Theoretical and Applied Climatology (2019) 138:1231–1240
https://doi.org/10.1007/s00704-019-02873-1

ORIGINAL PAPER

Adjustment of Thornthwaite equation for estimating evapotranspiration in Vojvodina

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Received: 2 February 2019 / Accepted: 15 April 2019 / Published online: 18 May 2019

Abstract

Evapotranspiration is one of the crucial components of hydrological cycle. The Penman-Monteith method (PM) is recommended as the sole standard method for estimating reference evapotranspiration (ET_0). The usage of the PM method is limited in many regions due to the lack of required weather data. In such circumstances, simple Thornthwaite equation is often used to estimate ET_0. The main objectives of the present study are (i) to estimate reference evapotranspiration using different Thornthwaite approaches, (ii) to develop optimal adjusted equation, and (iii) to consider the spatial variability of the empirical coefficient(s) of adjusted equation for the study area. In this study, six Thornthwaite approaches were compared to the full set PM equation using weather data from Vojvodina region, Serbia. The original Thornthwaite equation was very poor in estimating ET_0 and greatly underestimated PM values at all locations. It can be concluded that an adjustment of the Thornthwaite equation is necessary. The obtained results indicate that ET_0 could be estimated from the new Th65 approach (effective temperature, $k =$ 0.65), which reproduced statistical characteristics better compared to other Thornthwaite approaches. The spatial variability of the empirical k coefficient showed that k values varied from 0.62 to 0.69 across the study area with deviations of −5% to 6% compared to a unique k value of 0.65. These results suggested that single regional k value can be successfully used for estimating ET_0.

1 Introduction

The process in which water stored in the soil and/or vegetation is converted from the liquid into the vapor phase and transferred to the atmosphere is called evapotranspiration. Water is converted on the one hand from soil through evaporation, and on the other hand from crop plant tissues by transpiration.

Evapotranspiration is a key process of water cycle and profoundly important for the energy cycle via latent heat transfer (Farzanpour et al. 2019; Shiri 2019). Evapotranspiration plays a crucial role in myriad scientific and management issues, including hydrological, climatological, and agricultural studies, as well as water resources management and natural hazards management (Almorox et al. 2018; Kiafar et al. 2017; Landeras et al. 2018; Paredes et al. 2018; Shiri 2017).

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Irrigation water requirement is usually calculated based on the reference evapotranspiration (ET_0), which is defined as the evapotranspiration rate from a surface of hypothetical grass reference crop with an assumed crop height (12 cm) and a fixed canopy resistance (70 s m^{-1}) and albedo (0.23).

There are a plenty of empirical equations that have been developed for ET_0 estimation. The Penman-Monteith method (PM) is recommended as the sole standard method (Allen et al. 1998). The main limitation of this method is the difficulty in obtaining all necessary input data (air temperature, humidity, solar radiation, and wind speed). In such circumstances, simple equations are often used to estimate ET_0.

The Thornthwaite (1948) equation is widely used as a simple method for ET_0 estimation (Almorox et al. 2015; Amatya and Harrison 2016; Wang et al. 2018). Many well-known drought indices (such as PDSI, RDI, SPEI) use the Thornthwaite equation for estimating evapotranspiration (Palmer 1965; Tsakiris and Vangelis 2005; Vicente-Serrano et al. 2010).

This equation correlated mean monthly temperature with evapotranspiration as determined by water balance studies carried out for the eastern/central USA and is most appropriately applied to climatic conditions similar to that where it was developed. In fact, weak results can be expected when the Thornthwaite equation is extrapolated to other climatic regions without recalibrating the constants involved in the equation.

Trajkovic (2005) and Trajkovic and Kolakovic (2009) showed that the Thornthwaite equation underestimated annual FAO-56 PM ET_0 at Western Balkans. The poor results of Thornthwaite equation were in good agreement with data reported by Jensen et al. (1990), Lu et al. (2005), and Quej et al. (2019).

Camargo et al. (1999) proposed an adjustment of the Thornthwaite equation by introducing effective temperature (T_{eff}) instead of mean temperature. This approach was tested against the Penman–Monteith FAO-56 ET_0 on 86 locations around the world. Pereira and Pruitt (2004) also applied T_{eff} in the Thornthwaite equation and obtained acceptable results using lysimeter data from Davis (California, USA) and Piracicaba (Sao Paolo, Brazil). Dinpashoh (2006) estimated the ET_0 by T_{eff} using data from 81 Iranian stations. In Ahmadi and Fooladmand (2008), the Thornthwaite equation was spatially calibrated based on the Penman-Monteith method for every month of the year, using the data of 14 Iranian stations. Trajkovic (2005) used linear regression for the calibration of the Thornthwaite equation in Western Balkans. Xu and Singh (2001) and Bautista et al. (2009) adjusted the Thornthwaite equation using empirical coefficient, which is correlated to pan evaporation (Xu and Singh 2001) and PM equation (Bautista et al. 2009), respectively.

The main objectives of the present study are (1) to estimate reference evapotranspiration using different Thornthwaite approaches, (2) to develop optimal adjusted equation, and (3) to consider the spatial variability of the empirical coefficient(s) of adjusted equation for the study area of Vojvodina region, Serbia.

2 Methods and materials

2.1 Study area and data set

The study area is Vojvodina region, which is situated in the southeastern part of the Pannonian Basin. Vojvodina is a region in northern Serbia, at 44.6°N to 46.2°N latitude and 18.8°E to 21.6°E longitude, with a total land area of 21,500 km^2. The climate is moderate continental, with hot and humid summers and cold winters. The mean annual precipitation of the study area ranges from 540 to 660 mm (Tosic et al. 2014). The amount of precipitation is relatively low and unevenly distributed throughout the year.

Data from Novi Sad (1980–2015), Palic (1980–2015), Sombor (1980–2015), Sremska Mitrovica (2002–2017), and Kikinda (2002–2017) were used in this study. Necessary time series were obtained from the Republic Hydrometeorological Service of Serbia (RHMZ). Weather data included the daily values of the following parameters averaged over each month: minimum and maximum air temperatures; actual vapor pressure, wind speed, and sunshine hours. The analyzed stations were chosen because they are well distributed over the latitude zone of the region of interest, and they represent all the climatic types existing in Vojvodina.

Data from three meteorological stations outside the study area (Szeged, Timisoara, and Belgrade) were also used in this study. Those data were obtained from CLIMWAT database. The outside stations were just used as auxiliary stations to assist in developing the adjusted equation. CLIMWAT database provides long-term monthly mean values of seven climatic variables (daily maximum and minimum air temperatures, mean relative air humidity, sunshine duration, solar radiation, wind speed, and rainfall) as well as ET_0 estimated using the FAO-56 PM equation. Information regarding the mean climatic conditions of the selected stations is given in Table 1, and the geographical locations of the stations are mapped in Fig. 1.

Differences in the mean weather data for these locations are not very substantial. The annual average temperature (T) varied between 10.8 and 12.2 °C. The average wind speed (U_2) ranged between 1.6 and 3.4 m s^{-1}. The average sunshine (n) varied between 4.6 and 6.2 h day^{-1}, and the average reference evapotranspiration ranged from 2.1 to 2.6 mm day^{-1}. Precipitation (P) varied from 495 to 684 mm. All elevations range from 81 to 132 m above sea level, thus illustrating the plain geography of the study area. According to the UNEP aridity index, all the observed stations were classified as humid ($P/ET_{pm} > 0.65$) or sub-humid ($0.5 < P/ET_{pm} < 0{:}65$).

2.2 FAO-56 Penman-Monteith method

The FAO-56 Penman–Monteith (FAO-56 PM) equation was presented in Allen et al. (1998) as follows:

$$ET_{pm} = \frac{0.408\cdot\Delta\cdot(R_n - G) + \gamma\frac{900}{T+273}U_2\cdot(e_s - e_a)}{\Delta + \gamma(1 + 0.34\cdot U_2)} \quad (1)$$

where ET_{pm} = reference evapotranspiration (mm day^{-1}), Δ = the slope of the saturation vapor pressure function (kPa $°C^{-1}$), γ = psychometric constant (kPa $°C^{-1}$), R_n = net radiation (MJ m^{-2} day^{-1}), G = soil heat flux density (MJ m^{-2} day^{-1}), T = mean air temperature (°C), U_2 = average 24 h wind speed at 2 m height (m s^{-1}), e_s = saturation vapor pressure (kPa), e_a = actual vapor pressure (kPa).

Table 1 General description of weather stations used in the present study

Stations	LAT (°N)	LONG (°E)	ELEV (m)	T (°C)	U_2 ($m\ s^{-1}$)	P (mm)	*n* ($h\ day^{-1}$)	ET_{pm} ($mm\ day^{-1}$)	Aridity Indexd
RHMZ									
Palic	46.10	19.76	102	11.6	1.88	550	6.0	2.4	SH
Kikinda	45.83	20.47	81	12.2	2.22	550	6.2	2.6	SH
Sombor	45.76	19.12	87	11.5	1.62	588	5.7	2.3	H
Novi Sad	45.33	19.85	87	11.7	1.89	647	5.6	2.4	H
S. Mitrovica	44.97	19.62	82	12.2	2.26	622	5.7	2.5	H
CLIMWAT									
Szeged	46.25	20.15	83	10.8	3.43	495	5.5	2.5	SH
Timisoara	45.76	21.23	88	11.2	2.17	593	5.8	2.1	H
Belgrade	44.80	20.47	132	12.2	1.73	684	4.6	2.2	H

LAT latitude, *LONG* longitude, *ELEV* elevation, *H* humid, *SH* sub-humid

2.3 Thornthwaite method

The Thornthwaite method (Thornthwaite 1948) is a temperature-based method for the estimation of ET_0 as a function of the average monthly temperature:

$$ET_{0th} = \begin{cases} 0, & T_{avg} < 0^{o}C \\ 16\cdot\left(\frac{10\cdot T_{avg}}{I}\right)^{a}, & 0^{o}C \le T_{avg} \le 26.5^{o}C \\ -0.43\cdot T_{avg}{}^{2} + 32.24\cdot T_{avg} - 415.85, & T_{avg} > 26.5^{o}C \end{cases} \quad (2)$$

$$I = \sum_{k=1}^{12} (0.2\cdot T_k)^{1.514}, \quad (3)$$

$$a = 0.000000675\cdot I^3 - 0.0000771\cdot I^2 + 0.01792\cdot I + 0.49239, \quad (4)$$

where ET_{0th} = reference evapotranspiration estimated by Thornthwaite equation (mm $month^{-1}$), T_{avg} = mean monthly air temperature (°C), I = thermal index imposed by the local normal climatic temperature regime, and a = exponent being a function of I. The value of a varies from 0 to 4.25, while the thermal index I varies from 0 to 160.

Camargo et al. (1999) improved the performance of the Thornthwaite method using an effective temperature (T_{eff}) instead of the T_{avg}. The T_{eff} is computed as a function of T_{avg} and of the daily temperature amplitude ($A = T_{max} - T_{min}$):

$$T_{eff} = k\cdot(T_{avg} + A) = 0.5\cdot k\cdot(3\cdot T_{max} - T_{min}), \quad (5)$$

where k = calibration coefficient. Camargo et al. (1999) found that $k = 0.72$ is the best value for estimating monthly ET_0, while Pereira and Pruitt (2004) recommended $k = 0.69$ for estimating daily ET_0.

Trajkovic (2005) expressed the Thornthwaite equation as

$$ET_{0Th,i} = \frac{16N_i}{360}\left(\frac{10T_i}{\sum_{i=1}^{12}(0.2T_i)^{1.514}}\right)^{0.016\sum_{i=1}^{12}(0.2T_i)^{1.514}+0.5} \quad (6)$$

where ET_{0th} = reference evapotranspiration estimated by the Thornthwaite equation (mm day^{-1}); N_i = maximum possible duration of sunshine (h day^{-1}); T_i = mean air temperature in the *i*-th month (°C); i = 1, 2,...12.

The data from Serbian stations Palic, Belgrade, and Nis were used to calibrate the Thornthwaite equation (Trajkovic 2005):

$$cET_{0,Th} = 0.88ET_{0,Th} + 0.565 \quad (7)$$

where cET_{0th} = ET_0 estimated by the calibrated Thornthwaite equation (mm day^{-1}).

Bautista et al. (2009) calibrated the Thornthwaite equation by changing the value of the corresponding constant $p = 16$:

$$p_{adj} = \frac{16ET_{pm}}{ET_{0,Th}} \quad (8)$$

where ET_{pm} = ET_0 estimated by the FAO-56 PM equation (mm day^{-1}); ET_{0th} = ET_0 estimated by the Thornthwaite equation (mm day^{-1}); p_{adj} = new value of the Thornthwaite constant.

2.4 Evaluation parameters

Several parameters can be considered for the evaluation of ET_0 estimates. In this study, the analyzed criteria involve the

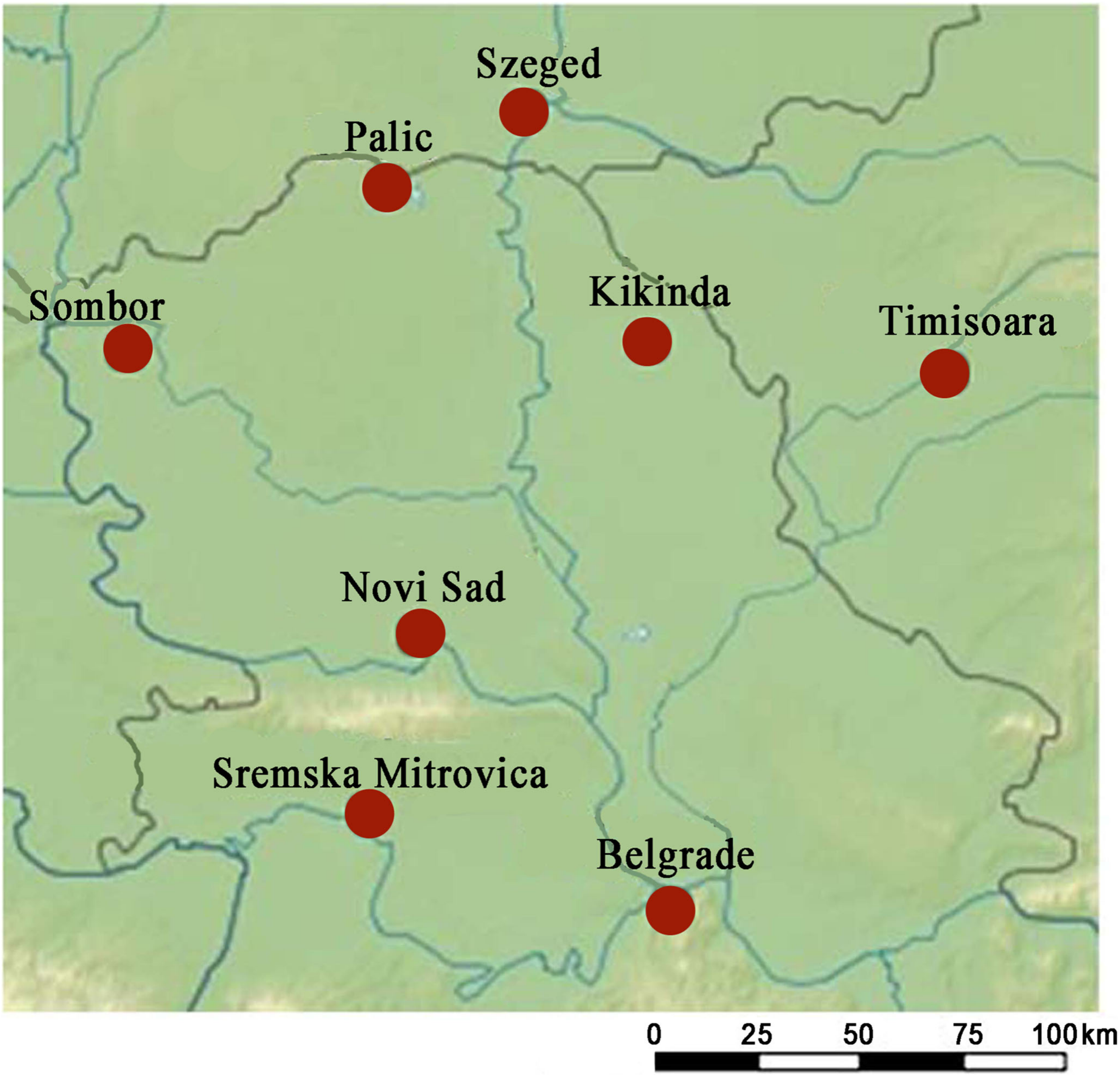

Fig. 1 Spatial distribution of weather stations used in this study

following statistical characteristics: mean absolute error (*MAE*), root-mean-squared error (*RMSE*), scatter index (*SI*), and the coefficient of determination (R^2).

The corresponding definitions are summarized as follows:

$$MAE = \frac{\sum_{j=1}^{M} \left(\left| ET_{pm,j} - ET_{eq,j} \right| \right)}{M} \quad (9)$$

$$RMSE = \left[\frac{\sum_{j=1}^{M} \left(\left| ET_{pm,j} - ET_{eq,j} \right| \right)^2}{M} \right]^{0.5} \quad (10)$$

$$SI = \frac{RMSE}{\overline{ET}_{pm}} \quad (11)$$

$$R^2 = \frac{\left[\sum_{j=1}^{M} \left(ET_{pm,j} - \overline{ET}_{pm} \right) \left(ET_{eq,j} - \overline{ET}_{eq} \right) \right]^2}{\sum_{j=1}^{M} \left(ET_{pm,j} - \overline{ET}_{pm} \right) \sum_{j=1}^{M} \left(ET_{eq,j} - \overline{ET}_{eq} \right)} \quad (12)$$

where ET_{pm} = ET_0 estimated by the full-set FAO-56 PM equation (mm day^{-1}); ET_{eq} = corresponding ET_0 estimated by the comparison equation (mm day^{-1}); and M = the total number of observations.

3 Results and discussion

Six Thornthwaite approaches were used in this study: Th ($T = T_{avg}$, Thornthwaite 1948), Th72 ($T = T_{eff}$, $k = 0.72$ (Camargo et al. 1999)), Th69 ($T = T_{eff}$, $k = 0.69$ (Pereira and Pruitt 2004)), cTh (Trajkovic 2005), pTh (Bautista et al. 2009), and new Th65 approach (the optimum $k = 0.65$ for this Thornthwaite approach, which is obtained through the trial and error method in order to gain the lowest value of RMSE for all selected locations).

These equations were compared to the full set FAO-56 PM equation using weather data from five Serbian locations and using data from three CLIMWAT stations. The statistical summary including average ET_0 estimates expressed as percentages of the corresponding FAO-56 PM ET_0 values, RMSE, SI, MAE, and R^2 values for each Serbian location is presented in Table 2.

The original Thornthwaite equation was very poor in estimating ET_0. The RMSE values varied from 0.57 to 0.66 mm day^{-1}. This equation underestimated annual FAO-56 PM ET_0 at all locations from 15 to 19%. However, the Thornthwaite equation gave acceptable estimates of average peak ET_0 at all locations except Kikinda with the deviations of −2% to −4% relative to the ET_0 obtained by the FAO-56 PM equation. The MAE values ranged from 0.30 to 0.51 mm day^{-1}. This approach was the lowest ranking approach at Kikinda and the second lowest at the other four locations.

The Th72 approach based on Camargo et al. (1999) provided very poor results estimating FAO-56 PM ET_0 with RMSE values from 0.38 to 0.65 mm day^{-1}. This approach overestimated annual FAO-56 PM ET_0 values from 8% at Kikinda to 20% at Sombor. The MAE values ranged from 0.30 to 0.50 mm day^{-1}. The Th72 approach was the lowest ranking approach at Sombor.

The Th69 approach based on Pereira and Pruitt (2004) was reasonably good at all locations with RMSE values varied from 0.28 to 0.50 mm day^{-1}. This approach overestimated annual FAO-56 PM ET_0 values from 1% at Kikinda to 13% at Sombor. The MAE values ranged from 0.23 to 0.39 mm day^{-1}. The Th69 approach was the first ranking approach at sub-humid stations (Palic and

Table 2 Statistical summary of ET_0 estimates for five RHMZ stations

Methods	RMSE (mm day^{-1})	SI (−)	MAE (mm day^{-1})	R^2 (−)	ET_{eq}/ET_{pm} (%/100)	pET_{eq}/ET_{pm} (%/100)
Palic						
Th	0.61	0.26	0.48	0.93	0.83	0.96
Th72	0.44	0.18	0.40	0.96	1.09	1.09
Th69	0.36	0.15	0.28	0.96	1.03	1.09
Th65	0.37	0.15	0.29	0.96	0.95	1.03
cTh	0.46	0.19	0.37	0.93	0.96	0.96
pTh	0.62	0.26	0.52	0.93	1.00	1.16
Kikinda						
Th	0.66	0.26	0.52	0.93	0.81	0.93
Th72	0.38	0.15	0.30	0.97	1.08	1.08
Th69	0.28	0.11	0.23	0.97	1.01	1.02
Th65	0.33	0.13	0.27	0.97	0.93	0.94
cTh	0.50	0.19	0.40	0.93	0.93	0.92
pTh	0.58	0.23	0.47	0.93	0.97	1.11
Sombor						
Th	0.57	0.25	0.44	0.93	0.85	0.98
Th72	0.65	0.28	0.51	0.96	1.20	1.18
Th69	0.50	0.21	0.39	0.96	1.13	1.11
Th65	0.36	0.15	0.29	0.96	1.05	1.03
cTh	0.44	0.19	0.36	0.93	0.99	0.99
pTh	0.64	0.28	0.54	0.93	1.02	1.18
Novi Sad						
Th	0.60	0.25	0.46	0.93	0.83	0.96
Th72	0.51	0.22	0.40	0.96	1.13	1.13
Th69	0.39	0.17	0.31	0.96	1.07	1.07
Th65	0.33	0.14	0.26	0.96	0.98	0.98
cTh	0.44	0.19	0.33	0.93	0.97	0.96
pTh	0.63	0.27	0.63	0.93	1.00	1.15
Sremska Mitrovica						
Th	0.63	0.25	0.49	0.93	0.83	0.96
Th72	0.60	0.24	0.47	0.97	1.17	1.18
Th69	0.44	0.18	0.34	0.97	1.10	1.11
Th65	0.36	0.15	0.28	0.97	1.06	1.07
cTh	0.48	0.19	0.38	0.93	0.96	0.96
pTh	0.64	0.26	0.51	0.93	1.00	1.15

Kikinda), and the second or third ranking approach at humid locations.

The new Th65 approach provided very good estimates of both peak and annual ET_0 at all locations. This equation slightly underestimated annual FAO-56 PM ET_0 at all locations except Sombor. The RMSE values varied from 0.33 to 0.37 mm day^{-1} and the MAE values ranged from 0.25 to 0.28 mm day^{-1}. The Th65 approach yielded the smallest RMSE and MAE values at all humid locations, and the second smallest RMSE and MAE values at all sub-humid locations.

VThe regionally calibrated Thornthwaite equation (cTh) was reasonably good in estimating ET_0 with RMSE values varied from 0.33 to 0.40 mm day^{-1}. The MAE values ranged from 0.23 to 0.39 mm day^{-1}. This approach gave acceptable estimates of both peak and annual ET_0 at all locations. The cTh approach was the fourth ranking approach at sub-humid stations (Palic and Kikinda) and the second or third ranking approach at humid locations.

The pTh approach based on Bautista et al. (2009) provided very poor results estimating FAO-56 PM ET_0 with RMSE values from 0.58 to 0.64 mm day^{-1}. This approach overestimated peak ET_0 values from 11 to 18%. The pTh approach was the lowest ranking approach at four locations and the second lowest at Kikinda.

VFFigure 2 depicts a plot of monthly ET_0 values estimated by the Th65 approach versus the corresponding full-set FAO-56 PM ET_0 estimates at Novi Sad (1980–2015). It is interesting to note that the estimates determined by Th65 provide ET_0, which were near to the full set FAO-56 PM estimates. The average underestimation was about 2%.

The three most successful Th approaches were additionally tested using data from three CLIMWAT stations. The statistical summary is presented in Table 3. The obtained results were in good agreement with results reported in Table 2.

The Th69 approach was the first ranking approach at sub-humid station (Szeged) and the second or third ranking approach at humid locations with RMSE values from 0.13 to 0.51 mm day^{-1}. The Th65 approach was the first ranking approach at Belgrade and the second ranking at Szeged and Timisoara. The RMSE values varied from 0.17 to 0.30 mm day^{-1}. This approach gave acceptable estimates of peak ET_0 at all locations. The calibrated Thornthwaite equation (cTh) was reasonably good in estimating ET_0 at humid locations (Timisoara and Belgrade) and poor at sub-humid Szeged with RMSE values from 0.21 to 0.38 mm day^{-1}. Overall results indicate that the Th65 approach yielded the lowest RMSE (0.22 mm day^{-1}) and the lowest MAE (0.19 mm day^{-1}) compared to other two analyzed approaches.

The mean monthly ET_0 values for Belgrade as estimated by the FAO-56 PM equation (PM) and two Thornthwaite approaches (Th69 and Th65) are plotted in Fig. 3. At this location, the Th69 equation consistently overestimated ET_0 obtained by the FAO-56 PM equation except winter months. The Th65 equation followed PM estimates very well.

The optimal *k* values and corresponding statistical parameters for all stations are given in Table 4. The optimum *k* value has been obtained through the trial and error method in order to gain the lowest RMSE at each location. The results showed that RMSE values varied between 0.27 mm day^{-1} and 0.34 mm day^{-1} for RHMZ datasets and between 0.13 and 0.17 mm day^{-1} for CLIMWAT datasets. The optimal k values provided excellent estimates of both peak and annual ET_0 at all locations with a slight deviation of 2%. As a whole, *k* values ranged from 0.62 to 0.69 across the study area showing

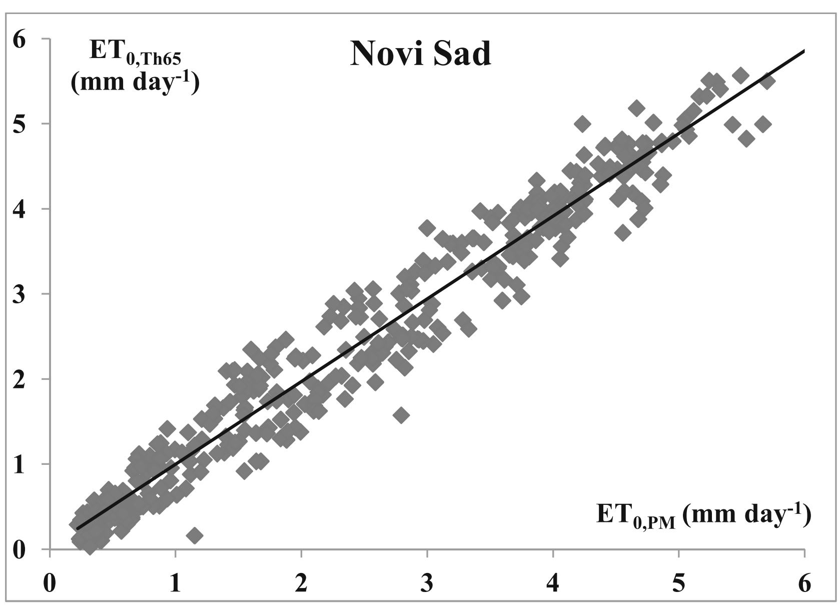

Fig. 2 Relationship between adjusted Thornthwaite (Th65) vs. full set FAO-56 PM ET_0 estimates

Table 3 Statistical summary of ET_0 estimates for three CLIMWAT stations

Methods	RMSE (mm day^{-1})	MAE (mm day^{-1})	R2 (−)	ET_{eq}/ET_{pm} (%/100)	pET_{eq}/ET_{pm} (%/100)
Szeged					
Th69	0.13	0.10	1.00	1.01	1.01
Th65	0.19	0.17	0.98	0.94	0.94
cTh	0.38	0.33	0.95	0.89	0.89
Timisoara					
Th69	0.51	0.45	0.99	1.21	1.13
Th65	0.30	0.26	0.98	1.12	1.04
cTh	0.22	0.18	0.94	1.06	0.98
Belgrade					
Th69	0.28	0.23	0.99	1.07	1.09
Th65	0.17	0.14	0.97	0.98	1.00
cTh	0.21	0.19	0.98	1.04	1.04
Average					
Th69	0.32	0.26	0.99	1.10	1.08
Th65	0.22	0.19	0.98	1.01	0.99
cTh	0.27	0.23	0.96	1.00	0.97

an average variation of 2% compared to the unique *k* value of 0.65. This indicates that using a single regional *k* value results in very accurate ET_0 estimations. This approach is simpler than the Ahmadi and Fooladmand (2008) approach, which used 12 different monthly *k* values for each station.

Figure 4 illustrates the spatial distribution of the optimal *k* value in Vojvodina. This map is ideally coinciding with the map of aridity in Vojvodina presented in Hrnjak et al. (2014). This fact confirms a great influence of aridity type to optimal *k* values in Vojvodina. The north and northeastern parts of Vojvodina have sub-humid climate, while the southern part has humid climatic conditions. Generally, about 75% of the territory of Vojvodina is characterized by humid climate. As shown, the optimal *k* values tended to increase from the humid towards the sub-humid locations.

Hence, based on this study and the given map, reference evapotranspiration can be easily estimated for any location in the study area with the temperature data and the adjusted Thornthwaite equation.

4 Conclusions

The FAO-56 Penman-Monteith (FAO-56 PM) equation has been proposed as the standard for estimating reference evapotranspiration. The basic obstacle to using the FAO-56 equation widely is the required weather data, which are not available in most of the stations. In such circumstances, a simple empirical Thornthwaite equation is often used. This equation is developed from water balance studies for the eastern-central USA and is most appropriately applied to climatic conditions similar to where it was developed.

In this study, six Thorthwaite approaches were compared to the full set FAO-56 PM equation using weather data from Vojvodina region, Serbia. The original Thornthwaite equation was found to be in very poor agreement with the full set FAO-56 PM. This equation greatly underestimated FAO-56 PM values at all locations. These results indicated that a calibration of this equation is necessary.

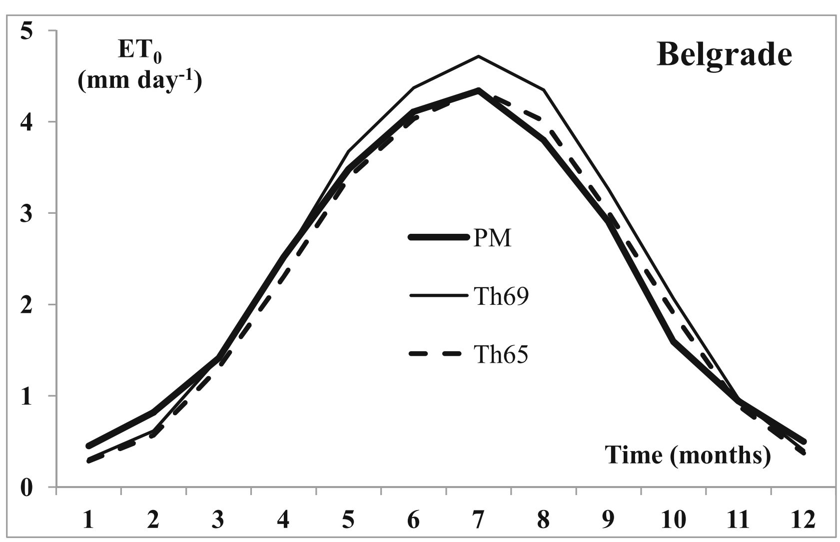

Fig. 3 Comparison of monthly ET_0 computed using the FAO-56 Penman-Monteith (PM) and two Thornthwaite approaches (Th69 and Th65)

Table 4 Optimal k values and statistical summary of corresponding ET_0 estimates

Stations	k (–)	Aridity Index	RMSE (mm day^{-1})	SI (–)	MAE (mm day^{-1})	R^2 (–)	ET_{eq}/ET_{pm} (%/100)	pET_{eq}/ET_{pm} (%/100)
RHMZ								
Palic	0.67	SH	0.34	0.14	0.27	0.96	0.99	0.99
Kikinda	0.68	SH	0.27	0.11	0.23	0.98	0.99	1.00
Sombor	0.64	H	0.34	0.15	0.27	0.96	1.02	1.01
Novi Sad	0.65	H	0.33	0.14	0.26	0.96	0.98	0.98
S.Mitrovica	0.64	H	0.31	0.12	0.24	0.98	0.99	1.00
CLIMWAT								
Szeged	0.69	SH	0.13	0.05	0.10	1.00	1.01	1.01
Timisoara	0.62	H	0.13	0.06	0.09	0.99	1.02	0.97
Belgrade	0.65	H	0.17	0.08	0.14	0.97	0.98	1.00

H humid, *SH* sub-humid

Camargo et al. (1999) proposed an adjustment of the Thornthwaite equation by introducing empirical coefficient of 0.72 to estimate the effective temperature instead of mean temperature.

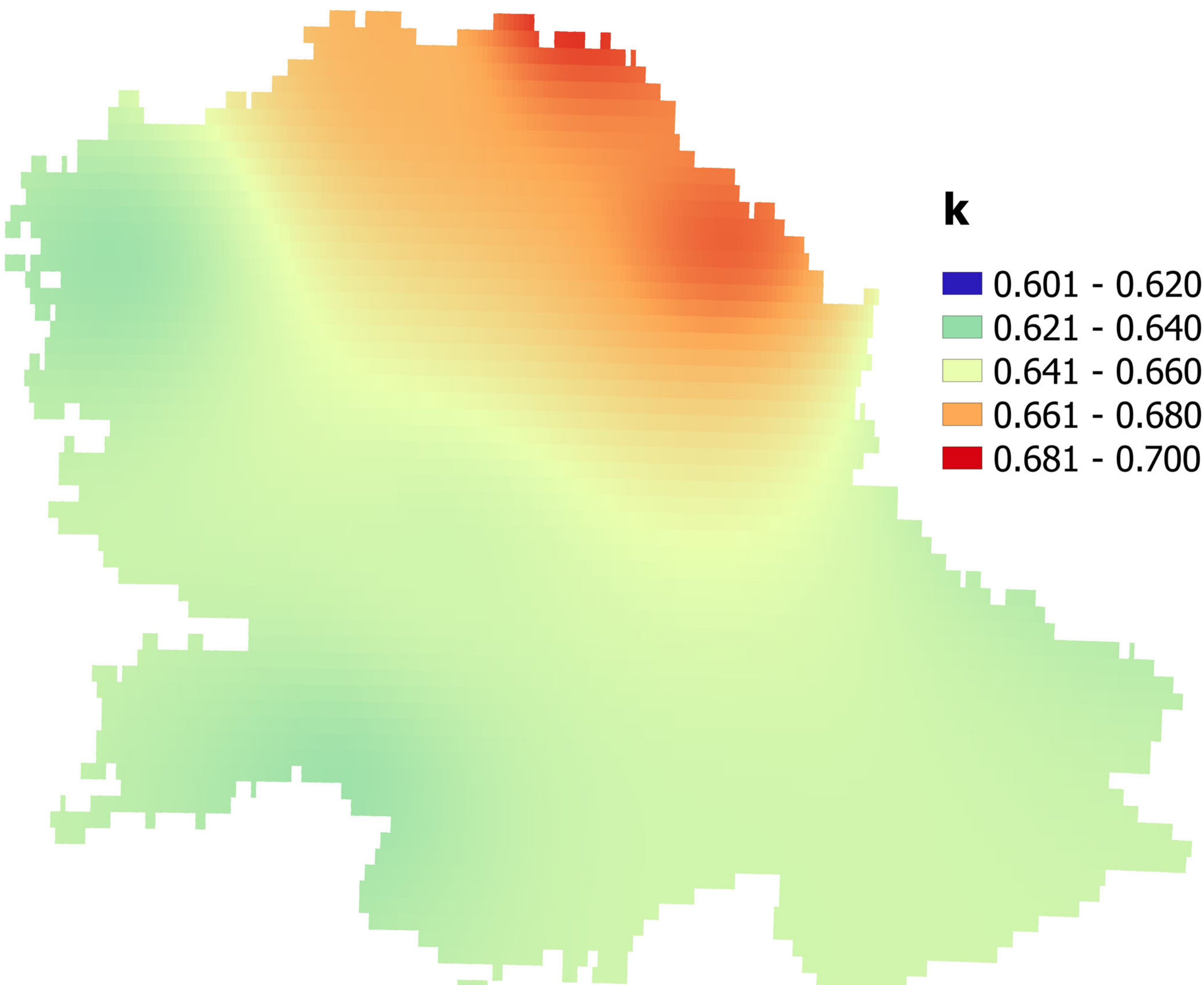

Fig. 4 Spatial distribution of k value in Vojvodina

The Th72 approach based on Camargo et al. (1999) and the pTh approach based on Bautista et al. (2009) also provided very poor results estimating FAO-56 PM ET_0. The pTh approach was the lowest ranking approach at most locations.

The regionally calibrated Thornthwaite equation (cTh, Trajkovic 2005) and Th69 approach based on Pereira and Pruitt (2004) were reasonably good in estimating ET_0. The cTh approach gave acceptable estimates of both peak and annual ET_0 at all locations.

The new Th65 approach provided the best agreement with the full-set PM ET_0 estimates. It gave the most reliable calculation at all RHMZ stations. This approach yielded the smallest RMSE values at the three locations, and the second smallest RMSE at other two locations.

The Thornthwaite approaches were additionally tested using data from three CLIMWAT stations. The results suggest that ET_0 could be computed from the Th65 approach, which yielded statistical better results compared to the Th69 and cTh approaches. All other approaches resulted in poor estimation of ET_0 for the analyzed CLIMWAT stations.

The spatial variability of the empirical k coefficient showed that *k* values varied from 0.62 to 0.69 across the study area showing less than 6% variation compared to the unique *k* value of 0.65. It can be concluded that using a single regional *k* value result in very accurate ET_0 estimations.

The overall results show very clearly that the Th65 approach is the most suitable for estimating ET_0. In this study, a *k* value of 0.65 is proposed instead of the original 0.72 and it should be used in the adjusted Thornthwaite equation in Vojvodina region.

Further research is required in order to assess the adjusted Thornthwaite equation in other areas. The approach presented in this study could be applied in other regions for obtaining suitable regional calibrations of the Thornthwaite equation.

Funding information The paper is a part of the research done within the bilateral project "Project changes of hydrological hazards (extreme precipitation and drought) in Hungary and Serbia" financed by the Serbian Ministry of Education, Science and Technology (TR37003) and Hungarian Ministry of Science.

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