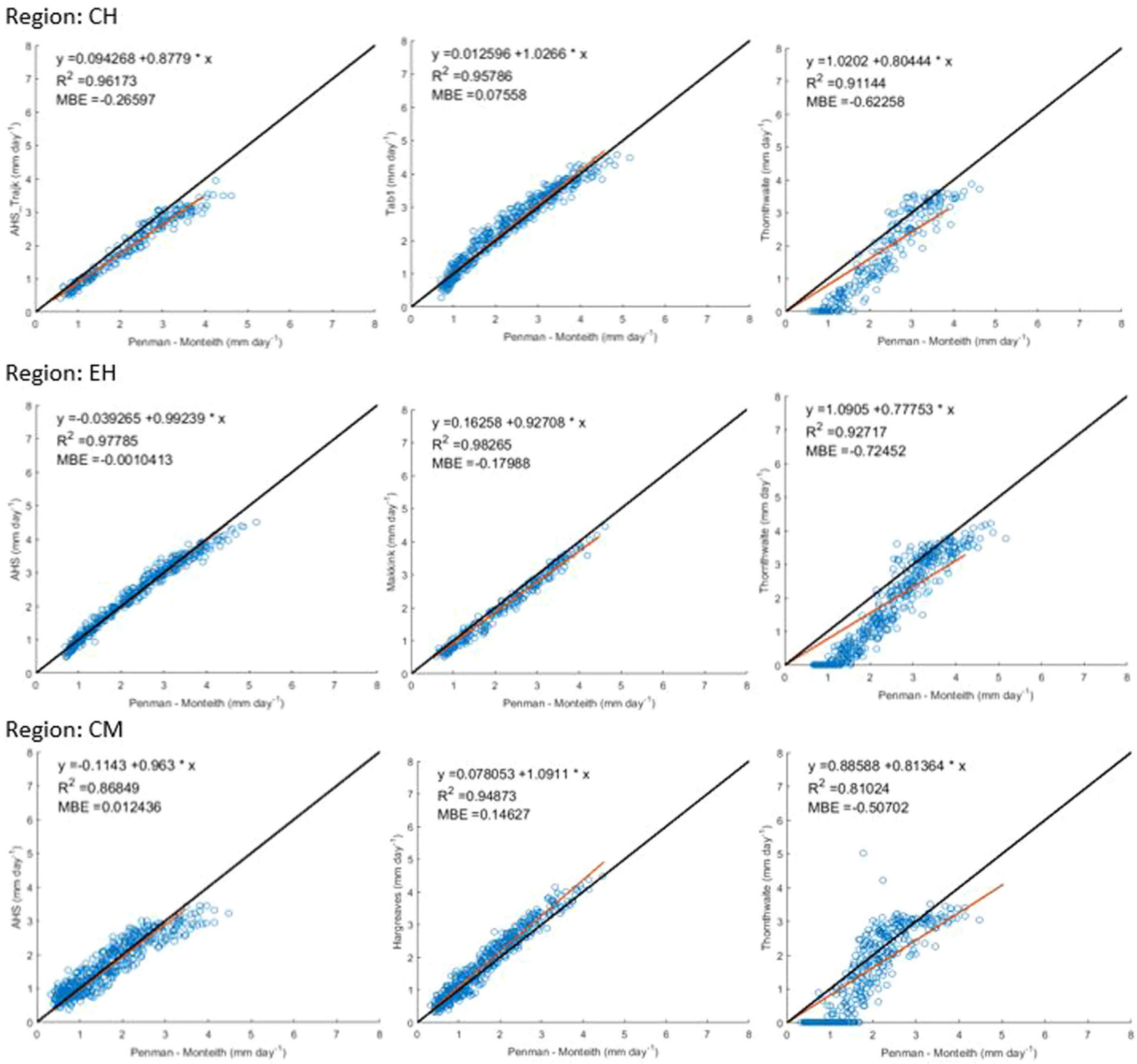

Fig. 6. Relationship between daily FAO-PM ET_0 values and estimates by Thornthwaite method, best combination method and best temperature method for CH, EH and CM regions (Ivan Sedlo, Sokolac and Bjelašnica).

2009; Jabloun & Sahli, 2008; Sentelhas, Gillespie, & Santos, 2010; Todorovic et al., 2013; Berti et al., 2014; Bogawski & Bednorz, 2014; Temeeopattanapongsa & Thepprasit, 2015; Dorji et al., 2016; Ren et al., 2016). Regional calibration is important in decreasing the bias, especially if it includes monthly calibration coefficients (Shahidian et al., 2012), but we also found that *RMSD* and *MAE* values are important for BiH conditions. Calibration proved to be very important in BiH, especially in case of the temperature methods based on Hargreaves and Samani (1985) method, which became not only better than original equations but also better than certain combination methods (e.g. Priestley-Taylor, Turc, Makkink, Hargreaves, Irmak, etc.).

The usage of the Hargreaves and Samani (1985) equation (Eq. (17)) without calibration procedure comes down to pure luck. If the kR_s value of the "real" local value is the same or close to the original value of 0.17 (Samani, 2004; Todorovic et al., 2013), the results will be good, otherwise not. As stressed by Samani (2004), using a kR_s value of 0.17, which was the kR_s value for Salt Lake City, works quite well for most cases, but care should be taken not to overextend the use of Eq. (17) for locations where climate conditions significantly differ from conditions in which Eqs. (9), (17), and (18) were developed. Using kR_s values of 0.16 for interior and 0.19 for coastal regions (Hargreaves, 1994; Popova et al., 2006) recommended by FAO (Allen et al., 1998) proved to be inadequate for BiH. This is due to the fact that all the analyzed WS in Bosnia and Herzegovina are located in the interior part of the country, but obtained kR_s values ranged from 0.12 to 0.20.

Smaller *RMSD*, *MAE*, S_d^2 and bigger *MBE*, *R* and R^2 values were achieved with kR_s values obtained by Trial and error procedure rather than Allen (1997) or Samani (2000, 2004) method. The exception is a Southern region WS Mostar, where Allen (1997) method in HS equation (Eq. (29)) performed better than the AHS equation.

Two most frequently used ET_0 (*PET*) calculation methods in BiH, Thornthwaite and Turc, ranked amongst the lowest in our study, 25th and 24th, respectively. Globally, the Turc equation is highly recommended for humid areas (Jensen et al., 1990; Shahidian et al., 2012; Trajkovic & Kolakovic, 2009a), but the results of this method were not satisfactory in our study ($RMSD > 0.448$ mm day^{-1}). This may be due to the large number of negative ET_0 values obtained by this method.

When validating alternative ET_0 equations for certain areas, many authors (Irmak et al., 2003; DehghaniSanij et al., 2004; Gavilan et al., 2007; Trajkovic, 2007, Trajkovic & Kolakovic, 2009b; Tabari et al., 2011; Heydari & Heydari, 2014; Pandey et al., 2014; Ren et al., 2016,) classify the regions and results based on the climate character (arid to humid). Based on our results, we found a significant difference between most suitable equations and values of empirical coefficients in Hargreaves-Samani equations within the same climate and same climate character in BH. It is our opinion that the area classification based on climate subtype (Köppen–Geiger) rather than climate character (arid to humid), would be more accurate and comprehensive.

5. Conclusions

The main objective of this research was validation of alternative temperature or combination-based ET_0 equations for the climatological and agro-ecologically diverse conditions of BiH. Results of in this research tested 12 alternative ET_0 calculation methods and 21 transformed and adjusted versions of same equations show that the most suitable and reliable alternative equation for monthly ET_0 calculation in BiH is the locally adjusted Trajkovic method (AHS_Trajk). This method had low $RMSD$ (from 0.157 to 0.243 mm day^{-1}), MAE (from 0.121 to 0.173 mm day^{-1}), MBE (from -0.266 to 0.080) and high R^2 (from 0.952 to 0.980) values.

The combination methods performed much better in the mediterranean and the mountainous locations, while the temperature-based methods with locally calibrated empirical coefficients (kR_s and $T_{mean}+17.8$), become better than the original forms of equations as well as all tested calibration methods in temperate climate regions. Local adjustment and calibration of empirical coefficients proved to be very important in BiH, especially in the case of the temperature methods based on Hargreaves and Samani (1985) method. In the case when only basic climatic data are available, reliable monthly ET_0 values for different locations in BiH can be obtained by using the following methods: AHS_Trajk > AHS > AHS_Prcp > AHS_Boga > AIrmak > HS_Trajkovic > Makkink > ATab2 > HS_Boga > Penman.

The results for the two most frequently used ET_0 calculation methods in BiH until now, Thornthwaite and Turc, ranked amongst the lowest in our study. This especially relates to the Thornthwaite method, which had the values of MAE and $RMSD$ $>$ 0.5 mm day^{-1} for all sixteen analyzed locations. Based on our results, this method is not reliable, and we do not recommend its usage for monthly ET_0 calculations in BiH.

Our efforts to distinguish regions in BiH with same ET_0 ranking results led to a conclusion that locations cannot be classified and grouped into regions based on the area of their climate character (arid/humid). We found that locations with same climate type and climate character had large differences in results, and area classification based on climate subtype would be more accurate and comprehensive.

Further research is required in order to assess the effect of using reduced-set weather data for daily ET_0 estimates instead of monthly ET_0 estimates used in this study. Also, for more precise values of FAO-PM ET_0 determination of local and regional a_s and b_s coefficients in Ångström equation is recommended.

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