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Performance of simple temperature-based evaporation methods compared with a time series of pan evaporation measures from a standard 20 m^2 tank

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Abstract

Evaporation and evapotranspiration is crucial part of hydrological and water resource management studies e.g. water footprinting. Proper methods for estimating evaporation/potential evapotranspiration using limited climatic data are critical if the availability of climatic data is extremely limited. In a large scale studies are very often used generalized (modelled or gridded) input data. For a large scale water footprint studies is also important to find methods as simple as possible with quantifiable error. In our study, nine simple temperature-based empirical equations were compared with a long term time series of real evaporation data from a 20 m^2 tank at Hlasivo station. In the first step, we used real temperature measured at Hlasivo station for validation of equations. In the second step, the gridded temperature data (interpolated datasets) derived from the meteorological stations were used. For both datasets, the differences between observed and predicted values were categorized into three groups of accuracy and the statistical indices of each equation were calculated. Very good results were achieved with the Hamon equation from 1961 and the Oudin equation for both datasets with index of agreement (d) higher than 0.9, cross-correlation coefficient (R^2) around 0.7 and root mean square error ($RMSE$) around 0.5 mm·(24 h)$^{-1}$ The Kharrufa equation, which was developed for semi-arid or arid areas, also provides results with sufficient accuracy. Comparison of the results with similar studies showed a lower accuracy of very simple equations against more complex equations, which have $RMSE$ lower than 0.25 mm·(24 h)$^{-1}$. But for some kind of studies, quantifiable errors with sufficient accuracy can be more important than the absolute accuracy.

Key words: *20 m^2 tank, evaluation, evapotranspiration, pan evaporation, temperature-based methods*

INTRODUCTION

Accurate computation of the water balance is necessary for many hydrological, water management, and climatic purposes [DYCK 1985]. Water surfaces and land cover significantly contribute to the return of water to the atmosphere. The need to know the quantity of water lost from lakes through evaporation is common in mass balance studies of lake water and lake chemistry [WINTER *et al.* 1995]. The water lost from vegetation through evapotranspiration respectively green water plays a prominent role in the global crop production [MEKONNEN, HOEKSTRA 2011] with environmental impact [QUINTEIRO *et al.* 2018]. The evapotranspiration is assumed equal to the evaporation demand which is normally represented by pan evaporation or potential evapotranspiration [MORTON 1983]. Evaporation/potential evapotranspiration losses are difficult to measure directly, so different calculation methods have been developed. The hydrological literature contains a wealth of evaporation/potential evapotranspiration equations with different data requirements [Oudin *et al.* 2005]. Xu and Singh [2001] classified methods for measurement and estimation of evaporation/potential evapotranspiration into five groups:

1) water budget [Guitjens 1982],
2) mass-transfer [Harbeck 1962],
3) combination [Penman 1948],
4) radiation [Jensen, Haise 1963; Priestley, Taylor 1972],
5) temperature based [Blaney, Criddle 1950; Thornthwaite 1948].

Overviews and evaluation of many of these methods are found in a lot papers or books [Azhar, Perera 2011; Brutsaert 1982; Djaman *et al.* 2015; Jensen, Allen (eds.) 2016; Lu *et al.* 2005; Morton 1994; Oudin *et al.* 2010; Pandey *et al.* 2016; Parmele, McGuinness 1974; Rácz *et al.* 2014; Rosenberry *et al.* 2004, 2007; Singh, Xu 1997; Tabari *et al.* 2013; Trajkovic, Kolakovic 2009; Winter *et al.* 1995; Xystrakis, Matzarakis 2011].

The methods for calculation of evaporation/potential evapotranspiration, respectively requirements of the input data, temporal or spatial resolution and so on, should be optimized for the aims of the study. Our study is focused on the use of equations in the water footprint studies with large scale or regional/global coverage. These type of studies typically use data with an important level of uncertainty or data defined in the Life cycle assessment standards as "secondary" [ISO 14046:2014]. The uncertainties in data used in water footprint accounting can be very significant [Hoekstra *et al.* 2011]. More authors (Hoekstra *et al.* [2011], Pfister, Bayer [2014], Boulay *et al.* [2015]) recommend solving water footprint studies in the monthly step.

The Penman–Monteith equation [Allen *et al.* 1998] has been revealed as the most accurate model of evapotranspiration under various climatic conditions [Allen *et al.* 1998; Ali, Shui 2009; Jensen *et al.* (eds.) 1990]. On the other hand, it necessitates several climatic parameters that are not always available [Djaman *et al.* 2015]. For these situations, more simple empirical equations for evaporative loss needs are used and evaluation of equations is usually done according to the Penman–Monteith equation. Rarely, the evaluation is done according to the evaporation pan measurement. An evaporation pan provides measurement of the combined effect of temperature, humidity, wind speed, and sunshine on evaporative demand and is used for practical applications in water resource planning and management. It was recommended by the World Meteorological Organization (WMO) to use a 20 m^2 tank as an international interim reference tank [Shiklomanov (ed.) 2009]. Studies with long data series using these tanks are rare and serve to assess or calibrate models and smaller evaporimeters [Cabrera *et al.* 2016].

MATERIALS AND METHODS

STUDY AREA

The study was carried out in Jihočeský region in the Czech Republic at the Hlasivo evaporation and climatological station of the T. G. Masaryk Water Research Institute, public research institution. Hlasivo station is situated in the South of the Czech Republic near the city of Tábor (49.4981083 N, 14.7560247 E) at an altitude of 540 m a.s.l. Hlasivo station was built in 1957; it has a 20 m^2 tank (from 1956), GGI-3000 pan (from 1957), and Class-A pan (from 1962). In the past, there were other types of pans, but at present only these three types remain. The water level is measured by a digital sensor located directly on the stainless steel tank. The principle of measurement is the sensing of hydrostatic water pressure. Daily evaporation in the tank (E_{20}) results from the difference between subsequent readings corrected with rainfall. Currently, these meteorological data are measured at Hlasivo station: air temperature at 2 m above ground level, relative humidity at 2 m above ground level, wind speed at 10 m above ground level, solar radiation, precipitation, and water temperature in the pans [Beran, Vizina 2013]. Since 1998 soil temperatures have also been measured at 5, 10, 20, 30 and 50 cm below ground level. Evaporation is measured from May to October. Statistical characteristics of measured evaporation are shown in Table 1. Mean monthly evapotranspiration and temperature at Hlasivo station are shown in Figure 1. The dependence of evaporation from the 20 m^2 tank on air temperature at Hlasivo station is shown in Figure 2.

Table 1. Characteristics of average monthly evaporation at Hlasivo station 1957–2016

Characteristics of evaporation	Evaporation (mm·(24 h)$^{-1}$)						
	May–October	May	June	July	August	September	October
Max	4.97	3.63	4.20	4.97	4.54	3.29	3.25
Mean	2.51	2.64	3.07	3.26	2.92	1.99	1.19
Median	2.60	2.60	3.09	3.18	2.87	1.97	1.12
Min	0.37	1.23	1.73	1.59	1.58	1.27	0.37
Standard deviation	0.91	0.52	0.52	0.71	0.60	0.46	0.52
Interquartile range	2.51	0.83	0.57	0.74	0.71	0.63	0.33

Source: own study.

EVAPORATION/POTENTIAL EVAPOTRANSPIRATION ESTIMATION EQUATIONS

The selection of nine equations was based on their simplicity in terms of a number of climate parameters necessary to solve them. For the study, only equations based on average air temperature (T_{mean}) were selected. The equations used T_{mean} selected in the form of used temperature in Celsius degrees. Some equation use other variables such daylight (*d* or *D*) or extra-terrestrial radiation (*Ra*), but these variables are not dependent on the climatic conditions.

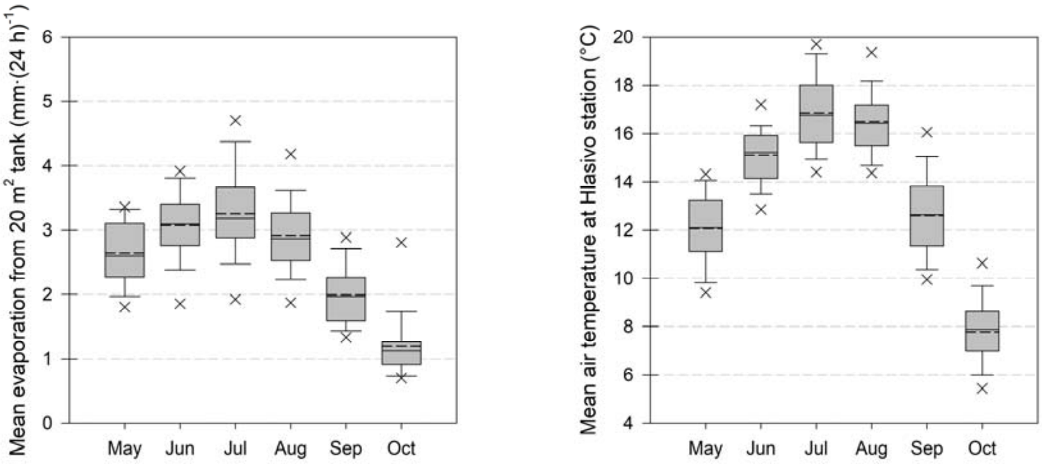

Fig. 1. Evaporation from 20 m^2 tank and mean temperature at Hlasivo station; the ends of the boxes define the 25th and 75th percentiles, with a solid line for the median and dashed line for the average value; error bars define the 10th and 90th percentiles and crosses define the 5th and 95th percentiles; source: own study

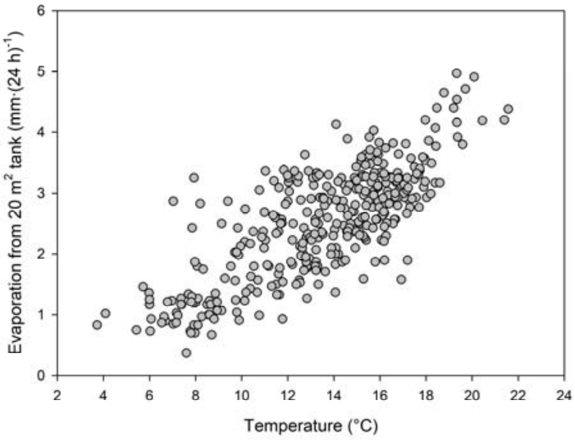

Fig. 2. The dependence of the evaporation from 20 m^2 tank on the air temperature at Hlasivo station; source: own study

In the 1950s, measurements were taken of evaporation with the floating pans in four water reservoirs in the former Czechoslovakia. Two empirical equations based on mean air temperature and mean saturation deficit were derived from these measurements [ŠERMER 1961]. For this study we use the equation for daily evaporation (E) in mm per day based on mean temperature:

$$E_1 = 10^{0.0452T_{\mathrm{mean}} - 0.204} \tag{1}$$

Data from Hlasivo station were analysed by several hydrologists. BERAN and VIZINA [2013] developed several equations which use different climatological variables and data from 2006–2012. For this study we used the equation in the form:

$$E_2 = 0.2157T_{\mathrm{mean}} + 0.113 \tag{2}$$

Earlier, MRKVIČKOVÁ [2007] published several equations. These equations were developed by statistical analysis of data from 2001–2005. For this study we used the equation for daily evaporation (E) in mm per day based on mean temperature only:

$$E_3 = 1.2061{T_{\mathrm{mean}}}^{1.0712} - 1.3906T_{\mathrm{mean}} + 1.7986 \tag{3}$$

THORNTHWAITE [1948] defined his empirical equation based on annual heat index I.

$$E_4 = 16\left(\frac{10T_{\mathrm{mean}}}{I}\right)^{67.5\cdot10^{-8}\,I^3 - 77.1\cdot10^{-6}\,I^2 + 0.01791I + 0.49239} \frac{d}{12}\frac{N}{30} \tag{4}$$

Where: d is the duration of average monthly daylight in hours and N is the number of days in the given month (28–31). For calculation d we used the CBM model [FORSYTHE *et al.* 1995]. The annual value of the heat index I is calculated by summing monthly indices over a 12-month period. The monthly heat index i for month j is obtained from the equations:

$$i = \left(\frac{T_{\mathrm{mean}}}{5}\right)^{1.514} \text{ for } T_{\mathrm{mean}} > 0 \tag{5}$$

$i = 0$ for $T_{\mathrm{mean}} \leq 0$ and

$$I = \sum_{j=1}^{12} i_j \tag{6}$$

The Thornthwaite equation has been widely criticized for its empirical nature but is widely used [XU, SINGH 2001] and it has been shown to estimate best in humid climates and to substantially underestimate in arid or semi-arid climates [JENSEN *et al.* (eds.) 1990]. Due to missing T_{mean} values for all months in the years before 2006, we only calculated evapotranspiration by the Thornthwaite equation for 2006–2016 in our study.

HAMON [1961] derived a potential evapotranspiration method based on mean air temperature in the form:

$$E_5 = CD^2P_t \tag{7}$$

for $T_{\mathrm{mean}} > 0$.

Where C is constant 13.97 for calculation E in mm per day, D is the hours of daylight for a given day (in units of 12 h) and P_t is a saturated water vapour density term. XU and SINGH [2001] calculate P_t by:

$$P_t = \frac{4.95e^{0.062T_{\mathrm{mean}}}}{100} \tag{8}$$

For calculation D we used the CBM model [FORSYTHE *et al.* 1995]. The Hamon equation can be modified to form:

$$E_5 = 13.97 D^2 \frac{4.95 e^{0.062 T_{\text{mean}}}}{100} = 0.6915 D^2 e^{0.062 T_{\text{mean}}} \tag{9}$$

Later HAMON [1963] published a simplified equation:

$$E_6 = C D P_t \tag{10}$$

Where: C is constant 0.1651 for calculation E in mm per day. LU *et al.* [2005] calculate P_t by:

$$P_t = \frac{6.1078 e^{\frac{17.26939 T_{\text{mean}}}{t+237.3}}}{T_{\text{mean}}+273.3} \tag{11}$$

The Hamon equation from 1963 can be modified to form:

$$E_6 = 218.5270 D \frac{1}{T_{\text{mean}}+273.3} e^{\frac{17.26939 T_{\text{mean}}}{T_{\text{mean}}+237.3}} \tag{12}$$

The next widely applied formula is an equation by BLANEY, CRIDDLE [1950]. This formula was used often in the water footprint studies due to its simplicity [CHARCHOUSI *et al.* 2015; MIGLIETTA *et al.* 2018; ZOTOU, TSIHRINTZIS 2017]. The usual form of the Blaney–Criddle equation converted to metric units [BLANEY, CRIDDLE 1964] is:

$$E_7 = c(0.457 T_{\text{mean}} + 8.13)p \tag{13}$$

Where: c is an adjustment factor which depends on minimum relative humidity, sunshine hours and daytime wind estimates [DOORENBOS, PRUITT 1977], p is percentage of total daytime hours for the used period (daily or monthly) out of total daytime hours of the year (365 · 12) and can be calculated by:

$$p = 100 \frac{d}{\sum_{i=1}^{365} d_i} \tag{14}$$

Where: d is the duration of daylight and we calculated it by the CBM model [FORSYTHE *et al.* 1995]. In the first step we calculated E_7 with $c = 1$ and for the derivation of c value we used a linear regression equation:

$$E_{20} = c E_7 \tag{15}$$

Where: E_{20} is the observed value of evaporation from 20 m^2 tank. For arid areas, KHARRUFA [1985] published a simple equation based on the Blaney–Criddle equation in the form:

$$E_8 = C p {T_{\text{mean}}}^{1.3} \tag{16}$$

Where: C is a climatic coefficient representing the linear dependence of evapotranspiration E and percentage of total daytime hours p. For Hlasivo station we have evaluated an average ratio $E{:}p$ and average temperature for three months with the highest evaporation in the year (June, July, August) according to the Kharrufa methodology [KHARRUFA 1985], and in the nomogram (Fig. 1) we selected coefficient $C = 0.25$.

The last equation selected for our study was presented by OUDIN *et al.* [2010] for temperatures higher than –5°C:

$$E_9 = \frac{0.408 R_a (T_{\text{mean}}+5)}{100} \tag{17}$$

Where: R_a is extraterrestrial radiation. For calculation of R_a we used equations described by ALLEN *et al.* [1998].

EVALUATION OF EQUATIONS

A dataset of monthly evaporation from 20 m^2 tank in period 1957–2016 for May, June, July, August, September and October was available for the study. We calculated the average daily evaporation (E_{20}) in each month of this period.

Two datasets of average monthly temperature were used for the study. The first data set contains measured data at the Hlasivo station for period 1957–2016. This dataset was used for statistical analysis of deviations of equations described above. Unfortunately, for the period 1957–2005 was available only average monthly temperature data for the May, June, July, August, September and October. It leads to the evaluation of Thornthwaite equation (4) only in the period 2006–2016. All other equations were evaluated for the whole period.

The second data set contains temperature data for the period 1961–2017. The data come from a grid dataset with a resolution of 25 × 25 km created according to the methodology described by ŠTĚPÁNEK *et al.* [2011]. Interpolated data for the catchment area are then calculated according to the long-term average of 1981–2010, which is obtained from the detailed raster with a resolution of 1 × 1 km. The detailed raster respects the orography of the terrain and is constructed according to the methodology described by ŠERCL [2008]. This dataset represents common situation when the real measured temperature is not available for studied location but interpolated or gridded data are available. The correlation between measured and interpolated temperature is very high with cross-correlation coefficient $R^2 = 0.958$.

Statistical analysis for each temperature data set was divided into two steps. In the first step, deviation between the observed value of evaporation (E_{20}) and predicted values of evaporation/potential evapotranspiration were calculated by individual equations (E_x) described above.

$$\Delta = E_x - E_{20} \tag{18}$$

Each predicted value was classified into one of three categories. The first category included predicted values which have an absolute distance from the observed value lower than 0.5 mm per day ($-0.5 < \Delta < 0.5$). The value of 0.5 mm per day represents the approximate standard deviation of measured mean evaporation in the individual month at Hlasivo station (see Table 1). The second category included predicted values which have a distance between ±0.5 and ±1.0 per day ($0.5 \leq |\Delta| \leq 1.0$), and the last category included predicted values with a distance from the observed value higher than ±1.0 mm per day ($|\Delta| > 1.0$).

In the second part of the statistical analyses, statistical indices were calculated. Pearson's product-moment correlation coefficient (r) describes collinearity between observed (E_{20}) and predicted (E_x) variates, although it is criticized by some authors (e.g. WILLMOTT [1981]). WILLMOTT [1981] suggests computing and reporting the index of agreement (d). The root mean square error (*RMSE*) and the mean absolute error (*MAE*) summarize the mean difference between observed and predicted values. *MAE* is less sensitive to large forecast errors and is preferred for small or limited data sets. *RMSE* is practical as it shows the errors in the same unit and scale as the parameter itself [EFTHIMIOU *et al.* 2013]. The mean squared error (*MSE*) penalizes large forecasting errors since the errors are squared. The mean bias error (*MBE*) describes the bias of predicted values.

Computational forms of all the indices are given below:

$$r = \frac{\sum_{i=1}^{n}(E_x-\overline{E_x})(E_{20}-\overline{E_{20}})}{\sqrt{\sum_{i=1}^{n}(E_x-\overline{E_x})^2\sum_{i=1}^{n}(E_{20}-\overline{E_{20}})^2}} \qquad (19)$$

$$d = \frac{\sum_{i=1}^{n}\Delta_i^2}{\sum_{i=1}^{n}(|E_x-\overline{E_{20}}|+|E_{20}-\overline{E_{20}}|)^2} \qquad (20)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}{\Delta_i}^2} \qquad (21)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|\Delta_i| \qquad (22)$$

$$MSE = \frac{1}{n}\sum_{i=1}^{n}{\Delta_i}^2 \qquad (23)$$

$$MBE = \frac{1}{n}\sum_{i=1}^{n}\Delta_i \qquad (24)$$

Where: $\bar{E}$ is mean value calculated by:

$$\bar{E} = \frac{1}{n}\sum_{i=1}^{n}E_i \qquad (25)$$

In the last part of the study, we compare results of statistical analysis for both temperature data sets.

RESULTS

Comparison of each empirical equation was made between mean monthly evaporation/potential evapotranspiration and observed evaporation from the 20 m^2 tank at Hlasivo station. Evaporation from the 20 m^2 tank was selected as a benchmark method for comparison, taking into account that is recommended by the WMO as an international interim reference evaporation pan.

MEASURED TEMPERATURE DATASET

The correlations between the nine empirical methods against pan evaporation when the measured temperature was used in equations are shown in Figure 3, where the *X*-axis represents mean monthly evaporation from the pan and the *Y*-axis represents the mean evaporation/potential evapotranspiration estimated from the above-mentioned nine equations. In order to have a quantitative evaluation, the correlations between results obtained by the nine empirical methods against evaporation from the 20 m^2 tank were analysed using the linear regression equation:

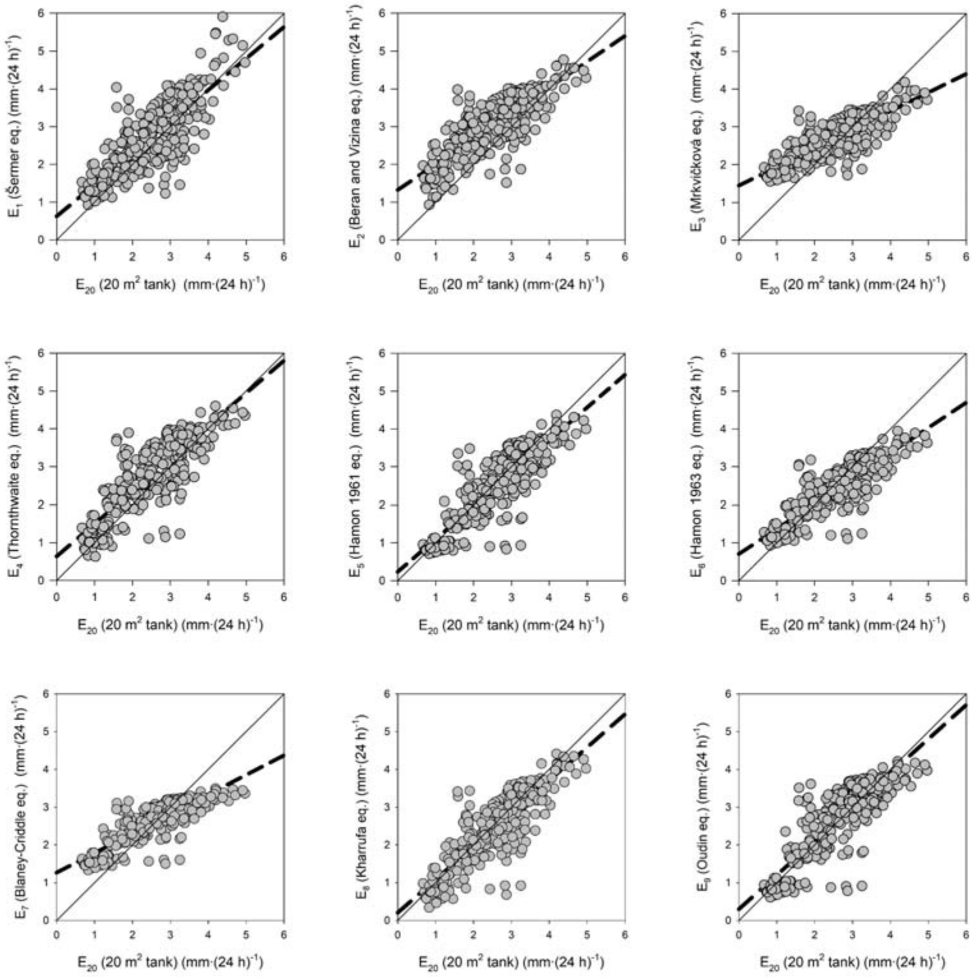

Fig. 3. Mean evaporation vs. evaporation/potential evapotranspiration obtained by nine empirical equations for Hlasivo station (measured temperature); dashed lines represent linear regression; source: own study

Table 2. Summary statistics of evaporation/potential evapotranspiration estimated methods (measured temperature) tested against evaporation from the 20 m^2 tank at Hlasivo station

Index	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	E_9
Mean	2.705	3.023	2.674	2.814	2.409	2.372	2.557	2.393	2.561
SD	0.911	0.748	0.539	1.019	0.912	0.693	0.550	0.919	0.960
a (slope)	0.782	0.647	0.466	0.902	0.844	0.642	0.506	0.841	0.884
b (intercept)	0.741	1.397	1.504	0.174	0.288	0.759	1.286	0.280	0.339
R^2	0.604	0.614	0.613	0.817	0.703	0.705	0.695	0.687	0.696
r	0.777	0.783	0.783	0.904	0.839	0.840	0.833	0.829	0.835
d	0.870	0.802	0.813	0.947	0.919	0.902	0.854	0.906	0.920
MSE	0.404	0.578	0.372	0.209	0.277	0.266	0.294	0.299	0.293
RMSE	0.636	0.760	0.610	0.457	0.526	0.516	0.542	0.546	0.541
MAE	0.523	0.642	0.502	0.375	0.391	0.383	0.428	0.409	0.407
MBE	0.193	0.510	0.161	–0.113	–0.104	–0.141	0.044	–0.119	0.049

Explanations: *SD* = standard deviation, *a*, *b* = regression coefficients, R^2 = cross-correlation coefficient, *d* = index of agreement, *RMSE* = root mean square error, *MSE* = mean squared error, *MAE* = mean absolute error, *MBE* = mean bias error, $E_1 – E_9$ = as in Fig. 3.
Source: own study.

$$E_x = aE_{20} + b \tag{26}$$

The resulted regression coefficient *a* and *b*, together with the cross-correlation coefficient (R^2), are presented in Table 2 and in Figure 3.

The deviations (Δ) between observed and predicted values were categorized into the three categories and the results are shown in Figure 4. The first three equations (1–3) given by Šermer, Beran–Vizina, and Mrkvičková, which do not include daylight or extra-terrestrial radiation, reached the lowest amount of Δ in category 1 (Δ is between –0.5 and +0.5 mm·(24 h)$^{-1}$). The Thornthwaite equation (4) achieves the best values of Δ and in four months does not have Δ in category 3 (|Δ| > 1.0). It should be noted that the Thornthwaite equation was only tested from 2006–2016. The Thornthwaite equation gave the best-predicted values, resulting in a value of Pearson's product-moment correlation coefficient *r* = 0.904 (*d* = 0.947) and a slope close to unity (*a* = 0.902), and a low value of intercept (*b* = 0.174). In addition, it has *MAE*, *RMSE* and *MSE* closest to zero; only *MBE* is fourth closest to zero. On the other hand, the mean (2.814 mm·(24 h)$^{-1}$) and standard deviation *SD* (1.019 mm·(24 h)$^{-1}$) of predicted values from the Thornthwaite equation are relatively different from the mean (2.51 mm·(24 h)$^{-1}$) and *SD* (0.90 mm·(24 h)$^{-1}$) of observed values. The Hamon equation from 1961 (9), Kharrufa equation (16) and Oudin equation (17) can also be described as sufficient for prediction of evaporation/potential evapotranspiration in conditions similar to those at Hlasivo station. These equations have slope *a* relatively close to the unit (between 0.841 and 0.884), low value of intercept *b* (between 0.280 and 0.339), index of agreement *d* is close to the unit (between 0.906 and 0.920), and *MBE* is close to zero (between –0.119 and +0.049). *RMSE* and *MAE* of these equations are only slightly worse than the Thornthwaite equation. The Hamon equation from 1963 (12) has similar values of statistical indices except slope (*a* = 0.642), intercept (*b* = 0.759) and standard deviation (*SD* = 0.693). The Blaney–Criddle equation (13) has worse statistical indices than other equations but is a little bit better than equations (1–3), which only use temperature as an independent variable.

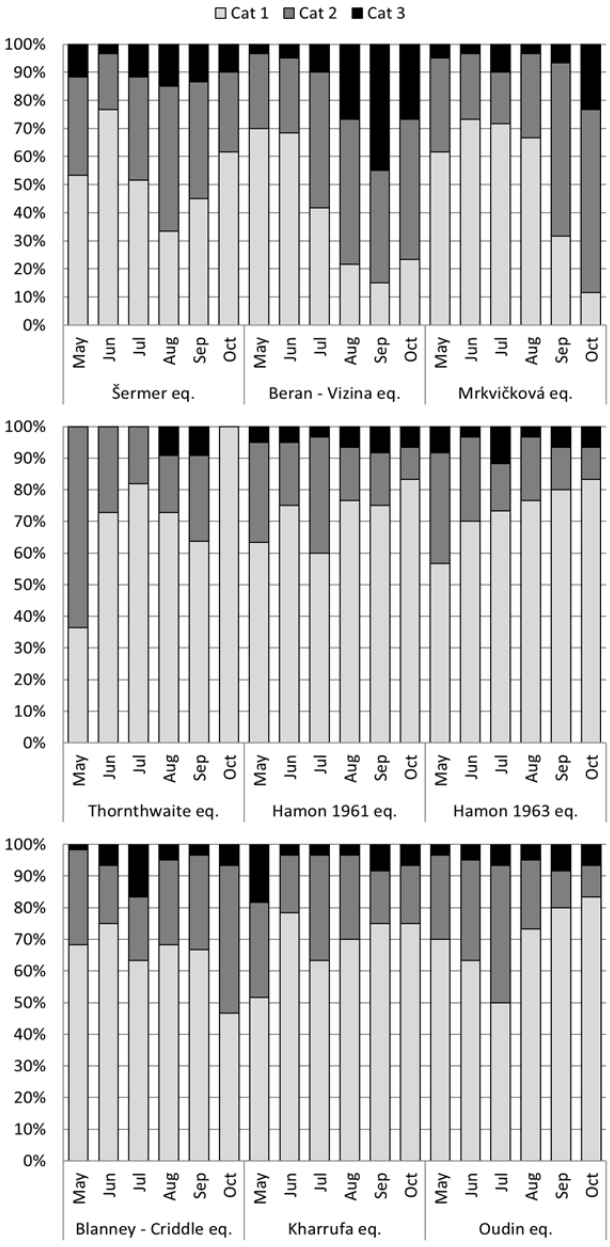

Fig. 4. Distribution of deviation Δ into the categories for measured temperature; source: own study

INTERPOLATED TEMPERATURE DATASET

The correlations between the nine empirical methods against pan evaporation when the interpolated temperature was used in equations are shown in Figure 5. The resulted regression coefficient *a* and *b*, together with the cross-correlation coefficient (R^2), are presented in Table 3 and in Figure 5. The deviations (Δ) between observed and predicted values were categorized into the three categories and the results are shown in Figure 6.

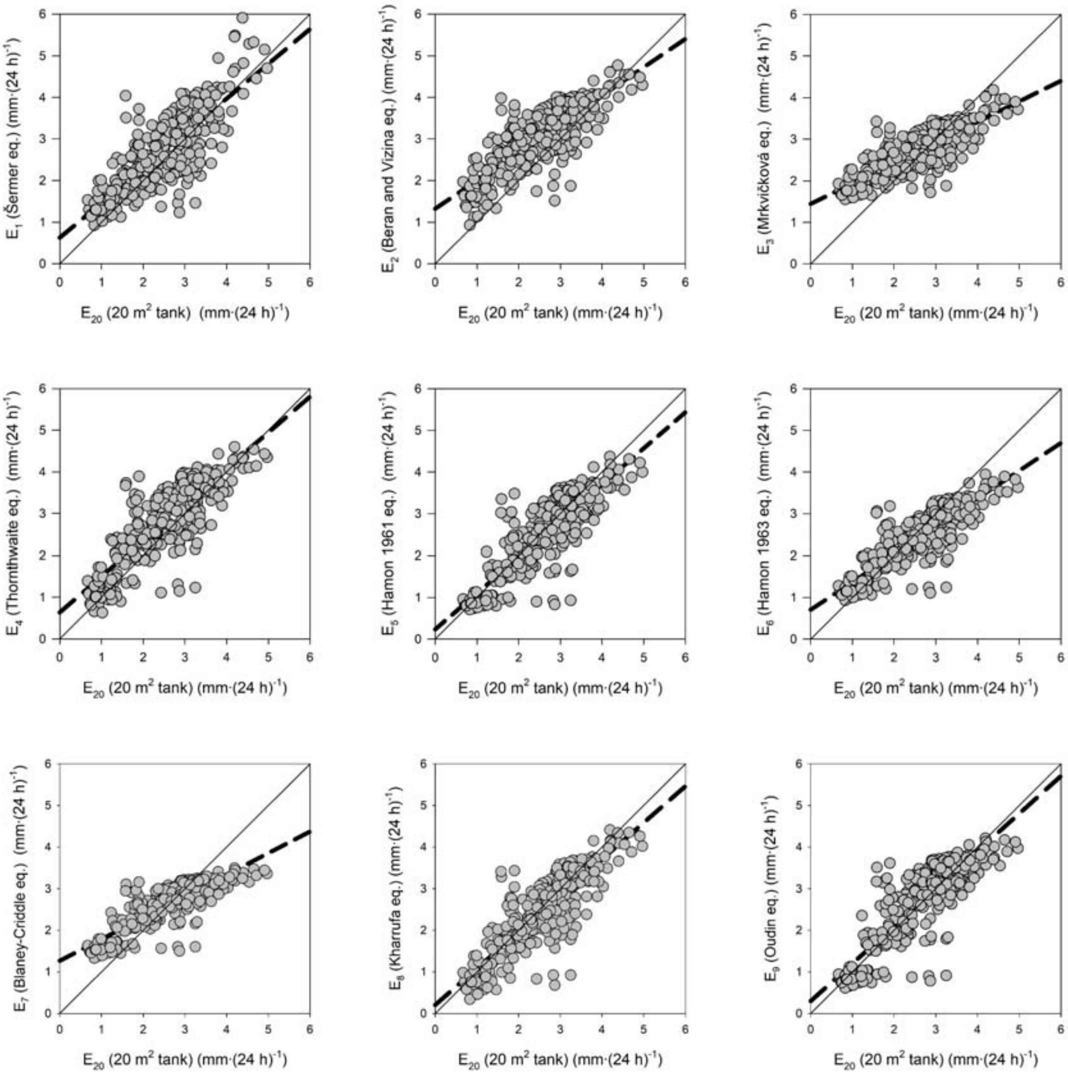

Fig. 5. Mean evaporation vs. evaporation/potential evapotranspiration obtained by nine empirical equations for Hlasivo station (interpolated temperature); source: own study; dashed lines represent linear regression

Table 3. Summary statistics of evaporation/potential evapotranspiration estimated methods (interpolated temperature) tested against evaporation from the 20 m^2 tank at Hlasivo station

Index	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	E_9
Mean	2.744	3.047	2.694	2.820	2.431	2.392	2.575	2.422	2.580
SD	0.942	0.765	0.552	0.941	0.931	0.709	0.560	0.941	0.979
a (slope)	0.835	0.680	0.493	0.914	0.868	0.665	0.517	0.876	0.901
b (intercept)	0.629	1.325	1.447	0.211	0.235	0.708	1.266	0.205	0.299
R^2	0.648	0.652	0.656	0.691	0.716	0.726	0.703	0.715	0.704
r	0.805	0.807	0.810	0.831	0.846	0.852	0.839	0.846	0.839
d	0.885	0.819	0.834	0.895	0.916	0.901	0.861	0.916	0.914
MSE	0.379	0.553	0.343	0.372	0.270	0.249	0.286	0.276	0.291
RMSE	0.615	0.744	0.586	0.610	0.520	0.499	0.535	0.525	0.539
MAE	0.497	0.627	0.477	0.482	0.384	0.364	0.418	0.382	0.403
MBE	0.213	0.515	0.163	0.289	–0.100	–0.140	0.044	–0.109	0.049

Explanations as in Tab. 2.
Source: own study.

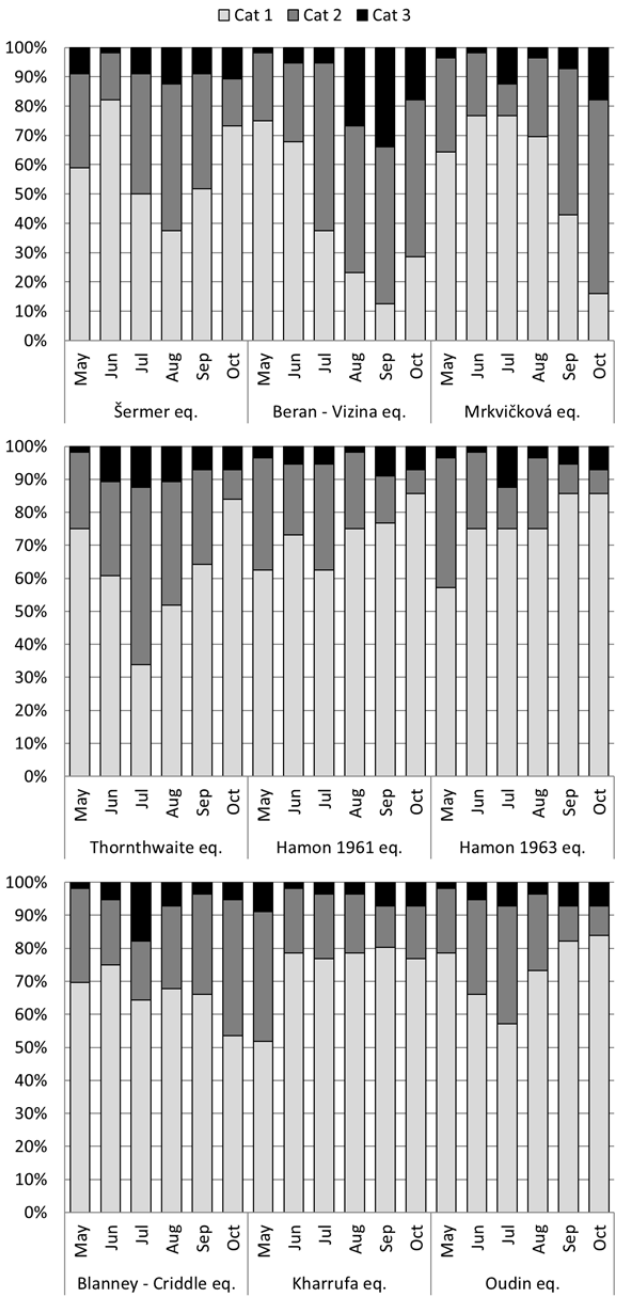

Fig. 6. Distribution of deviation Δ into the categories for interpolated temperature; source: own study

DISCUSSION

Evaporation from a water surface and evapotranspiration from a surface are important parts of the hydrological cycle. Climate change can disturb the hydrological cycle mainly through evapotranspiration. Accurate accounting of evaporation/potential evapotranspiration is crucial, particularly in the context of climate change.

One-parametric temperature-based models of evaporation/potential evapotranspiration can provide relatively sufficient estimations of these natural phenomena. A lot of similar studies have been published evaluating more complex models in similar humid conditions and provided the same or similar statistical indices of agreement of models e.g. TRAJKOVIC, KOLAKOVIC [2009], EFTHIMIOU *et al.* [2013] and ČADRO *et al.* [2017]. More complex models and models with locally adjusted empirical coefficients have, in most cases, better statistical indices and it can be assumed that these models provide the most accurate estimations, like the simple equations evaluated in our study. The importance of local adjustment and calibration procedure has been highlighted by many authors worldwide e.g. XU *et al.* [2012], BOGAWSKI and BEDNORZ [2014], DORJI *et al.* [2016] and ČADRO *et al.* [2017]. GAO *et al.* [2015] compared 19 methods in a humid part of China. The best two equations have *RMSE* of 0.15 and 0.15 mm·(24 h)$^{-1}$; the *RMSE* of these equations were 0.010 and 0.025 mm·(24 h)$^{-1}$ after calibration. ČADRO *et al.* [2017] validated 12 equations according to an estimation-based FAO Penman–Monteith method with data from eight weather stations in Bosnia and Herzegovina. *RMSE* uncalibrated methods varied between 0.29 and more than 3 mm·(24 h)$^{-1}$. The best calibrated method has *RMSE* from 0.157 to 0.243 mm·(24 h)$^{-1}$, *MAE* from 0.121 to 0.173 mm·(24 h)$^{-1}$, *MBE* from –0.266 to 0.080, and high R^2 from 0.952 to 0.980. ČADRO *et al.* [2017] also tested the Thornthwaite equation. The *RMSE* of the uncalibrated Thornthwaite equation varied from 0.708 to 1.308 mm·(24 h)$^{-1}$, *MAE* from 0.625 to 1.198 mm·(24 h)$^{-1}$, and *SD* from 0.27 to 0.55. Calibration did not significantly improve estimation by the Thornthwaite equation.

CONCLUSIONS

The main objective of this study was an evaluation to see if simple one-parametric equations can provide an estimation of evaporation/potential evapotranspiration at a sufficient level of agreement. The study evaluated nine equations against observed evaporation from a 20 m^2 tank at Hlasivo station in the South of the Czech Republic.

The strictly statistical approach was represented by the Šermer equation (1), Beran and Vizina equation (2), and Mrkvičková equation (3). These equations were developed with data from the Czech Republic and former Czechoslovakia and only used temperature as an independent explanatory variable. These equations do not provide sufficient results and other evaluated equations with the same data requirements provide better results.

The second group of equations adds the effect of the season due to daylight or extra-terrestrial radiation to the model. These explanatory variables are calculated and do not need any measured data. Comparison with similar published studies showed that these very simple models have worse statistical indices than models, which use more climatological parameters.

The Thornthwaite equation (4) provides the best result in case of measured temperature, but this equation was evaluated on a very short time series due to missing data. In the case of interpolated temperature dataset, the results are not the best. The Oudin equation (17) and Hamon equation from 1961 (9) can provide a sufficient estimation of agreement with observed data like the Thornthwaite equation for measured temperature dataset and for interpolated. Temperature dataset. Although the Kharrufa equation (E_8) was developed for semi-arid or arid areas, this equation provides a sufficiently accurate estimation of evaporation in humid conditions in the Czech Republic for both datasets. We can suggest for estimation of potential evapotranspiration or evaporation from free water surface:

- Oudin equation (17),
- Hamon equation from 1961 (9).
- Kharrufa equation (16).

Accurate estimation of evaporation/potential evapotranspiration is essential for a lot of application such a real-time irrigation scheduling or water resource planning and management. On the other hand, there are still groups of applications, which do not need a high accuracy of evaporation/potential evapotranspiration estimation, but it is important to find a model as simple as possible with sufficient accuracy of results and to be able to quantify errors in a model. For example, global studies focused on general water use or water balance with high uncertainties of input data, such as life-cycle assessment studies, water footprint studies or virtual water studies, use evaporation and evapotranspiration as an important input to the simulations but it is only one of many other inputs. For these types of applications, the simple empirical equations can be an effective way to achieve the aims of the study. For these types of applications, the inclusion of next explanatory variables in the calculation may not result in an increase of accuracy because these parameters usually are not measured but modelled with some error.

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Porównanie prostych metod określania parowania na podstawie pomiarów temperatury z seriami czasowymi pomiarów parowania ze standardowego zbiornika o powierzchni 20 m^2

STRESZCZENIE

Parowanie i ewapotranspiracja są kluczowymi częściami badań hydrologicznych i analiz zarządzania zasobami wodnymi. Właściwe metody szacowania ewapotranspiracji i potencjalnej ewapotranspiracji są krytyczne w sytuacji, gdy dostępność danych klimatycznych jest silnie ograniczona. W badaniach na dużą skalę często używane są dane uogólnione (za pomocą modelowania bądź przetwarzania sieciowego – grid). W takich badaniach ważne jest także znalezienie najprostszych metod z błędem możliwym do ilościowego określenia. W prezentowanych w pracy badaniach porównano dziewięć prostych równań empirycznych bazujących na pomiarze temperatury z długą serią danych rzeczywistego parowania ze zbiornika o powierzchni 20 m^2 w stacji Hlasivo. W pierwszym etapie wykorzystano rzeczywiste wartości temperatury mierzonej w stacji Hlasivo do szacowania równań. W etapie drugim użyto sieciowych danych temperaturowych (zbiór danych interpolowanych) ze stacji meteorologicznych. Dla obu zbiorów danych różnice między obserwowanymi a przewidywanymi danymi przypisano do trzech kategorii dokładności i obliczono statystyczne wskaźniki dla każdego równania. Bardzo dobre wyniki uzyskano w odniesieniu do równania Hamona z 1961 r. i równania Oudina dla obu zbiorów danych. Równanie Kharrufa, które opracowano dla obszarów półpustynnych i pustynnych, dało również wyniki o wystarczającej dokładności. Porównanie wyników z badaniami o podobnej tematyce wykazało mniejszą dokładność bardzo prostych równań względem równań bardziej złożonych. Dla niektórych rodzajów badań policzalne błędy o wystarczającej dokładności mogą być jednak ważniejsze niż dokładność bezwzględna.

Słowa kluczowe: *ewapotranspiracja, metody bazujące na pomiarze temperatury, ocena, parowanie z powierzchni zbiornika, zbiornik 20 m^2*