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Comparison of Several Methods for Calculation of Reference Evapotranspiration

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Abstract – The knowledge of the evapotranspiration of natural ecosystems and plant populations is of fundamental importance in several branches of science, research and practical uses. Nevertheless, the harmonisation of the large number of methods and user needs often causes problems. The objective of the analyses was to explore the output range and sensitivity of models of different physical approaches under local conditions. We performed descriptive statistical and sensitivity analysis of 10 commonly used estimation models – one of them with two variants. Correlation between modelled and measured evapotranspiration data series was assessed. The magnitude of the model outputs, their variability and responses to the changes of selected atmospheric parameters were evaluated. Priestley–Taylor, Penman–Monteith–FAO-56, Shuttleworth–Wallace (parameterized with alternative radiation balance), Szász and Makkink proved to be the most sensitive methods. As regards the systematic error, Makkink and Shuttleworth–Wallace showed the best agreement with pan evaporation, while Shuttleworth–Wallace, Blaney–Criddle and Makkink models were found to be the closest to the Penman–Monteith–FAO-56 method as a reference value.

evapotranspiration /estimation models / sensitivity analysis

Kivonat – A referencia párolgás néhány becslő módszerének összehasonlító vizsgálata. Számos tudományterület és kutatási téma, valamint gyakorlati alkalmazás számára bír alapvető fontossággal a növényállományok, természetes ökoszisztémák evapotranspirációjának ismerete. A nagyszámú módszer és a változó felhasználói igények összeegyeztetése azonban gyakran problémát okoz. A vizsgálatok célja az volt, hogy helyi viszonyok között is megismerhessük az eltérő fizikai megközelítést tükröző modellek kimeneti értéktartományát, érzékenységét. Leíró statisztikai-, valamint érzékenységvizsgálatot végeztünk 10 gyakran alkalmazott becslő modell eredményeire, ezek egyikének esetében két modellváltozatra is. Vizsgáltuk a kiválasztott módszerek korrelációját egymáshoz, illetve mért adatsorhoz képest. Értékeltük a modellkimenetek nagyságrendjét, azok változékonyságát, valamint az egyes légköri paraméterek változására adott reakcióját. A vizsgált módszerek közül a Priestley–Taylor, Penman–Monteith–FAO-56, Shuttleworth–Wallace (egyedi sugárzási egyenleggel parametrizálva), Szász és Makkink modell bizonyult a legérzékenyebbnek. Szisztematikus hiba tekintetében a Makkink és a Shuttleworth–Wallace mutatta a legjobb egyezést a mért értékekkel, míg a Penman–Monteith–FAO-56 módszert referenciaként választva ahhoz a Shuttleworth–Wallace, a Blaney–Criddle és a Makkink modell állt a legközelebb.

evapotranspiráció / becslő modellek / érzékenységvizsgálat

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1 INTRODUCTION

Research of evapotranspiration plays an important role in the field of agro- and hydrometeorology. Due to the complexity of evapotranspiration as a biophysical phenomenon, several approaches and variants were developed.

In physical sense, evapotranspiration (ET) is the sum of the evaporation (E) from the water and soil surfaces and the amount of water transpired by plants (transpiration, T). It is often limited by the currently available evaporable water, as well as by characteristics of the plant cover and the soil. Based on these factors, two values can be distinguished, namely potential (PET or ET_p) and actual evapotranspiration (AET or ET_a). Reference evapotranspiration (ET_0) represents theoretical evapotranspiration from an extensive surface of green grass of uniform height, actively growing, completely shading the ground, and not short of water (Allen et al. 1998). This concept is suitable for deriving ET values for any crop, although significant differences between values of diverse model equations may be confusing for practical users.

For each of the wide range of applications, such as hydrological and ecosystem models, aridity assessments, or irrigation planning etc. (FAO 1996, Lieth 1975), it is crucial to find the most appropriate method to estimate ET_0. Differences among methods often reach hundreds of millimetres per growing season (Federer et al. 1996), and accuracy of a given method depends heavily on the climatic conditions of the study site. For humid climate the Penman-Monteith-FAO-56 method is generally recommended (Jensen et al. 1990, Sumner – Jacobs 2005, Yoder et al. 2005, McMahon et al. 2012), and its extensions e.g. the Shuttleworth–Wallace equation also proved to be effective (Zhou 2011) because of its robust physical basis. Several studies preferring Priestley-Taylor's approach (Lu et al. 2005, Adeboye et al. 2009), point out that under such climatic conditions it performs better than any other radiation and temperature based methods. Most of the authors confirmed that temperature and radiation based methods tend to give the highest, while pan-coefficient based ones result in the lowest ET_0 values (Yates – Strzepek 1994, Tabari et al. 2011). Under arid and semi-arid climates radiation based models may perform poorly (Er-Raki et al. 2010), however, use of locally calibrated equations can make them more accurate than temperature based and even combination type ones (Bois et al. 2005, Schneider et al. 2007). In general, Penman-Monteith-FAO-56 and radiation based methods estimate ET_0 higher than pan-coefficient methods do (Rao – Rajput 1992) in arid environment.

The necessity of comparison, sensitivity testing and calibration of methods in a local context is emphasized by a large number of studies. Additionally, in continental climate of Eastern Hungary, there is a considerable variability of humid and arid characteristics, thus, to find the most suitable models, a local test appeared to be indispensable.

For our assessment we selected two methods of each the four basic ET_0 approaches. Since it is also highly recommended by literature (Federer et al. 1996, McMahon et al. 2012) to consider locally measured data, we decided to involve pan evaporation data series as a reference value.

The main objectives of our study were the following:

- statistical evaluation of the outputs of several approaches to evapotranspiration assessment,
- evaluation of the sensitivity of addressed approaches to change in input climate variables.

2 DATA AND METHODS

2.1 Climate data

The weather data used in our study were daily mean values derived from hourly values of the basic parameters (global radiation (kJ m^{-2} $hour^{-1}$), temperature at 2 m (°C), relative humidity (%), sunshine duration (hour day^{-1}) and wind speed at 10 m height (m s^{-1}), all measured at Debrecen Airport station of the Hungarian Meteorological Service. Therefore, we obtained a useful basis for comparison with the pan evaporation values measured at the same location.

Pan evaporation measurements represent a conventional measurement method and long data series are available at several Hungarian meteorological stations. The method refers to the daily amount of water evaporated from the open surface of a water filled pan. Although such measurements may be subject to error due to e.g. oasis effect, drinking animals, etc. (Tanner 1968, Lim et al. 2011), it is still a widely used method. Our data series contains the daily *ET* ('Pan', E_{pan} in mm day^{-1}) data measured by class-A evaporation pan at Debrecen Airport station (lat.: N47.490°; lon.: E21.611°) of the Hungarian Meteorological Service (OMSZ) during the growing seasons (April – October) of test years (2005–2010). In *Table 1.* we provide the descriptive statistics for the pan evaporation data series.

Table 1. Descriptive statistics of the pan evaporation data for the growing season (Apr.–Oct.)

	2005	2006	2007	2008	2009	2010
Sum	613.6	751.1	1015	802.8	1091	750.7
Mean	87.66	107.3	145	114.7	155.8	107.2
St.D.	1.59	1.88	2.60	2.01	2.29	2.04
CV	1.81	1.75	1.79	1.75	1.47	1.90

Unit: mm day^{-1}
St.D.: standard deviation, **CV**: coefficient of variation (%)

2.2 Methods for modelling potential evapotranspiration

Equations for the applied models can be seen below, sorted by type.

Pan coefficient-based methods ***(time step: day)***

Pereira model: (Pereira et al. 1995): *('Per', hereinafter)*

$$ET_0 = E_{pan} \cdot K_1 \tag{1}$$

$$K_1 = \frac{0.85(\Delta + \gamma)}{[\Delta + \gamma(1 + 0.33u_2)]} \tag{2}$$

FAO-56 (Allen et al. 1998): ('FAO56')

$$ET_0 = E_{pan} \cdot K_2 \tag{3}$$

$$K_2 = 0.51206 - (0.000321u_2 + 0.0422\ln(F) + 0.1434\ln(RH) - 0.000631[\ln(F)]^2 \ln(RH) \tag{4}$$

Temperature-based methods ***(time step: month or longer)***

Blaney–Criddle-model: (Blaney–Criddle 1950, Doorenbos–Pruitt 1977a, Burman–Pochop 1994): *('B&C')*

$$ET_0 = a_1 + b_1\left[p(0.46T + 8.13)\right] \tag{5}$$

$$a_1 = 0.0043RH_{\min} - (n/N) - 1.41 \tag{6}$$

$$b_1 = 0.82 - 0.0041RH_{\min} + 1.07(n/N) + 0.066u_{2d} - 0.006RH_{\min}(n/N) - 0.0006RH_{\min}u_{2d} \tag{7}$$

Szász method (Szász 1973): *('Szász')*

$$ET_0 = 0.00536 \cdot (T + 21)^2 \cdot (1 - RH)^{\frac{2}{3}} \cdot f(u) \tag{8}$$

$$f(u) = 0.0519 \cdot \mathrm{u}_2 + 0.905 \tag{9}$$

Radiation-based methods ***(time step: day/month)***

Makkink–FAO-24 (Makkink 1957, Doorenbos–Pruitt 1977b): *('Mak')*

$$ET_0 = a_2 + b_2\left(\frac{\Delta}{\Delta + \gamma}\right)\frac{R_g}{\lambda} \tag{10}$$

$$a_2 = -0{,}3 \tag{11}$$

$$b_2 = c_0 + c_1RH + c_2u_{2d} + c_3RHu_{2d} + c_4RH^2 + c_5u_{2d} \tag{12}$$

Priestley–Taylor-model (Priestley–Taylor 1972, McNaughton – Jarvis, 1983): *('P&T')*

$$ET_0 = \frac{\alpha\frac{\Delta}{\Delta + \gamma}(R_n - G)}{\lambda} \tag{13}$$

$$\alpha = 1 + \frac{\gamma}{\Delta + \gamma} \cdot \frac{r_c}{r_a} \tag{14}$$

Methods based on mass-transfer ***(time step: day)***

WMO-1966 (WMO 1966): *('WMO66')*

$$ET_0 = (0.1298 + 0.0934u_2) \cdot (e_s - e_a) \tag{15}$$

Mahringer-model (Mahringer 1970): *('Mah')*

$$ET_0 = 0.1572 \cdot \sqrt{3.6u_2} \cdot (e_s - e_a) \tag{16}$$

Combination-type methods ***(time step: day)***

Penman–Monteith–FAO-56-model (Allen et al. 1998): *('PMF56')*

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T + 273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{17}$$

Shuttleworth–Wallace-model (Shuttleworth–Wallace 1985): *('S&W' and 'S&W#2')*

$$ET_0 = \frac{C_c \cdot ET_c + C_s \cdot ET_s}{\lambda} \tag{18}$$

Terms of the above equations are given in details in *Table 2*.

Table 2. Abbreviation of variables, coefficients and units used in equations 1–17

Notation	Name of variable	Unit	Equation no.
u_2	daily mean wind speed at 2 m height	km day^{-1}	2, 4, 9, 15, 16, 17
u_{2d}	mean wind speed of daylight hours at 2 m height	m s^{-1}	7, 12
γ	psychrometric constant	kPa $°C^{-1}$	2, 10, 13, 14, 17
Δ	slope of the vapor pressure curve	kPa $°C^{-1}$	2, 4, 10, 13, 14, 17
F	the fetch distance above the reference surface	m	4
RH	daily mean relative humidity	%	4, 8, 12
RH_{min}	daily minimum of relative humidity	%	6, 7
a_1, b_1	parameters for equation 5	–	5
a_2, b_2	parameters for equation 10	–	10
(n/N)	relative sunshine duration	–	6, 7
T	daily mean temperature at 2 m height	°C	5, 7, 8, 17
c_0, c_1, c_2, c_3, c_4, c_5	coefficients for equation 12	–	12
R_g	global radiation	cal m^{-2} day^{-1}	10
R_n	net radiation	MJ m^{-2} day^{-1}	13
	water equivalent of net radiation	mm day^{-1}	17
G	soil heat flux	MJ m^{-2} day^{-1}	13
	water equivalent of soil heat flux	mm day^{-1}	17
λ	latent heat of vaporization	cal m^{-2} day^{-1}	10
		MJ kg^{-1}	13, 18
α	Priestley-Taylor coefficient	–	13
r_a	aerodynamic resistance	s m^{-1}	14
r_c	canopy resistance	s m^{-1}	14
e_s	saturation vapor pressure	hPa	15, 16
		kPa	17
e_a	actual vapor pressure	hPa	15, 16
		kPa	17
C_c	weighting coefficient for canopy	–	18
C_s	weighting coefficient for soil	–	18
ET_c	transpiration	mm day^{-1}	18
ET_s	evaporation	mm day^{-1}	18

During the selection of the models, attributes taken into consideration were input data requirements, sensitivity for different climatic variables and suitability to different humidity conditions according to literature.

Pan-evaporation derived methods are relatively simple, computation is based on measured E_{pan} values and an empirically determined pan-coefficient as a correction factor. An advantage of these methods, such as Per and FAO56, is their very little input data.

Temperature- and radiation based methods are also simple with low number of input variables, however, calculation of empirical coefficients used can be difficult. These methods are recommended to be used for monthly or longer periods of time.

Methods based on mass-transfer mainly use temperature and humidity parameters. This approach considers the energy and water vapour transfer between the surface and the air. Equations are typically simple, with daily time step.

Combination-type methods unify aerodynamic and energy-balance theories. PMF56 and S&W methods are particularly widely used and considered to be accurate and robust models with the disadvantage of high input data requirements. S&W equation, which is a modification of PMF56, allows for local calibration and parameterization, though it requires abundant data describing air, soil and vegetation conditions either.

The analysis was performed for the period of 2005–2010. Winter periods during the analysis, were deliberately neglected. However, daily values of ET_0 could be considerable in several cases, it has very little significance for agro- and hydrometeorological use.

For our alternative Shuttleworth-Wallace 'S&W#2' test-variant, estimated net radiation values were used. Net radiation data was calculated from global radiation of D.-Airport, with linear regression method on the basis of four components net radiation measurements. Net radiation was measured at Debrecen-Kismacs Agrometeorological Observatory (lat.: N47.577°; lon.: E21.582°), approximately 10 km north to the Airport station.

2.3 Methods for data analysis

The comparative analysis consisted of two parts. First, a descriptive analysis was performed; the values of the final results obtained from each estimation algorithm, i.e., evapotranspiration sums during the growing season and monthly amounts were examined in six test years. Furthermore, the average differences of values from the pan evaporation data were also evaluated in the respective periods. By means of basic descriptive statistical indices, such as absolute maximum, absolute minimum, mean value, total range of values, standard deviation, coefficient of variation and variance, models were subjected to a statistical. Also, cross analysis of the models' root mean square error (RMSE) between model outputs was performed. RMSE is an informative which denotes the error between a model and a certain basis for comparison. In this study we paired every single model to all the others to assess the magnitude of discrepancy between each pair. In a similar way we carried out a Pearson's correlation test. In addition to cross-analyses we examined residues calculated on the basis of Pan and PMF-56 methods. Outputs of each model were compared to Pan and PMF-56 thus, and for ΔET_0 values basic statistics (e.g. absolute maximum and minimum, mean bias error (MBE), standard deviation, variance and total range) were calculated.

All the indices were calculated on the basis of daily data in the entire examination period except for the analysis of monthly or seasonal sums.

Next, a sensitivity analysis was carried out to evaluate the response of calculated ET to selected atmospheric parameters. Changes of model outputs and their variability induced by change in atmospheric variables were evaluated. Reason for the selection of these variables, such as temperature measured at 2 m height (T), relative humidity (RH), global radiation (R_g) and wind speed measured at 10 m (u), was that these variables are thought of as the most decisive in the control of ET values in most of equations used.

Mean values of these parameters and also from the ET_0 values of each model were calculated. Then we calculated the deviation (Δ) from these means for the daily data of the atmospheric parameters and the ET_0 values, respectively. In order to reach the best comparability between the effects of changes in all atmospheric variables, Δ values of each parameter and ET_0 were converted to changes in percentage. Finally, the mean of output changes (mean ΔET_0) and the total range (R) of the changes for the period were shown in diagrams indicating the magnitude of changes in the input on the x-axis.

3 COMPARATIVE ANALYSIS AND SENSITIVITY ANALYSIS

3.1 Descriptive statistics

Data in *Table 3* indicate that yearly sums of modelled ET_0 values differ remarkably among years and models. This high level of divergence occurs mostly between different types (e.g. temperature-based, radiation based, etc.) of methods and only to a lesser extent between methods of the same type.

Table 3. Sums of ET_0 during the growing seasons of the examined years

Year	Pan	Per	FAO56	B&C	Szász	Mak	P&T	WMO66	Mah	S&W	PMF56	S&W#2
2005	649	425	517	914	692	861	663	481	582	864	925	828
2006	751	493	597	951	708	893	674	520	628	895	948	853
2007	1015	644	771	1126	797	1046	746	755	885	1113	1148	1065
2008	803	512	628	971	708	923	710	557	657	922	979	883
2009	1091	690	830	1153	789	1041	737	799	937	1164	1183	1117
2010	751	477	595	877	648	844	683	446	527	799	868	763

ET_0: reference evapotranspiration (mm)

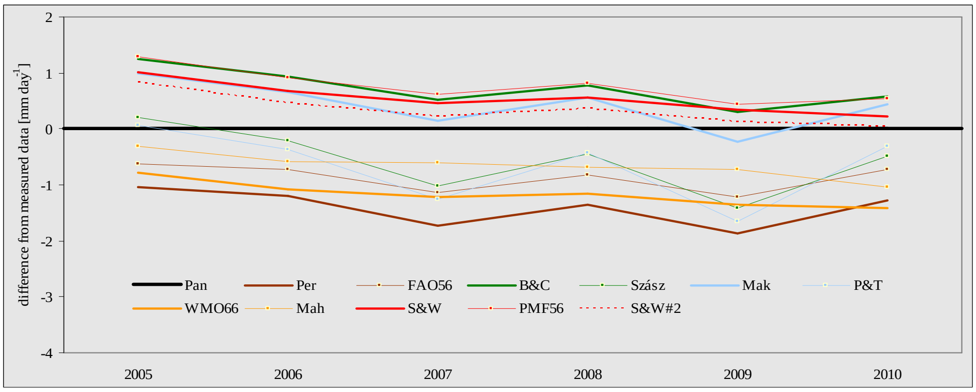
Table 4 implies that there are differences between the selected models in terms of their range and standard deviation. In addition, the group of models which estimate the highest maximum – and the widest range – of ET_0 (mass-transfer based and combination type methods) and those which show the highest standard deviation (B&C, Mak and combination type methods) is not necessarily the same. Notwithstanding, we could distinguish large fluctuation models by their high range and standard deviation values (Pan, B&C, mass-transfer based and combination-type methods) and also 'conservative' ones with less fluctuation can be specified (pan coefficient-based, Szász and P&T methods).

Table 4. Descriptive statistics calculated for the whole examined period (2005–2010)

	Pan	Per	FAO56	B&C	Szász	Mak	P&T	WMO66	Mah	S&W	PMF56	S&W#2
Max.	12.10	7.67	8.18	11.79	6.49	9.70	7.17	16.05	17.30	14.76	12.85	14.92
Min.	0.00	0.00	0.00	0.33	0.21	–0.05	0.24	0.04	0.05	0.15	0.23	0.08
Avg.	3.94	2.52	3.07	4.67	3.38	4.37	3.28	2.77	3.28	4.48	4.71	4.29
R.	12.10	7.67	8.18	11.46	6.28	9.75	6.93	16.00	17.25	14.61	12.62	14.84
St.D.	2.18	1.41	1.61	2.32	1.51	2.31	1.55	1.82	2.04	2.22	2.22	2.22
CV	0.55	0.56	0.53	0.50	0.45	0.53	0.47	0.66	0.62	0.50	0.47	0.52
Var.	4.75	2.00	2.60	5.40	2.27	5.35	2.41	3.32	4.18	4.92	4.91	4.94

Max.: absolute maximum (mm day^{-1}), **Min.**: absolute minimum (mm day^{-1}), **Avg.**: mean value (mm day^{-1}), **R.**: total range (mm day^{-1}), **St.D.**: standard deviation, **CV**: coefficient of variation, **Var.**: variance
For explanation of method abbreviations see chapter 2.2

Annual time series of residuals *(Figure 1.)* indicate that differences between modelled and measured values were relatively stable, but not constant. There are major changes in residuals either between model outputs or between Pan data and modelled ET_0 values.



(Meanings of abbreviations are given in chapter 2.2)

Figure 1. Average daily difference of the model outputs and measured values in the period 2005–2010

The temporal course of the differences compared to Pan data and the precipitation sums of the examined growing seasons correlates well in case of certain models. The following precipitation sums were recorded in the interval between April and October: 473 mm (2005), 438 mm (2006), 369 mm (2007), 396 mm (2008), 256 mm (2009) and 571 mm (2010). The value of the coefficients of determination (R^2) are 0.79 (Per), 0.82 (FAO56), 0.72 (Szász), 0.69 (Mak) and 0.82 (P&T).

It shows the fact that model response to the amount of evaporable water is stronger than that of the evaporation pan. Although it should be noted that in case of other models correlation was much weaker.

The quantification of the correlation of the models and the residuals compared to each other is closely linked to our statistical examinations. Correlation was calculated for each pair of models instead of averaging within model types. *Table 5* summarises the values of Pearson's correlation coefficient.

Table 5. Cross analysis of Pearson's correlation between modelled daily ET_0 data (2005–2010)

	Pan	Per	FAO56	B&C	Szász	Mak	P&T	WMO66	Mah	S&W	PMF56	S&W#2
Pan	–	0.97	0.99	0.83	0.78	0.81	0.80	0.81	0.82	0.87	0.86	0.85
Per	0.97	–	0.99	0.87	0.83	0.84	0.81	0.75	0.79	0.85	0.84	0.84
FAO56	0.99	0.99	–	0.84	0.80	0.82	0.81	0.76	0.79	0.84	0.84	0.83
B&C	0.83	0.87	0.84	–	0.95	0.96	0.92	0.81	0.85	0.93	0.94	0.90
Szász	0.78	0.83	0.80	0.95	–	0.97	0.95	0.72	0.77	0.89	0.91	0.86
Mak	0.81	0.84	0.82	0.96	0.97	–	0.97	0.75	0.80	0.92	0.95	0.89
P&T	0.80	0.81	0.81	0.92	0.95	0.97	–	0.70	0.73	0.88	0.92	0.85
WMO66	0.81	0.75	0.76	0.81	0.72	0.75	0.70	–	0.99	0.93	0.90	0.92
Mah	0.82	0.79	0.79	0.85	0.77	0.80	0.73	0.99	–	0.95	0.91	0.94
S&W	0.87	0.85	0.84	0.93	0.89	0.92	0.88	0.93	0.95	–	0.99	0.98
PMF56	0.86	0.84	0.84	0.94	0.91	0.95	0.92	0.90	0.91	0.99	–	0.97
S&W#2	0.85	0.84	0.83	0.90	0.86	0.89	0.85	0.92	0.94	0.98	0.97	–

n (number of cases) = 1284. Method abbreviations are explained in chapter 2.2

The closest correlation was observed between Pan and pan-based models due to the fact that these algorithms are closely related to the measured data by the use of a correction factor. Models that showed the weakest correlation with any other were mass-transfer-based ones. The weakest correlation of all has been found between mass-transfer and radiation-based methods. Also, from a different perspective, the difference between the two model types can be explained by use of different atmospheric parameters.

The same analysis was performed with RMSE (*Table 6*) to determine 'alignment' of the models compared to one another. With this analysis our purpose was to find possible reference values and evaluate error between models in this comparison.

Using *pan evaporation* measurement (Pan) as a standard Per and FAO56 models can be highlighted by their lowest RMSE values. Choosing *PMF56* to be the basis of comparison, the two variants of S&W show the best accordance, also because of belonging to the same type. As an alternative, we searched for the models that are closest to the *majority of methods* by selecting the lowest average RMSE. It is found that Per (0.7), Szász (0.73) and even P&T (0.78) showed considerably lower values than the rest of the models.

Table 6 Cross analysis of the Root-Mean-Square Error (RMSE) of modelled daily ET_0 data (2005–2010)

	Pan	Per	FAO56	B&C	Szász	Mak	P&T	WMO66	Mah	S&W	PMF56	S&W#2
Pan	–	0.34	0.20	1.31	0.94	1.36	0.94	1.06	1.16	1.11	1.14	1.17
Per	0.53	–	0.24	1.14	0.84	1.27	0.90	1.20	1.24	1.18	1.19	1.21
FAO56	0.28	0.21	–	1.27	0.91	1.33	0.91	1.18	1.26	1.19	1.20	1.24
B&C	1.23	0.69	0.88	–	0.45	0.65	0.61	1.08	1.06	0.80	0.77	0.95
Szász	1.36	0.79	0.97	0.69	–	0.57	0.50	1.26	1.30	1.01	0.90	1.13
Mak	1.28	0.77	0.93	0.66	0.37	–	0.37	1.20	1.24	0.86	0.70	1.02
P&T	1.31	0.82	0.95	0.92	0.49	0.55	–	1.30	1.40	1.05	0.88	1.18
WMO66	1.27	0.93	1.05	1.38	1.04	1.52	1.11	–	0.28	0.79	0.98	0.87
Mah	1.23	0.86	1.00	1.21	0.96	1.40	1.06	0.25	–	0.68	0.90	0.76
S&W	1.09	0.75	0.87	0.84	0.68	0.89	0.74	0.65	0.62	–	0.32	0.49
PMF56	1.12	0.76	0.88	0.81	0.61	0.73	0.62	0.81	0.83	0.32	–	0.51
S&W#2	1.15	0.77	0.90	1.00	0.76	1.07	0.82	0.72	0.70	0.49	0.50	–

n (number of cases) = 1284

Table 7. Descriptive statistics calculated for residues based on Pan and PMF56 (2005–2010)

ΔET_{0pan}

	Per	FAO56	B&C	Szász	Mak	P&T	WMO66	Mah	S&W	PMF56	S&W#2
Max.	0.00	0.00	5.21	3.44	4.91	3.20	4.68	5.20	6.44	6.21	7.15
Min.	–5.76	–4.00	–6.01	–7.76	–6.60	–7.39	–6.37	–6.16	–4.56	–4.33	–4.87
Avg. (MBE)	–1.42	–0.87	0.73	–0.56	0.43	–0.66	–1.17	–0.66	0.54	0.77	0.35
St.D.	0.88	0.61	1.34	1.38	1.40	1.33	1.27	1.26	1.14	1.17	1.21
Var.	0.77	0.38	1.79	1.89	1.95	1.76	1.62	1.58	1.30	1.37	1.46
R.	5.8	4.0	11.2	11.2	11.5	10.6	11.0	11.4	11.0	10.5	12.0

ΔET_{0PMF56}

	Pan	Per	FAO56	B&C	Szász	Mak	P&T	WMO66	Mah	S&W	S&W#2
Max.	4.33	2.07	2.88	3.20	0.24	1.24	0.35	3.19	4.45	1.91	3.68
Min.	–6.21	–8.96	–8.30	–3.90	–7.52	–4.35	–7.16	–4.42	–3.77	–2.27	–1.66
Avg. (MBE)	–0.77	–2.19	–1.65	–0.05	–1.33	–0.35	–1.43	–1.94	–1.43	–0.23	–0.42
St.D.	1.17	1.28	1.23	0.81	1.04	0.73	1.00	1.00	0.90	0.32	0.51
Var.	1.37	1.63	1.51	0.66	1.08	0.54	1.01	1.00	0.80	0.10	0.26
R.	10.5	11.0	11.2	7.1	7.8	5.6	7.5	7.6	8.2	4.2	5.3

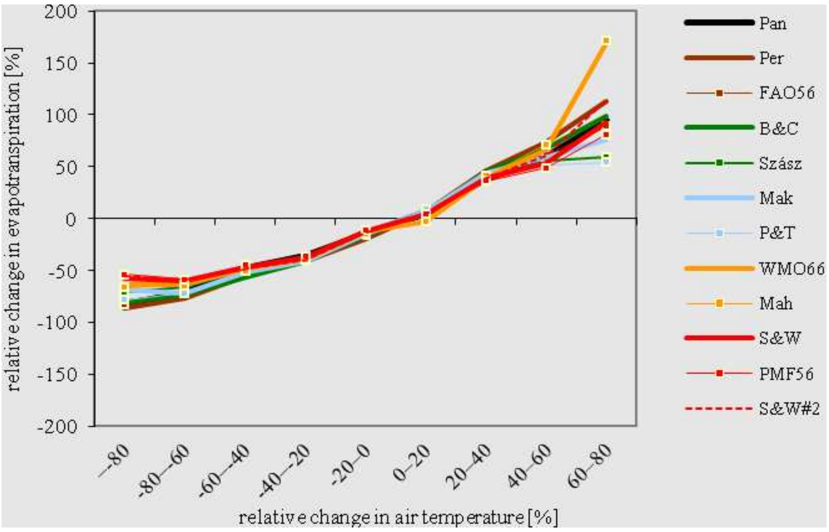
ΔET_0: residues compared to Pan and PMF56 daily output data, respectively; **Max.**: absolute maximum, **Min.**: absolute minimum, **Avg. (MBE)**: mean value, (i.e., systematic error, MBE – Mean Bias Error), all in mm day^{-1}; **St.D.**: standard deviation, **Var.**: variance, **R.**: total range

General descriptive statistics was performed for the residues (ΔET_0) specifically calculated based on the comparison outlined above, but only in relation to Pan and PMF56 *(Table 7)*. The smallest MBE, i.e. systematic error compared to the measured pan data was shown by Mak and the S&W#2 with modified radiation balance calculation. It is however the consequence of the fact that the differences having high standard deviation and variance compensate each other because of their inverse signs. Therefore, despite the less correlation, these models provided a relatively small MBE, which also implies a larger proportion of non-systematic error.

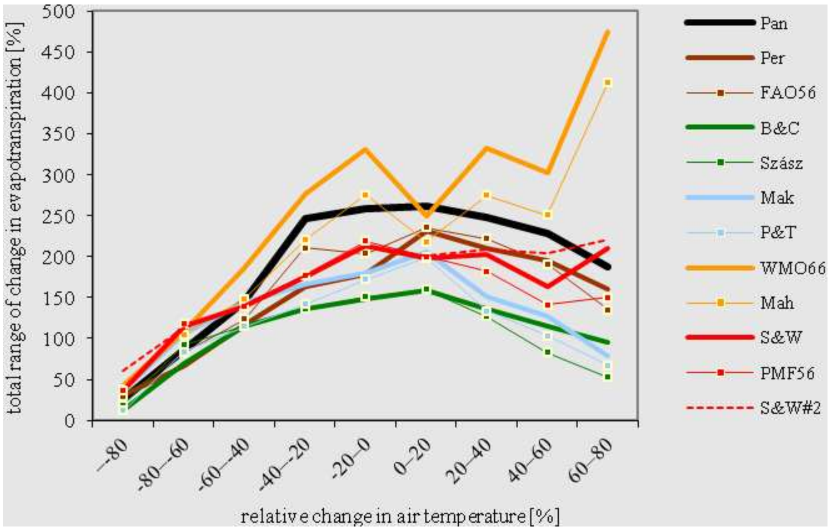
In comparison with the PMF56 model, the B&C and Mak models show the same features as the above, while S&W method provides a very similar result to the standard both in terms of its MBE and RMSE values. The real reason for this phenomenon is the similarity of the principal bases of these two methods. The error of the mentioned methods thus presumed mostly non-systematic.

3.2 Sensitivity analysis

In *Figure 2a*, the impact of temperature on the models and the measured 'Pan' data set is shown. The curve of average change (ΔET_0) of all models runs together in the –60 – +40% range, divergence can be seen above or below this range only. At the same time, the correlation between the input and output data changes is nearly linear. Total range (R) of the changes follows a typical span in most models *(Figure 2b)*. Small differences can be seen in case of input change is in the negative range, mostly peaking near the mean, then starting to decrease again with higher differences between the models. Nevertheless, the different behaviour of mass-transfer-based algorithms can be seen in this case, too, the total range of the output change continuously extends in these models. The lowest deviation of the two temperature-based (B&C, Szász) and the radiation-based (Mak, P&T) models is worth mentioning, as the model response to the change of T is the most stable in these methods.



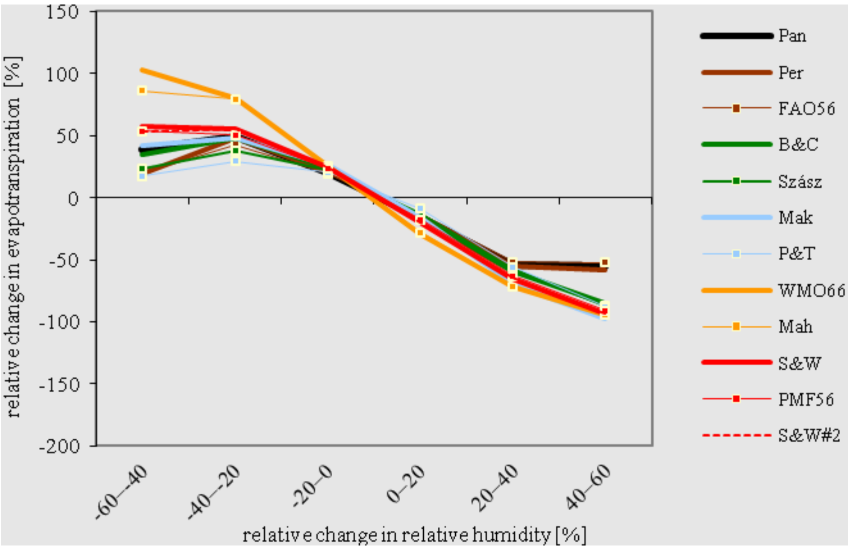
a)



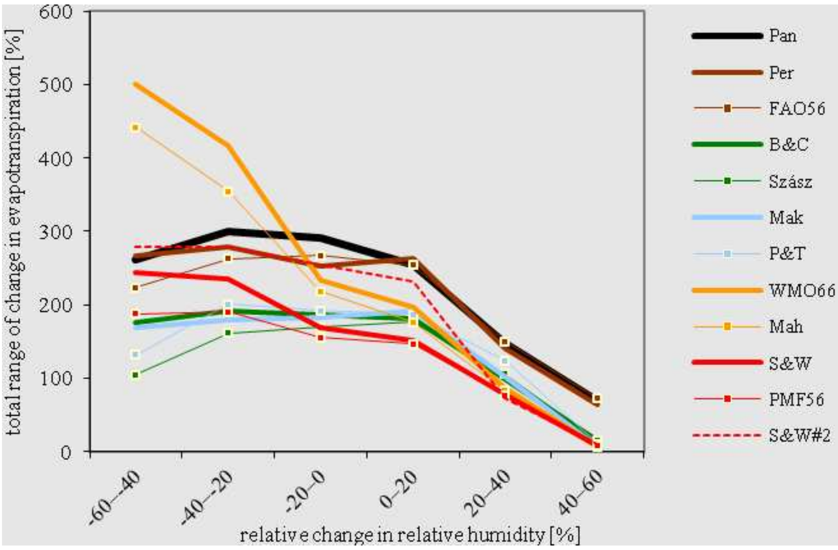
b)

In parameter changes 0% equals to 17.1 (lowest value: 1.3, highest value: 30.4) °C mean daily temperature. Meanings of abbreviations are given in chapter 2.2

Figure 2a–b. Impact of the change of temperature on model outputs



a)

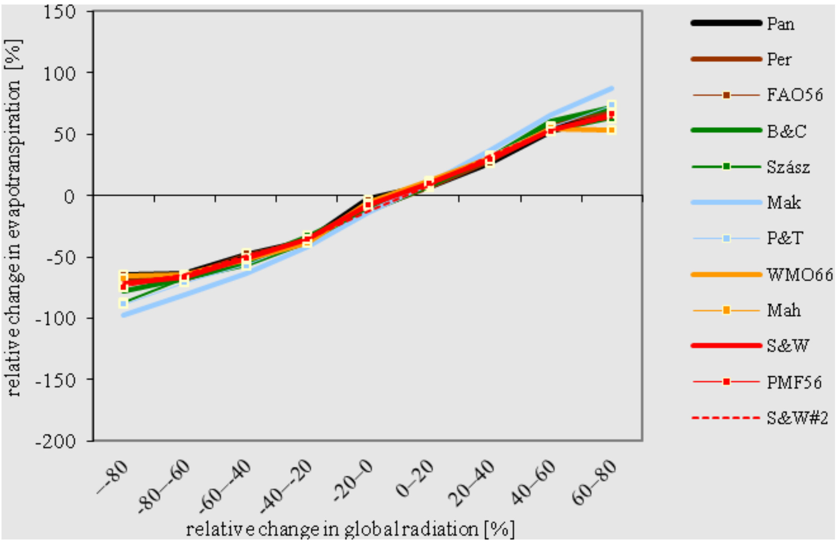


b)

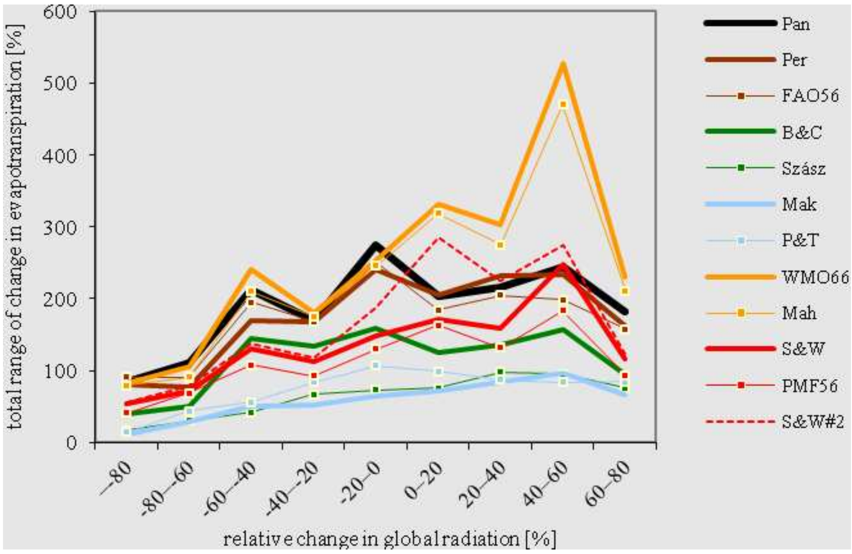
In parameter changes 0% equals to 67.9 (lowest value: 30.7, highest value: 99.0) % mean daily rel. humidity. Meanings of abbreviations are given in chapter 2.2

Figure 3a–b. Impact of the change of relative humidity on model outputs

Figure 3a shows the results of the sensitivity analyses performed in relation to relative humidity. Due to the set of RH values, the curve shapes are inverted, results of the analysis were still similar to temperature. The reason for the similarities is that relative humidity depends on temperature; therefore, the two parameters are related. Nevertheless, the correlation between the change in air humidity and the output changes can be best described with a logistic trend. It is a further difference that the models start to diverge after a 20% reduction of the parameter value. Also, as regards to the total range (*Figure 3b)*, Szász, S&W, Mak and PMF56 models resulted in the lowest values. Mass-transfer-based models proved to be of different behaviour again: their total range of change in output was above at 200% at -20% RH differences and below.



a)

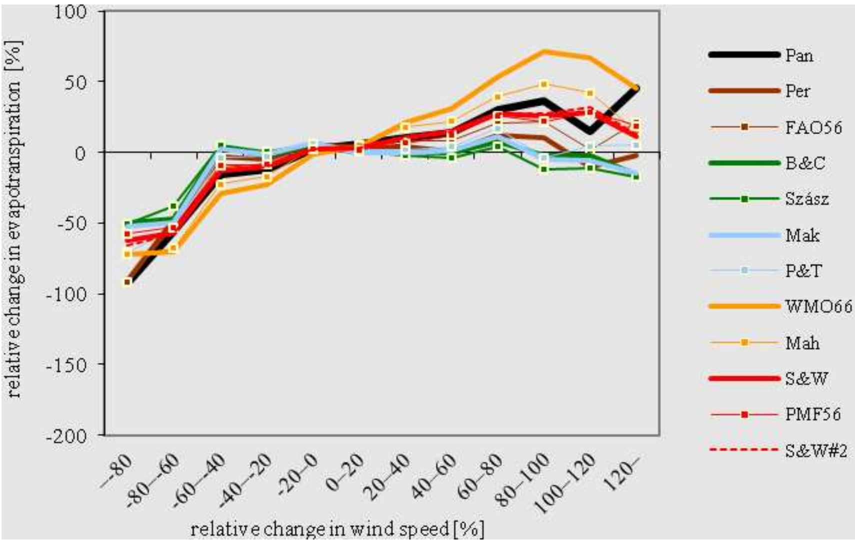


b)

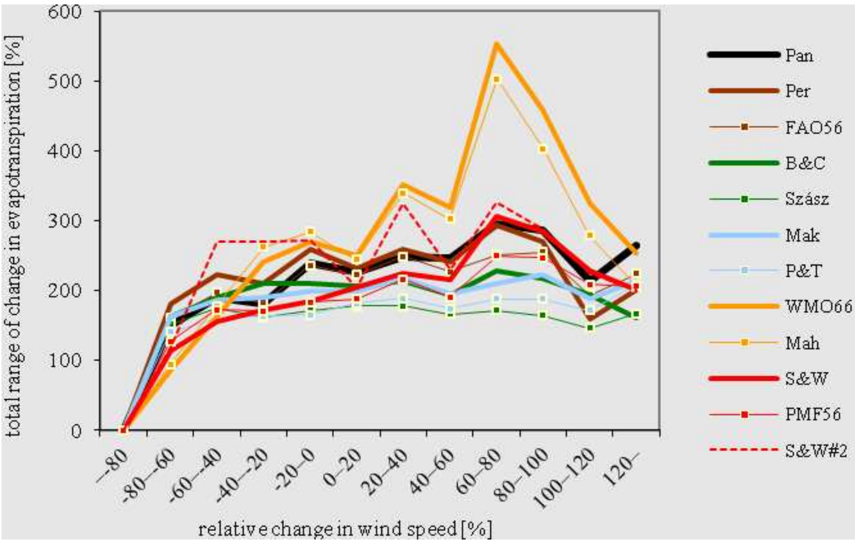
In parameter changes 0% equals to 17.1 (lowest value: 1.0, highest value: 30.3) MJ m^{-2} day^{-1} daily sum of global radiation. Meanings of abbreviations are given in chapter 2.2

Figure 4a–b. Impact of global radiation changes on the model outputs

The value of ET_0 estimated by the models linearly increases with the increase of global radiation (*Figure 4a*). Of the four meteorological parameters, it is the one where the correlation can be determined most clearly in relation to the models. The usual divergence can only be observed from around the ±80% levels. As regards the range of the output changes, mass-transfer-based models can be distinguished again, while the higher stability was observed in case of the Mak, Szász and P&T models. The benefits of using the latter model concerning the availability of the measured radiation data are also confirmed by other sources (Lu et al. 2005). The extent of total range is the lowest around the negative extreme value, above the mean value (17.1 MJ m^{-2} day^{-1}) it stagnates or slightly decreases at high uncertainty in the case of the majority of models (*Figure 4b*).



a)



b)

In parameter changes 0% equals to 2.8 (lowest value: 0, highest value: 9.3) m s^{-1} mean daily wind speed. Meanings of abbreviations are given in chapter 2.2

Figure 5a–b. Impact of wind speed change on the model outputs

Figure 5a shows ET response to change in wind speed. As opposed to the other parameters, there is not even a temporary linear correlation between the change dynamics of the parameter and the output in relation to wind. In this case, the correlation type is presumably logarithmic. On days with wind speed below the average (0.5–2.8 m s^{-1}) the models provide results with rather close correlation. Approximately above the level of –50% wind speed change (1.4 m s^{-1} and above), the extent of estimated evaporation abruptly increases in each model. After reaching the average value, the extent of evaporation keeps its level. It peaks mostly between 80–100% increases of wind speed (5.1–5.7 m s^{-1}), although 5 models do not show any increase notable. These models (Szász, P&T, B&C, Mak, Per) appear to be insensitive to any further stiffening of wind, as opposed to mass-transfer-based models. As regards the total range of the deviation (*Figure 5b)*, the same models are the steadiest (except for the Pereira model); thereby further strengthening their 'conservative' classification.

4 CONCLUSIONS

Based on monthly and yearly amounts of estimated ET_0, it was concluded that evaluation on the basis of seasonal sums is very sensitive to systematic differences between daily model results. Differences of the order of even several hundred millimetres can evolve during a growing season. Nevertheless, the highest sums were provided by the Blaney–Criddle, Penman–Monteith–FAO-56, Shuttleworth–Wallace and Makkink methods, while the lowest amounts were provided by the Pereira, FAO-56, WMO-1966 and Mahringer models.

On the basis of seasonal dynamics of the model outputs, the distinct behaviour of mass-transfer-based models (WMO-1966, Mahringer) and the sensitivity of pan-coefficient models (Pereira, FAO-56), temperature-based (Szász), and radiation-based models (Makkink and Priestley–Taylor) to the precipitation amounts could be detected.

Large fluctuation models with high R and St.D. values (Pan, B&C, mass-transfer based and combination-type methods) and 'steady' ones (pan coefficient-based, Szász and P&T methods) with less variability of outputs were identified. Furthermore, mass-transfer-based methods showed wide standard deviation and total range of the output data even in the case of relatively low ET_0 levels.

Based on the correlations between the model results, Pereira and FAO-56 models agreed the most to the pan evaporation measurements, while Shuttleworth-Wallace model showed the most similarity to the Penman–Monteith–FAO-56 method. As regards the systematic error, Makkink and Shuttleworth–Wallace model were the closest to pan evaporation, while Shuttleworth–Wallace, Blaney–Criddle and Makkink models were the closest to the Penman–Monteith method.

With the sensitivity analyses, two main groups were defined: the Szász, Makkink, Priestley–Taylor and Penman–Monteith–FAO-56 models can be considered steady, i.e. these methods responded with lower fluctuations to the changes of atmospheric variables. At the same time, WMO-1966, Mahringer, Shuttleworth–Wallace methods, the pan evaporation measurements and Pereira model are rather sensitive. These showed large magnitude and high range of changes in ET_0 as a response to the increase or decrease of the four main atmospheric inputs (temperature, air humidity, global radiation and wind).

In the light of these conclusions, Priestley–Taylor, Penman–Monteith–FAO-56, Shuttleworth–Wallace parameterized with alternative radiation balance, Szász and Makkink methods were found to be the best performing models for ET calculation. In order to perform properly accurate estimations, however, it is necessary to carry out further parameterization of each model in accordance with local circumstances.

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