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Evaluation of the applicability of potential evapotranspiration models in Hungary

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Abstract

One of the most challenging problems in hydrometeorology is the quantification of potential evapotranspiration (PET) rates. The aim of this study was to identify PET models that can reliably approximate the FAO Penman–Monteith reference evapotranspiration or available PET data provided by the Hungarian Meteorological Service (HungaroMet) for Hungary while requiring fewer meteorological input variables. Nevertheless, an understanding of PET values and trends can offer invaluable insights into the drought sensitivity of an area. We analysed the performance of 18 PET models for Hungary based on meteorological data from 2010 to 2022 and identified and ranked the most relevant ones. The PET values were calculated at 16 meteorological stations using different models and subsequently ranked according to six distinct statistical indicators. As a basis for comparison, data from the nearest pan-evaporation measuring station and FAO Penman-Monteith (FAO-PM) values were calculated. PET provided by HungaroMet was used as the reference potential evaporation value. Model performances were ranked on a 1–120 scale. Our results showed that the temperature-based Oudin model had the most accurate performance, but in general, the radiation-based models were the most reliable. The spatial distribution of the data indicates that the performance of the PET models is somewhat inferior in the eastern and western regions of the country in comparison to that observed in the central areas. Our results are likely applicable to the temperate zone of similar subhumid climates.

Keywords: potential evapotranspiration (PET), model performance, pan-evaporation, Hungary

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Introduction

Concepts for describing the rate of evaporation and evapotranspiration

Evapotranspiration (ET) is the combined process of evaporation from soil and open water surfaces, and transpiration from plants and other organisms. As such, ET represents a key link between the water and energy cycles and plays a central role in the hydrological balance. To describe ET more precisely, different terms have been introduced. Reference evapotranspiration (ET_0) refers to the evapotranspiration from a standardized reference surface and is widely used in hydrological, agricultural, and environmental studies. The Food and Agriculture Organization (FAO) Penman–Monteith equation (FAO-PM) is recommended as the standard method for estimating ET_0 under different climatic conditions. Potential evapotranspiration (PET) expresses the maximum evapotranspiration under the assumption of an unlimited water supply, independent of soil water storage. In contrast, actual evapotranspiration (AET) refers to the real amount

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of water evaporated and transpired under existing soil moisture conditions, which is generally less than or equal to PET.

Quantifying ET using both measurements and numerical models is a complex and arduous task and is regarded as one of the greatest challenges in hydrometeorology. This difficulty arises because ET is not a single physical quantity, but the result of a constantly changing interaction between the atmosphere, soil, water availability, vegetation, and meteorological drivers such as vapour pressure deficit. For instance, Breuer, H. and Ács, F. (2010) demonstrated that crop surface resistance strongly influences ET rates, with the highest variability observed in summer months in Hungary.

The models utilized for PET estimation can be classified into four categories: aerodynamic, temperature-based, radiation-based, and combination models. The distinction between these models is based on the type of input data required. Aerodynamic models consider mass transfer; nonetheless, their margins of error are rather high. Temperature-based models, such as Thornthwaite's method (Thornthwaite, C.W. 1931) are relatively straightforward to parameterize and are widely utilized in literature (Blaney, H.F. and Criddle, W.D. 1950; Baier, W. and Robertson, G.W. 1965; Kharrufa, N.S. 1985; Oudin, L. *et al.* 2005). Radiative models integrate empirical data and the radiative equation, which may result in varying degrees of applicability across different regions. Combination models use multiple meteorological parameters, with the FAO-PM equation being the most widely accepted method (Allen, R.G. *et al.* 1998). However, FAO-PM has a relatively high data demand, which often restricts its use in areas with limited observations.

PET models are validated using several approaches, such as lysimeters, scintillation methods (Xu, Z. *et al.* 2013), Bowen ratio method (Douglas, E.M. *et al.* 2009), or pan evaporation (Brouwer, C. and Heibloem, M. 1986). Yet, evaporation pans and evaporimeters reflect only site-specific conditions and are often scarce. Consequently, PET models based on meteorological inputs are required to ensure applicability across different climatic zones and land use types

Climate and environmental conditions in Hungary

In general, continental climates are prone to weather extremes, which may be further intensified by climate change. The climate of Hungary has also shown noticeable changes during the 20th century (Breuer, H. *et al.* 2017). The unwanted impacts of climate change, especially under continental and semi-arid climates, are further exacerbated by increasing evaporation due to increased temperatures. It is indicated by the decreasing length of winters and the increasing length of summer days. Winters in the Northern Hemisphere have shortened by an average of 20 days between 1976 and 2012, while summers were extended by 13 days (Kutta, E. and Hubbart, J.A. 2016).

Recent research confirms that seasonal dynamics across Europe are undergoing substantial shifts. In Central and Northern Europe, the thermal growing season has lengthened mainly due to earlier onset and only secondarily to later termination (Miś, F. and Tomczyk, A.M. 2025). At the same time, regional climate model projections indicate a marked prolongation of compound dry–hot seasons throughout Europe, primarily driven by rising temperatures and, thus, higher evaporative demand, while precipitation changes exert regionally opposing effects by amplifying the signal in the south and moderating it in the north (Lhotka, O. *et al.* 2023). Working within a climatic water balance (P−PET) framework and using the Oudin PET model, Lhotka, O. *et al.* (2023) emphasize that temperature- and radiation-based PET formulations are particularly relevant for assessing evaporative demand trends in mid-latitude continental climates. Collectively, these findings justify a detailed evaluation of low-input PET models under the data-limited but hydroclimatically sensitive conditions characteristic of Hungary.

Continental climates also pose a variety of challenges for agriculture, as droughts caused by periods of water deficit can alternate with large riverine floods and flash floods of increasing frequency. These two dichotomous abiotic hazards have the highest probability of occurrence in Hungary (Pirkhoffer, E. *et al.* 2009; Lóczy, D. 2010). To highlight these extremes, in Hungary, the years of 2010 and 2011 were the wettest (959 mm), and the driest (407.4 mm), respectively, between 1901 and 2014 (Schmeller, G. *et al.* 2022).

According to the data published in the UNCCD National Report (2022), ten years were affected by some level of drought between 2006 and 2021, in which at least 30 percent of Hungary was impacted. The total area affected by extreme drought was the highest in the years 2000, 2003, 2011, and 2022 (UNCCD, 2022). The increasing trend of annual evapotranspiration and drought in Hungary has been revealed by many authors (e.g. Blanka, V. *et al.* 2013; Mezősi, G. *et al.* 2016; Szabó, Sz. *et al.* 2019).

Numerous studies have evaluated PET models worldwide, e.g. for Germany and China (e.g. Bormann, H. 2011; Yang, Y. *et al.* 2021; Li, Z. *et al.* 2024), but, to our knowledge, no study has systematically compared models representing all four methodological categories for Hungary.

Anda, A. and co-authors investigated evaporation processes in shallow aquatic environments in the Lake Balaton and Kis-Balaton regions, with particular focus on the effects of littoral sediments and submerged macrophytes. Their studies demonstrated that these factors could enhance evaporation compared to standard Class A pan measurements and should be considered when estimating evaporation and evapotranspiration in shallow lakes and wetlands (Anda, A. *et al.* 2015, 2016, 2018a, b).

The current study aims at analysing the performance of 18 PET models for Hungary, not only in aquatic environments, but also to identify the most applicable models for Hungary.

The specific objectives of the current research were the following:

1. Ranking the accuracy of 18 PET models by statistical methods using pan-evaporation and FAO-PM, and reference PET calculated by the Hungarian Meteorological Service (hereafter HungaroMet) as reference.

2. Research for regularities in the spatial distribution of the top-three models.

3. Examination of the potential for replacing high-input models with lower-input models.

Material and methods

Study area

The topography of Hungary is mainly dominated by alluvial plains (the Little and Great Hungarian Plain) with low mountain areas in the west and the north. Hungary is dominated by a subhumid continental climate with marked Mediterranean influence from the south and oceanic influences from the west. Climatic conditions are far from homogeneous over the country with considerable differences in an east-west direction and between the mountainous and lowland areas. Recent studies of the Carpathian Region, including Hungary, identify distinct climatic zones and spatial gradients shaped by topography and regional position, reflecting differences between lowland plains and mountainous areas as well as east–west climatic variation (Szelepcsényi, Z. *et al.* 2014; Szabó, A.I. *et al.* 2021).

The 30-year mean annual precipitation totals range between 500 and 800 mm, with a maximum in May and June and a minimum from February to April. The mean annual temperature is around 9–13 °C with 13+ °C over the past years from 2018 on, similar to the global climatic trends. The prevailing wind direction is from the west and northwest in the majority of the country (Bihari, Z. *et al.* 2018).

Sources of meteorological and pan-evaporation data used in the research

Meteorological data for 16 stations (*Figure 1*) were obtained from the database of HungaroMet Zrt. Class A evaporation pan data series

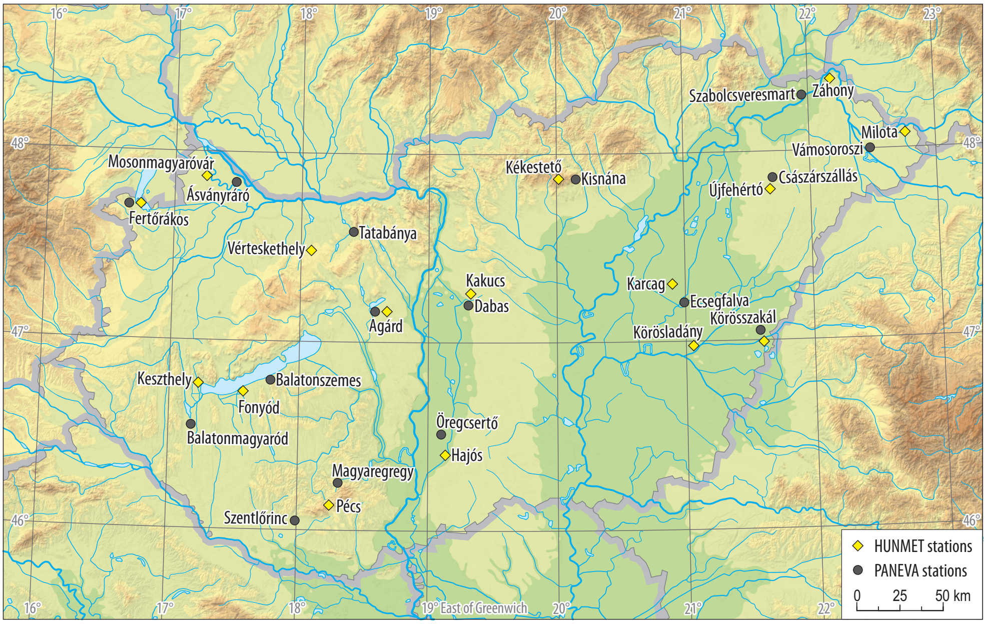

Fig. 1. Geographical location of the meteorological and pan-evaporation stations used.
Source: Authors' own elaboration.

(PANEVA) for 15 stations, used as a reference, were provided by the Hungarian General Directorate for Water Management for the period of 2010 to 2022. A total of 18 PET models (aerodynamic, temperature-based, radiation-based, and combination) were used for the calculation of PET (*Table 1*). The reference PET dataset is calculated by HungaroMet Zrt. (HUNMET) was used as a control data set.

Comparability of pan-evaporation data and PET

Pan-evaporation and PET are closely related, as both measure atmospheric demand for water loss, but they are not directly equivalent. Despite the high correlations between the two values, systematic biases exist. Pan evaporation often overestimates or underestimates PET depending on climate, season, and environmental conditions. The need for site-specific evaporation coefficients (K_p) and regular recalibration is emphasized to correct these biases and improve comparability (Mekoya, A. 2021).

The estimation of the K_p value is determined primarily by surface cover and micro-environmental factors (Allen, R.G. *et al.* 1998). To this end, GIS tools were utilised to estimate the K_p value for each pan evaporation station. Land cover information was derived from the CORINE Land Cover 2018 database (vector format, Europe-wide, version 2020_20u1, released in May 2020), provided by the European Environment Agency (EEA, 2020). For the present study, only the Hungarian subset was used (*Table 2*). To identify any potential differences, analyses were conducted using both raw pan-evaporation data and data adjusted with a K_p value (PANEVA_K).

Model ranking

To validate the numeric models, their results were compared with pan-evaporation data.

*Table 1. Potential evapotranspiration models used to calculate daily PET**

Type	Name of the PET model	Equation	Reference	Climate zone according to Köppen
Aerodynamic	Albrecht (ALBRCT)	$PET = (0.1005 + 0.297u_2) \times (e_s - e_a)$	Albrecht, F. 1950; Bormann, H. 2011.	Cfb, Cfa
	Brockamp-Wenner (BRWENR)	$PET = (0.543u_2^{0.456}) \times (e_s - e_a)$	Brockamp, B. and Wenner, H. 1963; Bormann, H. 2011.	Cfb
	Harbeck (HARBEC)	$PET = (0.0578u_8) \times (e_s - e_a) \times 25.4$	Harbeck, G.E. 1966; Singh, V.P. and Xu, C-Y. 1997.	Cfb, Dfb
	Rohwer (ROHWER)	$PET = 0.44 \times (1 + 0.27u_2) \times (e_s - e_a)$	Rohwer, C. 1931; Xu, C.Y. and Singh, V.P. 2002.	BSk, Dfa
Temperature-based	Baier-Robertson (BAROBR)	$PET = 0.157T_x + 0.158(T_x - T_n) + 0.109R_a - 5.39$	Baier, W. and Robertson, G.V. 1965.	Dfb, Cfb
	Hamon (HAMON)	$PET = \left(\frac{N}{12}\right)^2 \times \exp\left(\frac{T_a}{16}\right)$	Hamon, W.R. 1961; Oudin, L. *et al.* 2005.	Cfa, Cfb
	Romanenko (ROMANE)	$PET = 4.5 \times \left(1 + \frac{T_a}{25}\right)^2 \times \left(1 - \frac{e_a}{e_s}\right)$	Romanenko, V.A. 1961.	Dfb, Dfa
	Schendel (SCHEND)	$PET = 16\frac{T_a}{RH}$	Schendel, U. 1967; Bormann, H. 2011.	Cfb, Dfb
	Oudin (OUDIN)	$\begin{cases} PET = (\lambda\rho)^{-1} \times R_a\left(\frac{T_a + 5}{100}\right) & T_a > -5°C \\ PET = 0 & T_a \le -5°C \end{cases}$	Oudin, L. *et al.* 2005.	Cfb, Dfb, Dfc
	Reference PET (HUNMET)	$PET = 0.74 \times (e_s - e_a)^{0.7} + \left(1 + \frac{T_a}{273}\right)^{4.8}$	Antal, E. 1968; Antal, E. and Kozmáné T.E. 1968.	PET-based on climatology of Hungary

Table 1. Continued

Type	Name of the PET model	Equation	Reference	Climate zone according to Köppen
Radiation-based	Turc (TURC)	$\begin{cases} PET = 0.013 \times \left(\frac{T_a}{T_a + 15}\right) \times (R_s + 50) \times \left(1 + \frac{50 - RH}{70}\right) & RH < 50\% \\ PET = 0.013 \times \left(\frac{T_a}{T_a + 15}\right) \times (R_s + 50) & RH \geq 50\% \end{cases}$	Turc, L. 1955, 1961; Lu, J. *et al.* 2005.	Cfb, Cfa
	Jensen-Haise (JENHAI)	$PET = 25.4 \times (0.014T_a - 0.37) \times (0.000673R_s)$	Jensen, M.E. and Haise, H.R. 1963; Zheng, H. *et al.* 2017.	BSk, BSh
	Stephens-Stewart (STESTW)	$PET = 25.4 \times (0.0082T_a - 0.19) \times \left(\frac{R_s}{1500}\right)$	Stephens, J.C. and Stewart, E.H. 1963; Zheng, H. *et al.* 2017.	BSk
	Hargreaves (HARGRE)	$PET = 0.0135R_s \times \frac{T_a + 17.8}{\lambda}$	Hargreaves, G.H. 1975.	BWh, BSh, BSk
	Milly-Dunne (MILDUN)	$PET = \frac{0.8 \times (R_n - G)}{\lambda}$	Milly, P.C.D. and Dunne, K.A. 2016.	All climates
	Priestley-Taylor (PRITAY)	$PET = \alpha \times \frac{\Delta}{\Delta + \gamma} \times \frac{(R_n - G)}{\lambda}$	Priestley, C.H.B. and Taylor, R.J. 1972.	Af, Cfa, Cfb
Combination	Rijtema (RIJTEM)	$PET = \frac{\frac{\Delta(R_n - G)}{\lambda} + \gamma r u_2^{0.75} \times (e_s - e_a)}{\Delta + \gamma}$	Rijtema, P.E. 1965; Bormann, H. 2011.	Cfb, Cfa
	Wright-Jensen (WRIJEN)	$PET = \frac{\Delta(R_n - \mathrm{G})}{\lambda(\Delta + \gamma)} + \frac{\gamma}{\Delta + \gamma} \times 2.63 \times (0.75 + 0.993u_2) \times (e_s - e_a)$	Jensen, M.E. and Wright, J.L. 1978; Allen, R.G. and Pruitt, W.O. 1986.	BSk, BSh
	Penman (PENMAN)	$PET = \frac{\Delta(R_n - \mathrm{G})}{\lambda(\Delta + \gamma)} + \frac{\gamma}{\Delta + \gamma} \times \frac{6.43(1 + 0.536u_2) \times (e_s - e_a)}{\lambda}$	Penman, H.L. 1948; Shuttleworth, W.J. 1992.	All climates

Table 1. Continued

PET	Potential evapotranspiration	mm/day	–
u_2, u_8	Wind speed at 2 m and 8 m, respectively	m/s	–
e_s, e_a	Sturation and actual vapour pressure, respectively	kPa	hPa for Albrecht, F., and for Brockamp, B. and Wenner, H. inch Hg for Harbeck, G.E. mm Hg for Rohwer, C.
T_a	Average daily air temperature	°C	°F for Jensen, M.E. and Haise, H.R., and for Stephens, J.C. and Stewart, E.H.
T_n, T_x	Daily minimum and maximum air temperature, respectively	°C	–
R_a	Extraterrestrial radiation	MJ/m²/day	–
N	Hours of sunshine	h	–
RH	Relative humidity	%	–
λ	Latent heat of vaporisation	MJ/kg	2.45
ϱ	Water density	kg/m³	–
R_s	Incident solar radiation	MJ/m²/day	cal/cm²/day for Turc, L., for Jensen, M.E. and Haise, H.R., and for Stephens, J.C. and Stewart, E.H.
R_n	Net radiation	MJ/m²/day	–
G	Soil heat flux density	MJ/m²/day	can be considered as 0 in daily time steps
α	Priestley-Taylor parameter	–	1.26
Δ	Slope vapour pressure curve	kPa/°C	–
γ	Psychrometric constant	kPa/°C	–

*After Yang, Y. *et al.* 2021.

Potential Evapotranspiration (PET) and pan evaporation are two different concepts, although they are closely related and often used together to estimate water loss. Generally, PET represents the maximum water loss from the surface with *abundant water*, combining both evaporation from soil and transpiration from plants. Pan evaporation does not include plant transpiration. It is purely physical evaporation, which is highly affected by the heat storage and thermal properties of the metal pan, making it behave differently from natural water bodies or vegetation. Nevertheless, Class A pan measurements are widely used to estimate the evaporation of natural water bodies, providing a practical approach when direct measurements of reference evapotranspiration (ET_0) are not available. For example, Anda, A. *et al.* (2018a) applied Class A pans to quantify evaporation from a natural water body in the Keszthely region of Hungary, accounting for factors such as vegetation and sediment cover. Their results were compared with FAO-56 PM-based ET_0 estimates, demonstrating that pan-derived measurements, when properly adjusted, can provide reliable site-specific evaporation estimates. This highlights the continued relevance of pan-evaporation-based approaches for assessing water balance in natural environments, particularly where standard meteorological data may be limited.

Pan-evaporation stations are approximately evenly distributed across Hungary. The Körösszakál pan-evaporation dataset was used for both the Körösszakál and Körösladány modelled PET data, evaporation data from only 16 pan evaporation stations were used for analysis. For validation purposes, the geographically nearest weather station was selected for each pan evaporation station (see *Table 2*). Pan evaporation data was only available for the period of 1 April to 31 October each year, hereafter denoted as $\text{PET}_{\text{A-O}}$. Hence, weather data was only used for the same period of each year.

Calculated data was mapped with QGIS 3.38.0 software environment. Statistical data was processed using MS Excel, and MATLAB R2024b. The statistical indicators employed for the evaluation of the 18 PET models were as follows:

Table 2. Meteorological stations with the corresponding pan-evaporation stations used and the CORINE Land Cover classes with the K_p values

Pan-evaporation measurement station	Nearest HungaroMet weather station	CORINE class	K_p value
Agárd	Agárd	Intertidal flats	0.55
Fertőrákos	Fertőrákos	Road and rail networks and associated land	0.60
Balatonszemes	Fonyód		0.60
Öregcsertő	Hajós		0.65
Dabas	Kakucs		0.65
Ecsegfalva	Karcag		0.65
Kisnána	Kékestető		0.65
Balatonmagyaród	Keszthely, Tanyakereszt	Discontinuous urban fabric	0.70
Körösszakál	Körösladány		0.70
Körösszakál	Körösszakál	Vineyards	0.72
Vámosoroszi	Milota	Road and rail networks and associated land	0.65
Ásványráró	Mosonmagyaróvár		0.65
Magyaregregy/Szentlőrinc	Pécs, Egyetem	Salt marshes	0.55
Császárszállás	Újfehértó	Intertidal flats	0.55
Tatabánya	Vérteskethely	Industrial and commercial units	0.70
Szabolcsveresmart	Záhony	Road and rail networks and associated land	0.65

1. Mean Absolute Error (MAE) in mm/day;
2. Mean Percentage Error (MPE), dimensionless;
3. Mean Bias Deviation (MBD) in mm/day;
4. Mean Bias Error (MBE) in mm/day;
5. Nash-Sutcliffe Model Efficiency Coefficient (NSE), dimensionless;
6. Coefficient of Determination (R^2), dimensionless.

All statistics are calculated using daily PET estimates, and annual aggregations are derived from these daily values when needed. A cumulative scoring system has been applied, for PET model evaluation and show that comparing models with reference PET/ET_0 data is a common, established methodology in hydrological literature (see references: Bormann, H. 2011; Yang, Y. *et al.* 2021; Li, Z. *et al.* 2024, and Toušková, J. *et al.* 2025). All models were ranked according to each statistical method at each station. The maximum score for each statistical indicator was, thus, 19. The models that scored most frequently in positions 1-3, 4-6, and 7-9 at each station received an additional 6, 3, and 1 correction points, respectively. The correction points are representative of the range of use of the models. This gives a higher score to models that are applicable to a larger geographic area of the country. The maximum score a model could obtain was 120. Always, the results of comparisons with the PANEVA_K dataset were used in the ranking system; the HUNMET dataset was only used as a reference (e.g. for R^2 values).

Results

Model comparison without the K_p coefficient

The average calculated PET_{A-O} values of the 18 PET models range between 285 and 1516 mm over the period of 2010 to 2022 (*Figure 2*). The lowest value was calculated for the Harbeck method, while the highest value was obtained for the Jensen-Haise model. The overall average value was 805.5 mm, whereas the median value was 766.7 mm. The temperature- and radiation-based methods demonstrated the most optimal performance, and the aerodynamic models exhibited the least favourable model performance. For Hungarian conditions, particularly in the Cfb, Cfa, Dfb, and Dfa Köppen climate zones (see *Table 1*), several PET models are considered suitable, including Albrecht, Brockamp-Wenner, Harbeck, Baier-Robertson, Hamon, Romanenko, Schendel, Oudin, Turc, Rijtema, Milly-Dunne, Priestley-Taylor, and Penman. Models such as Rohwer, Jensen-Haise, and Wright-Jensen may be partially applicable under specific conditions, while Stephens-Stewart and Hargreaves should be used with caution due to their limited suitability for the region. The mean annual PANEVA value was 682.67 mm/year, whereas the mean annual PANEVA_K value was 436.06 mm/year.

The MAE values were more favourable in the central two-thirds of the country, particularly for data calculated with radiation-based models. The temperature-based Oudin and the combination-type Rijtema models yielded favourable MAE values. With regard to MAE, the most optimal fit was yielded at Vérteskethely station, calculated by the Oudin model (MAE = 0.571 mm/day). As the country approached the eastern and western extremes, the MAE values of the models exhibited a general deterioration. Given the intrinsic nature of MAE as an indicator, it does not indicate the direction of deviations, thus, under- or overestimation cannot be determined from it.

Due to its ability to detect under- and overestimation, MPE values are also plotted on a map for the top-three ranked PET models (compared with PANEVA and PANEVA_K, too) (*Figure 3*). The MPE results showed substantial variability among the evaluated methods and stations. Several models produced large positive MPE values, indicating systematic overestimation of evapotranspiration. In particular, the Jensen-Haise model frequently exhibited the largest positive MPE values across many stations, suggesting a consistent tendency to overestimate evapotranspiration. Similarly, Rijtema, Wright-Jensen were mostly overestimators. Of the models, the Harbeck

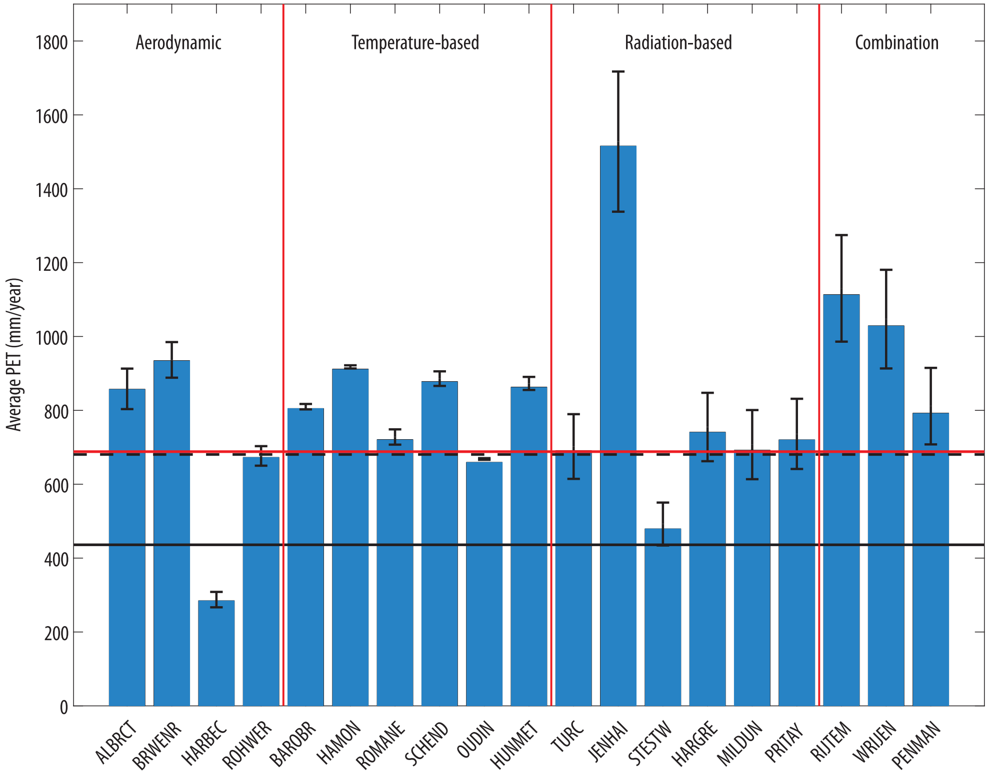

Fig. 2. The mean country-averaged $PET_{A\text{-}O}$ values (columns) for the 18 models and HUNMET reference PET (2010–2022 data). The black error bars show the total annual standard deviation for the different methods. The black dashed line marks the average annual PANEVA values (overlapped with FAO-PM reference ET_0), the continuous black line marks the average annual PANEVA_K values and red line represents FAO-PM reference ET_0 between April and October for the same years. *Source:* Authors' own elaboration.

and at some stations Stephens-Stewart models were shown to be net underestimators. Radiation-based models also showed elevated positive MPE values at several locations. In contrast, certain temperature-based approaches, including the Oudin and Turc models, often yielded lower MPE magnitudes, indicating a more balanced estimation behaviour at multiple stations. Among the spatial specificities, it is notable that the Baier-Robertson, Harbeck, Stephens-Stewart, Romanenko and Rohwer models underestimated the $PET_{A\text{-}O}$ values (columns) for the most elevated Kékestető station, while all other stations showed overestimated values. Oudin, in both cases, slightly or generally overestimated the PET values. The Stephens-Stewart (MPE = 2.8%) model showed the smallest percentage point deviations. In the case of STESTW model underestimation only occurred in Vérteskethely and Kékestető stations. On the other hand HARBEC estimated well PANEVA_K, generally with lower values, except for Mosonmagyaróvár and Fonyód stations. Of the models, Jensen-Haise has the worst error of 244.2 percent. It was examined whether there is any correlation between the best performing models at each station and the Péczely climate class at the station location, but no evidence of a relationship was found.

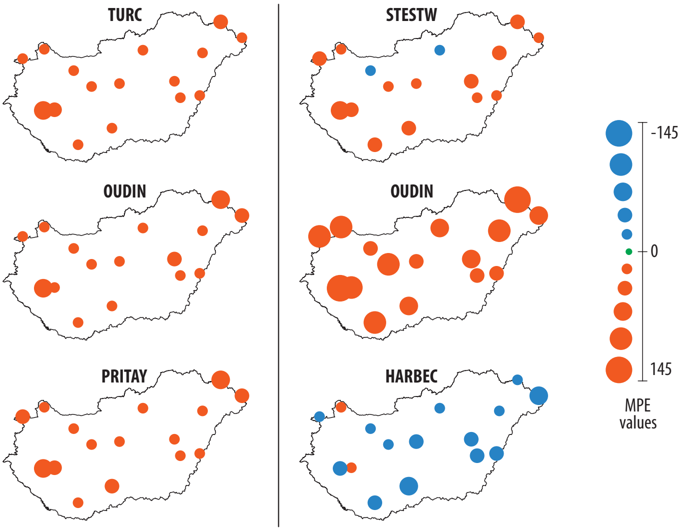

Fig. 3. Mean percentage error (MPE) of the top three PET models relative to pan-evaporation, without the pan coefficient applied (left) and with the K_pan coefficient applied (right), for each station.
Source: Authors' own elaboration.

The MBD and MBE values confirmed the under- and overestimation trends indicated by the MPE. In the analysed dataset, the results of these two indicators showed very similar patterns across the evaluated stations and models. Several methods exhibited positive bias values, indicating a general tendency toward overestimation of evapotranspiration. In particular, the Jensen-Haise model frequently produced relatively large positive MBD and MBE values at multiple stations, reflecting consistent overestimation. Radiation-based methods also displayed positive bias at several locations, although the magnitude of these deviations varied among stations. In contrast, some models occasionally produced negative MBD and MBE values, indicating underestimation of evapotranspiration under certain climatic conditions. The underestimation of the Harbeck and Stephens-Stewart models also emerged for these indicators. In contrast, the Oudin model exhibited both positive and negative deviations, although the magnitude of the bias remained relatively small, with MBD values ranging between -15 and +15.

The NSE indicator is a commonly calculated indicator in hydrological model calculations, which is why it was used in this study. Most models produced NSE values in the range of approximately 0.3–0.7, indicating acceptable but variable agreement with the reference dataset. The highest NSE values were typically obtained for several temperature-based and combination-type models, including Oudin, Turc, and Rijtema at multiple stations. In contrast, lower NSE values were frequently observed for models with strong systematic bias, particularly the Jensen-Haise method.. Furthermore, negative NSE values were also observed with considerable frequency in this latter group, which serves as an indicator of particularly high inaccuracy.

When plotting the data by station on boxplot diagrams (*Figure 4*), it is visible that the median of the PANEVA and HUNMET data series differed only slightly at the highest Pécs and Záhony. Moderate differences are noticed in stations: Keszthely and Fonyód. The range of the PET models analysed is also narrower at these stations, which are considered to be the extremes, than the coun-

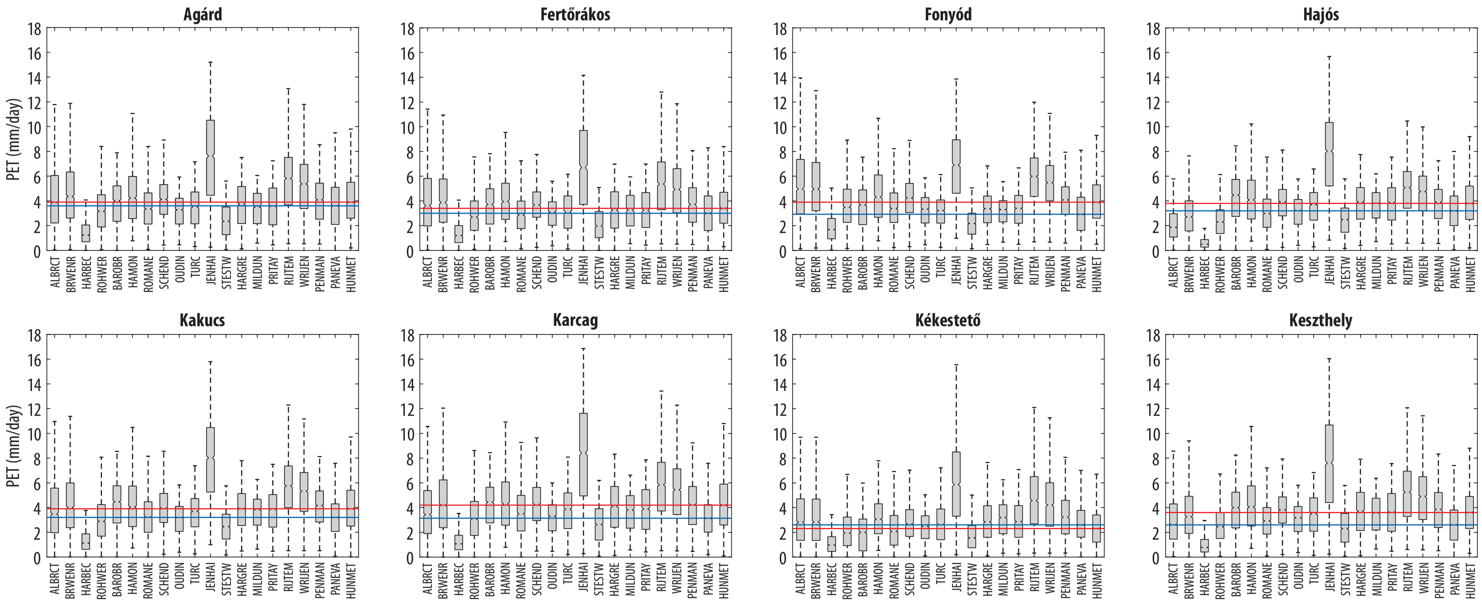

Fig. 4. Daily modelled $PET_{A\text{-}O}$ values for for the years between 2010 and 2022. The purple line represents the median of the PANEVA dataset and the orange line the median of the HUNMET dataset. *Source:* Authors' own elaboration.

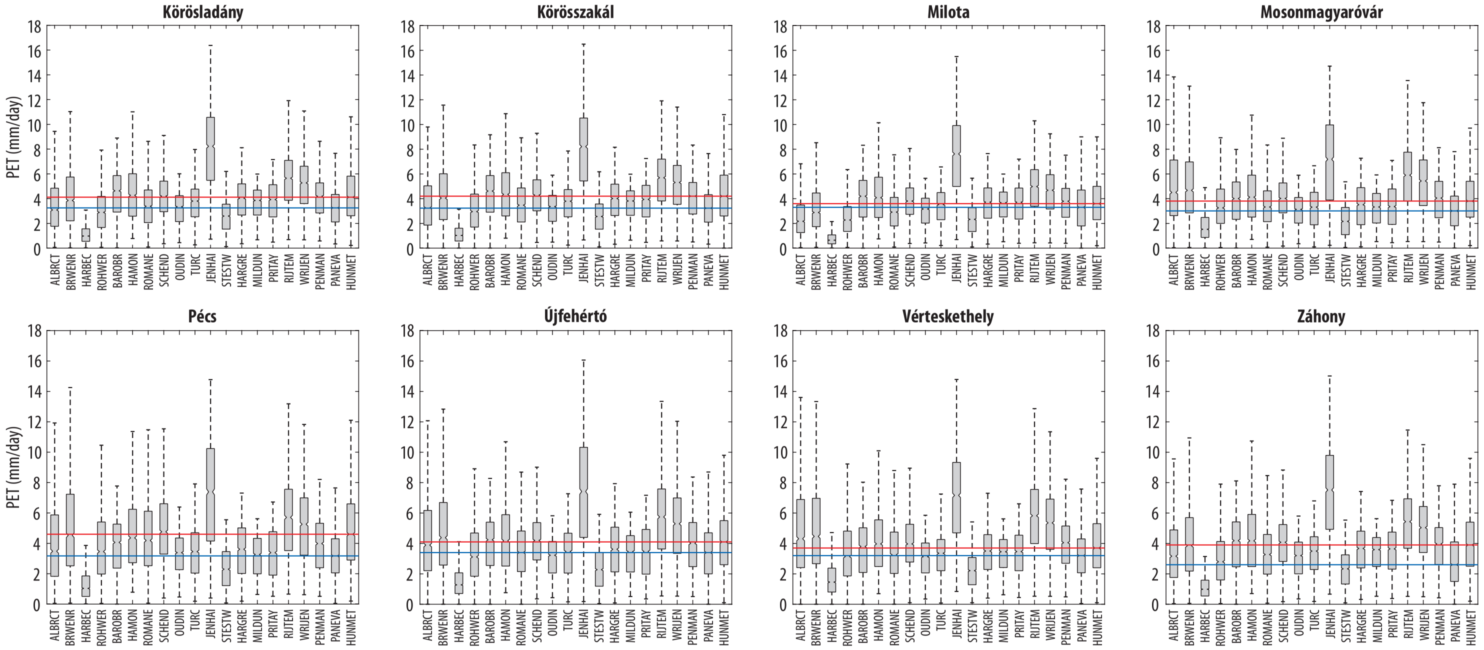

Fig. 4. Continued.

try average. The HARBEC and STESTW model consistently produced the smallest range across the stations, but also consistently behaved as a strong underestimator. Temperature-based models (e.g. Oudin, Hargreaves) generally show narrower IQRs and more stable distributions, with medians often close to the HUNMET reference PET and occasionally the pan evaporation reference. In contrast, several radiation-based and combination models display wider IQRs and longer whiskers, indicating greater variability and more frequent extreme values. The Jensen-Haise model frequently exhibits higher medians and extended upper whiskers, suggesting a tendency to overestimate PET. Overall, temperature-based models tend to produce more balanced estimates, while some radiation-based approaches show greater spread and uncertainty.

Most models achieved moderate correlations with the reference data (PANEVA), generally ranging between approximately 0.3 and 0.75 depending on the station and method. Higher R^2 values were commonly associated with models that also demonstrated higher NSE values, indicating stronger linear agreement with observed evapotranspiration. However, even models with relatively high R^2 values occasionally exhibited noticeable bias, highlighting the importance of evaluating multiple statistical indicators simultaneously when assessing model performance.

Country aggregated ranking

The 18 PET models were ranked according to the six statistical methods (MAE, MPE, MBD, MBE, NSE, R^2). When the country aggregated statistical data, the four PET methods were ranked: the temperature-based models performed the best, and the aerodynamic models performed the most poorly. In terms of the individual PET models the highest scores were achieved by the Turc (110 points), Oudin (109 points), and Priestley-Taylor (94 points) models (*Figure 5*, left). For the MAE, NSE and R^2 indicators, the temperature-based models scored highest (except for Jensen-Haise), and for the MBD and MBE indicators, the radiation-based models achieved the highest scores. The aerodynamic models had the lowest scores for all statistical indicators (except ROHWER). The group with the highest number of correction points was the radiation-based models, suggesting that this type of model gives valid $PET_{A\text{-}O}$ values over the widest area. Although the combination models did not perform well on average, the Penman model was ranked in sixth place. The aerodynamic models showed the lowest accuracy, with the Albrecht model being the most inaccurate.

Overall, the results demonstrate that the performance of empirical evapotranspiration estimation models varies substantially across both stations and model types. Temperature-based and combination-type approaches frequently provided balanced performance across several evaluation metrics, whereas some radiation-based models tended to produce larger systematic deviations at certain locations. These findings emphasize the importance of regional calibration and careful model selection when applying empirical evapotranspiration estimation methods under varying climatic conditions.

In the analysis using the PANEVA_K data set (*Figure 5*, right), significant changes can also be seen in the ranking. The average scores of the temperature-based, radiation-based, and aerodynamic models decreased slightly, while the combined models scored below median points. In both cases, radiation-based models dominate the top eight places. The average performance of the aerodynamic models is mainly due to the HARBEC and ROHWER model's rise in the rankings.

In the event that a potential substitution of the most optimal PET model is warranted, for instance, due to the absence of required data, alternative models must be selected. For the majority of Hungary, HUNMET reference PET can be optimally substituted by OUDIN, SCHEND, TURC, BAROBR, and HAMON models.

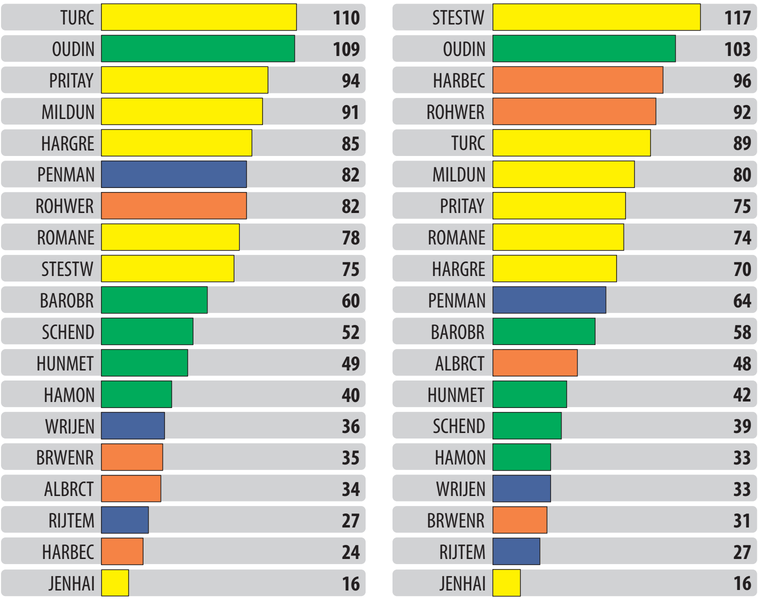

Fig. 5. Scores of each PET model based on the ranking system of this study (left: PANEVA, right: PANEVA_K). Yellow colours represent radiation-based methods, green for temperature-based methods, orange denote aerodynamic models and blue used to present combination methods. *Source:* Authors' own elaboration.

Changes in results using the K_p value

The results of the analysis show differences depending on whether the PANEVA or PANEVA_K data series is used for comparison. When using the PANEVA_K data series, the performance of the RIJTEM, STESTW, and PRITAY models also shows a statistically significant ($p < 0.05$) improvement. When using the PANEVA data set, the OUDIN model, which shows high performance, also improves, but in this case, we cannot observe a significant improvement ($p = 0.423$). At the same time, the PENMAN, WRIJEN, and TURC models show significantly worse reliability when using PANEVA_K.

A spatial analysis of the models reveals that the smallest differences in MPE values occur at the Kékestető, Vérteskethely, Hajós, Pécs, and Agárd stations when using the two bases. The largest differences are found at the Záhony, Mosonmagyaróvár, Keszthely, and Fonyód stations.The use of the pan-coefficient worsened the MPE values by an average of +38 percentage points in the annual aggregate results. It was also observed that the reliability of the model improved in proportion to the increase in altitude above sea level compared to the PANEVA_K data series.

The pan-coefficient recommended by the FAO reduced accuracy in nearly 80 percent of cases. Most of the models examined show a more accurate fit without K_p. The introduction of the correction caused a general overestimation and systematic biases.

Discussion

Varga, Gy. *et al.* (2018) have demonstrated that, on average, the amount of actual evapotranspiration in the annual water balance of Hungary is 85.9 percent of the annual precipitation sum. The dominant period of precipitation in the country occurs between May and October, which coincides with the period of pan-evaporation (Anda, A. *et al.* 2018b). This precipitation accounts for 68–70 percent of the 500–800 mm annual precipitation (Bihari, Z. *et al.* 2018).

A similar study was conducted in China by Li, Z. *et al.* (2024). Due to its vast geographic extent, China is represented by a multitude of climatic zones. In the temperate continental zone, the Penman model was found to be the most optimal, while the aerodynamic-based Rohwer and temperature-based Romanenko models also demonstrated satisfactory performance. In general, the combination models yielded the most precise results. In the case of Hungary, the radiation-based Turc model showed the best accuracy, followed by the temperature-based Oudin model in matching the pan-evaporation data series in most of the 16 meteorological stations, while the radiation-based Stephens-Stewart model showed the best fit with the pan-evaporation data series. This discrepancy between China and Hungary may be attributed to the fact that the climatic conditions in continental China tend to be more arid than those in Hungary, particularly in terms of relative humidity. The discrepancy between the models that demonstrate optimal performance in Hungary and those that exhibit superior results in the Chinese temperate continental zone may be attributed to the contrasting conditions of vapour pressure deficit and relative humidity. Therefore, vapour pressure deficit exerts a considerable influence on all models that function effectively in Hungary.

Yang, Y. *et al.* (2021) calculated PET with eighteen different empirical models for the major climatic regions of China, and they concluded that the combination models performed the best followed by the radiation-based models, whereas the temperature-based models obtained the worst performance.

The current study compares calculated $PET_{A\text{-}O}$ with the data of the closest pan-evaporation stations. However, PET is influenced by multiple parameters, hence the closest station may be inappropriate for direct comparison of calculated and measured data. For example, when a pan-evaporation station is located in a downwind direction from the weather station of interest, then it may be more adequate to compare it to the closest meteorological station in an upwind direction. It is also noteworthy that, as previously stated, the calculation of PET with models represents one of the most challenging tasks in meteorology, given the diverse range of inputs required. Evaporation is the result of a multitude of interacting effects. It can be posited that the meteorological and environmental influences that result in PET form a complex system that is not amenable to analysis using a single statistical indicator. It is recommended that as many statistical parameters as possible be examined, which is why a complex scoring system was used for the evaluation in this study. If only the R^2 and MPE values were considered, the performance of some PET models in our study would appear to be rather inaccurate. However, the MAE, MBD, and MBE values demonstrated high accuracy even for the worst-performing models in the point system.

Bormann, H. (2011) also studied the efficacy of the four main PET methods on the data obtained from six weather stations of distinctly different climates in Germany. The results demonstrated that models validated for the same climatological and geographical conditions should be selected when determining the appropriate PET model. Moreover, it has been verified that in regions where the effects of climate change and warming are more pronounced, the reliability of PET models is diminished, necessitating their correction.

Seiller, G. and Anctil, F. (2016) also confirmed that the selection of the right PET model is key in the simulated climate scenarios, as PET has a strong impact on each of the simulated global climate change outputs.

The selection of relevant meteorological stations for pan-evaporation stations has also been a pivotal issue in the present study. Although the nearest station might initially appear to be a suitable option, this approach neglects the influence of orographic characteristics, along with microclimatic (e.g.

prevailing wind direction) and microenvironmental (e.g. land use, aspect, and relief) variables. Similarly, the spatial linear interpolation and the Kriging method should be used with caution, as the numerous variables that influence the PET value make it challenging to obtain precise results through these methods.

Conclusions

The quantification of PET represents one of the most challenging problems in hydrometeorology. The majority of the models are only accurate under specific meteorological and microenvironmental conditions and are only valid for relatively small areas. It is, thus, necessary to employ PET models that have been previously validated for the specific geographic and micro- and mesoclimatic conditions. The aim of this study was to select the most appropriate model for Hungary. In order to achieve this, the applicability of 18 PET models in Hungary was investigated. The HungaroMet reference PET is calculated based on Antal, E. (1968) (cited in Antal, E. and Kozmáné Tóth, E. 1980), and it has been used as a reference potential evaporation method. Investigating already known formulae formerly used for the Carpathian Basin was not the goal of the present study. On the other hand, some may argue that omitting the already validated Carpathian Basin-specific models could be seen as a limitation. We also consider that future research should aim to integrate these models into the continuation of the present study.

Our results also demonstrate that models with high input requirements can be replaced by models with lower input requirements under appropriate conditions. This also means that monitoring points where the quality and availability of sensors are limited can be included in the countrywide monitoring network. The PM equation currently used is internationally recognised as a reliable and accurate model, but its input requirements are very high and its calculation is complicated. Most of the standard meteorological variables, such as air temperature, relative humidity, solar radiation, and wind speed, are generally available. However, the FAO Penman–Monteith equation also requires additional parameters (for instance, soil heat flux, surface resistance, psychrometric constant, etc.), which may not be readily obtained at all sites, particularly in complex environments such as forested areas, highlighting the continued relevance of simplified, site-specific PET models. On the other hand, lower-input models remain useful for historical analyses or simplified computations.

The accuracy of the Turc and Oudin model, which has been repeatedly positively evaluated in our study, is similar to that of the PM method, although it only requires daily mean temperature and extraterrestrial radiation as inputs. The measurement of temperature is cost-effective and can be measured at basically any meteorological station, while radiation can be calculated mathematically based on the geographic location of the measurement location. Models that have been calculated to produce accurate overall values may be appropriately parameterised by the application of numerical methods. These methods shall then be adapted to reflect the geographically specific climatic, orographic, and other environmental-meteorological characteristics of the site in which they are to be examined.

The key findings of the study:

- Countrywide, the radiation-based models were the most accurate, but in our ranking, the temperature-based Oudin model has also scored high. This may be due to the inclusion of extraterrestrial radiation as a coefficient in the Oudin equation. Presumably, in the continental climate of Hungary, temperature alone is not a sufficient proxy for the calculation of $PET_{A\text{-}O}$.
- The combination models demonstrated the least effective performance in this study. This does not imply that these models are inherently unsuitable for estimating PET; however, it is evident that they are not consistently applicable for tracking climate dynamics in Hungary, which is not free of extremes.

- The spatial distribution demonstrates that PET models are less effective in the easternmost and westernmost regions of the country. One potential explanation for this phenomenon is the uneven distribution of rainfall across the country. The western and eastern edges of the country exhibit higher mean annual rainfall totals than the central region.
- Our study has demonstrated that, due to its high reliability, the widely used but very high-input PM equation can be replaced by lower-input models (e.g. Oudin, Turc) in input-deficient cases without a notable loss of accuracy in the PET calculation. Pan-evaporation is not always the most appropriate reference because of frequent measurement errors, and it is not necessarily measurable at all periods of the year. The correlation was also more pronounced when comparing the models with PM values calculated by HungaroMet than when comparing with pan-evaporation. Nevertheless, this can be attributed to the fact that, as with the models under examination, PM is also a mathematical method, which evidently exhibits a stronger correlation with other mathematical methods than with a method based on observation and measurement. It is anticipated that this study will provide a valuable basis for the agricultural sector and meteorological research in the quantification of potential evapotranspiration as an indicator of drought risk. It should be emphasized that our results are well applicable in sub-humid continental climates similar to Hungary, during the period April to October.
- The HUNMET reference PET values showed a correlation of 0.87 with the reference evapotranspiration (FAO-PM) when annual sums were considered. In comparison, some empirical models, such as Turc and Stephens–Stewart, yielded higher coefficients of determination ($R^2 = 0.94$ and 0.96, respectively) at the annual scale. This suggests that certain investigated PET models may provide comparable or even closer agreement with the reference evapotranspiration than the currently applied HUNMET reference PET in terms of annual totals. However, it should be emphasized that long-term analyses were not performed in this study, and the daily structure and variability of PET were not examined in detail. Therefore, it is possible that under specific conditions, the HUNMET approach may perform better at finer temporal resolutions. Consequently, further investigations, particularly focusing on long-term behaviour and daily variability, would be necessary before drawing definitive conclusions regarding the replacement of the current operational method.
- The application and evaluation of different PET calculation methods may become increasingly relevant under changing climatic conditions. Although Hungary currently falls under the Dfa/Dfb climate categories, Beck, H.E. *et al.* (2018) showed that by the end of the century, it is likely to shift toward Cfa/Cfb conditions. Consequently, PET calculations may not be fully applicable at present, but they could gain significance for future climate assessments and become a valuable tool in climatological studies.
- The application of the pan coefficient in the complex evaluation system systematically rearranges the ranking. Radiation- and temperature-based models remain powerful in both cases. When using raw pan-evaporation (PANEVA) data, the OUDIN, TURC, and PRITAY models are the most reliable, while when using K_p-corrected data series (PANEVA_K), the STESTW, OUDIN, and HARBEC models offer greater reliability.

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