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Regional calibration of the Hargreaves model for estimation of reference evapotranspiration

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Abstract: Estimation of reference evapotranspiration values is crucial in climatological and hydrological research, agricultural engineering, and irrigation design. The Penman-Monteith method, endorsed by the Food and Agriculture Organization (FAO) of the United Nations and numerous research studies, is widely regarded as the gold standard. However, its extensive data requirements limit its applicability in regions with sparse meteorological networks or limited measurement capabilities. The Hargreaves method, which requires only basic air temperature inputs, offers an alternative solution.

The aims of this study were to calibrate the Hargreaves model for Central European climate conditions, considering altitudinal dependence, and to evaluate the temporal stability of the model parameters. In the first part of the research, we regionalized the Hargreaves coefficients using a curve-fitting method to ensure the best accuracy across 60 climatological stations in Slovakia. The regionalization of the Hargreaves coefficient improved accuracy by 10.1%, reducing the weighted absolute percentage error (WAPE) to 17.9%. However, our results showed that the accuracy of the modified Hargreaves model decreased with the increasing altitude of a climatological station. Incorporating altitude into the Hargreaves equation significantly improved model accuracy in stations at higher altitudes, providing a consistent level of accuracy across all climatological stations, regardless of their location and altitude. The results also indicated that the optimal model coefficient values change over time, showing a decreasing trend of –0.5 for the B coefficient and –0.1 for the C coefficient between the periods 1981–2000 and 2001–2020. Although regionalizing the Hargreaves model coefficients for local conditions can achieve good model performance, the model's accuracy is not stable over time. Thus, periodic validation of the model is necessary for short-term applications.

Keywords: Reference evapotranspiration; Hargreaves equation; Temporal stability of model parameters.

INTRODUCTION

Evapotranspiration is a key process in the hydrological cycle that influences the volume of the surface runoff, occurrences of droughts, water storage, and other climatological variables. By influencing water storage volumes and runoff dynamics, it directly impacts the distribution and availability of water (Szolgay et al., 2023). The FAO56 Penman-Monteith method is widely recommended for calculating reference evapotranspiration by many authors and authorities (Allen et al., 1998; Djaman et al., 2019; Jensen and Allen, 2016). One of the most discussed problems with the Penman-Monteith method is the number of required climatic variables, which raises questions about its applicability when the availability of data is limited. Identifying alternative methods that yield results closely matching those of the Penman-Monteith method based on available climatic data becomes imperative.

Previous research suggests that several models perform well in calculating reference evapotranspiration (Benli et al., 2010; Chauhan and Shrivastava, 2009; Islam and Alam, 2021; López-Urrea et al., 2006; Považanová et al., 2023). However, it is necessary to evaluate the performance of these models in local conditions and make modifications to improve their accuracy if necessary.

The Hargreaves method for calculating reference evapotranspiration requires only the minimum and maximum air temperatures, along with geographical data. Calibration of the coefficient in the Hargreaves equation has been used in much research for improving the accuracy of the Hargreaves model for local conditions. Subburayan et al. (2011) proposed the exponent value 0.653 for the hot and humid locations in the State of Tamil Nadu in India. Niranjan and Nandagiri (2021) estimated individual values of the Hargreaves equation coefficient for different climatic zones in India, significantly improving this model's accuracy. Maestre-Valero et al. (2013) suggested the optimal value of a coefficient for 66 automatic Spanish stations, ranging between 0.00227 and 0.00362, with a mean value of 0.0028. This approach was also used in Bogawski and Bednorz (2014), where the authors suggested the use of the Hargreaves method with calibrated constants for local conditions with values of 0.0004 and the value of the exponent of 0.724 to reach a good level of accuracy for stations in Poland. In addition, other research has been aimed at calibrating the Hargreaves coefficients without implementing the altitude of the stations in the equation (Gafurov et al., 2018; Lujano et al., 2023). The results from the research mentioned above seem to suggest that the values of the parameters for the Hargreaves equation range significantly in different climate zones. In previous studies the researchers have implemented continuous meteorological parameters for the Hargreaves equation, such as wind speed (Al-Asadi et al., 2023), radiation data (Jia et al., 2016), precipitation totals (Droogers and Allen, 2002) or the relative humidity and sun hours (Valiantzas, 2015). We would like to mention that the model's performance is important in the evaluation by taking into account not only the mean deviation of the results, but also the constant performance in each region and altitude. Ravazzani et al. (2012) focused on a modification of the Hargreaves equation for 51 meteorological stations in Alpine regions (Italy and Switzerland). The results show, that the implementation of a station´s altitude showed significant reduction in ET_0 errors.

Previous research has shown that the parameters of the Hargreaves model differ in various climatological conditions, in different elevation zones, and also in the seasons of the year, i.e., Gentilucci et al. (2021). The regional calibration of the model and temporal stability of model parameters in different climatological conditions is however still not well understood.

The main aim of this study is (1) to calibrate the Hargreaves model for Central Europe climate conditions, (2) to explore altitudinal dependence of model parameters and propose a new regional calibration framework (3) to evaluate temporal stability of the model parameters across different elevation zones in Slovakia.

METHODS

Calibration of the Hagreaves model

The original Hargreaves model estimates reference evapotranspiration ET_0 using following equation:

$$ET_0 = A\left(\frac{T_{max}+T_{min}}{2}+B\right)\left(T_{max}-T_{min}\right)^C R_a D \qquad (1)$$

where R_a is the extraterrestrial radiation [MJ m^{-2} d^{-1}]; T_{max} is the maximum air temperature [°C]; T_{min} is the minimum air temperature [°C]. The original Hargreaves equation is composed of four coefficients (A = 0.0023, B = 17.8, C = 0.5, and D = 0.408), which have been adapted by many researchers to better suit local conditions and enhance modelling accuracy. In our study, we calibrated three model parameters: A, B, and C, while the parameter D, used in the original Hargreaves methodology for unit conversion purposes, was fixed at its original value (D = 0.408). The model parameters were calibrated to fit the reference evapotranspiration estimated according to the Penman-Monteith model ($ET_{0,PM}$) (Allen et al., 1998):

$$ET_{0,PM} = \frac{0.408\Delta\left(R_N - G\right) + \Upsilon\frac{900}{T+273}u_2 + \left(e_s - e_a\right)}{\Delta + \Upsilon\left(1+0.34U_2\right)} \qquad (2)$$

where: $ET_{0,PM}$ is the daily reference evapotranspiration [mm day^{-1}]; R_N is the daily net radiation at the crop surface [MJ m^{-2} day^{-1}]; G is the daily soil heat flux density [MJ m^{-2} day^{-1}]; T is the mean daily air temperature at 2 m height [°C]; u_2 is the mean daily wind speed at 2 m height [m s^{-1}]; e_s is the mean daily saturation vapour pressure [kPa]; e_a is the actual vapour pressure [kPa]; D is the slope vapour pressure curve [kPa °C^{-1}]; Υ is the psychrometric constant [kPa C^{-1}].

The model parameters have been estimated using the Imfit Model class fitting method (Newville et al., 2014). The calibration objective function is minimising the weighted absolute percentage error (*WAPE*), estimated as:

$$WAPE = \frac{1}{n}\frac{\sum_{i=1}^{n}\left|O_i - M_i\right|}{\sum_{i=1}^{n}\left|O_i\right|}\times 100\% \qquad (3)$$

where: n is the number of measurements; O_i is the mean annual reference evapotranspiration according the Penman model, and M_i is the modelled mean annual reference evapotranpiration according Hargreaves model. We determined the *WAPE* values by comparing the modelled daily ET_0 time series from the Hargreaves model with the reference Penman-Monteith daily ET_0 time series.

We have calibrated the Hargreaves model using 3 variants:

1) **Variant 1** calibrates a regional model by minimizing the Weighted Absolute Percentage Error (WAPE) using measurements from all climate stations in the study region. In the station-specific model form, the model coefficients were calibrated individually at each climate station using a curve fitting method. For each station, we estimated the model parameters A, B, and C to ensure the best model accuracy.

2) **Variant 2** involves the calibration of general model parameters suitable for all climatological stations, denoted as $ET_{0,MODIF1}$. This variant is used to investigate the relationship between model parameters (individually calibrated at climate stations) and the altitude of the climate stations.

3) **Variant 3** represents an elevation-based Hargreaves model, denoted as $ET_{0,MODIF2}$, which incorporates elevation dependence using the following linear formula:

$$ET_0 = A\left(\frac{T_{max}+T_{min}}{2}+B\right)\left(T_{max}-T_{min}\right)^C R_a\, 0.408\left(\beta H+\alpha\right) \qquad (4)$$

where A, B, and C parameters are taken from Variant 2, and H is the altitude of the station. The slope α and intercept β are parameters of the regression between the altitude of the station and the slopes of the linear relationship between the station-specific mean Penman-Monteith $ET_{0,PM}$ and Hargreaves ET_0 values. The intercept β, along with the B and C parameters, were calibrated in the final step of the analysis using the curve fitting method to improve the model's accuracy.

Validation

For process of validation we used daily climatological data from nine independent climatological stations covering the period 1981–2020 (Fig. 1). The reference evapotranspiration estimated by modified Hargreaves model has been compared with Penman-Monteith reference ET_0 using the *WAPE* and Pearson correlation coefficient R:

$$R = \frac{\sum\left(M_i - \bar{M}\right)\left(O_i - \bar{O}\right)}{\sqrt{\sum\left(M_i - \bar{M}\right)^2 \sum\left(O_i - \bar{O}\right)^2}} \qquad (5)$$

where: $\bar{O}$ is the mean of the reference values and $\bar{M}$ is the mean of the modelled values. The slope of the trend in the parameter values we determined by the nonparametric Sen's slope estimator. Model accuracy was evaluated in each station individually from daily timeseries of ET_0 values.

We also verified the performance of our proposed model by comparing it with the results from the original Hargreaves model (labelled as Hargr.; A = 0.0023, B = 17.8, C = 0.5, and D = 0.408) and three widely used modifications of the Hargreaves model, which are labelled as M1 (Droogers and Allen, 2002), M2 (Berti et al., 2014) and M3 (Trajkovic and Kolakovic, 2009). This approach demonstrates how the performance of our model is improved compared to earlier modifications.

Assessment of temporal stability of model parameters

The temporal stability of model parameters has been evaluated by comparing calibrated Hargreaves model in individual climate stations in three different time periods (1981–2000, 2001–2020 and whole period 1981–2020). The differences were assessed using the bias of optimal model coefficients between periods and WAPE assessment. Additionally, we determined the slope of changes in optimal coefficient values over time using Sen's slope estimator.

DATA

The reference evapotranspiration has been estimated and compared at 69 climate stations in Slovakia (Fig. 1). The stations are situated at altitudes ranging from 100 to 2005 meters above sea level (m a.s.l.). We selected 60 stations that have more than 50% coverage of actual sunshine duration data for the period spanning 1981 to 2020 for model calibration. The meteorological variable data was obtained from the database of the Slovak Hydrometeorological Institute (SHMI). This wide range of altitudes enables the consideration of altitude-dependent variations in climatic factors, which is crucial for accurately estimating evapotranspiration across diverse landscapes in Slovakia. The stations are strategically situated to capture a range of morphological and climatic conditions prevalent in Slovakia. This diversity is essential for assessing the method's performance under different environmental contexts and to ensuring its robustness and reliability across varied landscapes of Central European region. By selecting stations based on these criteria, the study aims to develop a modified Hargreaves method that accurately accounts for the local climatic nuances of Slovakia, thereby enhancing the precision of reference evapotranspiration estimations crucial for various agricultural and water management applications in the region.

RESULTS

Calibration of the Hargreaves model at individual climate stations

Optimal stational values of Hargreaves coefficients we determined separately for each climatological station, using curve fitting method. Process of curve fitting we realised multiple times for each coefficient separately, using new values of other coefficients from previous iteration.

We set the allowed range of the coefficient values, to prevent noninterpretable results, only a small amount of the stations had the optimal parameter values out of the range allowed. This approach can be used because no significant relationship was identified between parameter values and the altitude of the station (Fig. 2). Therefore, the exclusion of the coefficient values with a more pronounced deviation from the mean does not cause a decrease in accuracy for a station with a certain altitude.

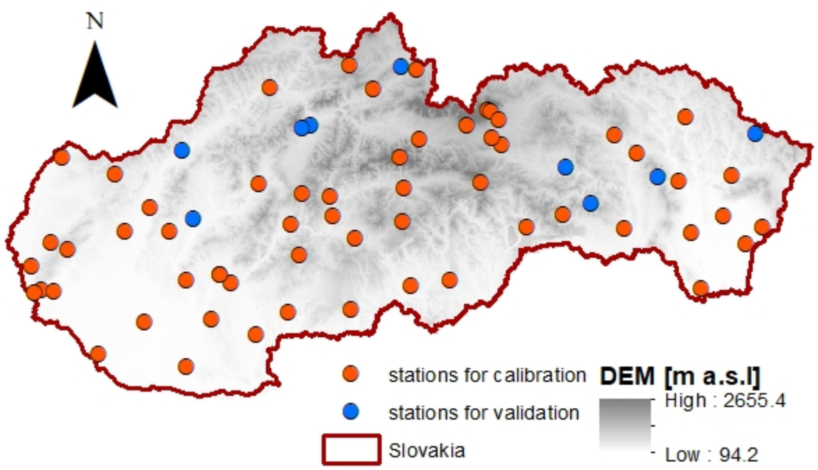

Fig. 1. Topography of Slovakia and localization of the climatological stations. Red and blue points represent stations used for Hargreaves model calibration and validation, respectively.

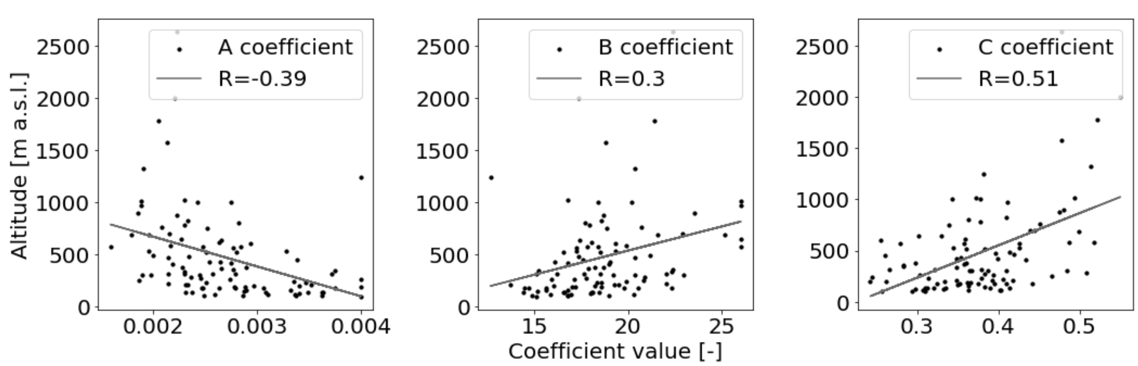

Fig. 2. Relationship between the calibrated parameter values of Hargreaves model (Variant 1, Eq. 1) and altitude of the climatological stations.

The values of the *A* coefficient varies from 0.0016 to 0.004 [–] with a mean value of 0.27[–] and a median of 0.26[–]. The *B* coefficient values ranged from 12.65 to 26 [–] with mean of 18.7 and median of 18.4[–], *C* coefficient values varied from 0.24 to 0.55[–], with a mean value of 0.38[–] and a median of the values 0.37[–]. Using of the specific coefficient values for each station provided a mean WAPE of 18.7%. There was not any identified spatial pattern of the coefficient values.

Calibration of general model parameters

The general values of Hargreaves coefficients were determined as one value for all the stations examined. The systematic minimalization of mean WAPE for the stations showed, that the optimal values of the coefficients, which decrease the mean WAPE of the stations to the minimal value are not the same as the mean and median of the stational coefficient. The mean $ET_{0,\ MODIF.1}$ WAPE for all the stations, considered independently by their altitude is 17.9%, ranging from 14.5% to 46.3% values. The best fitted of the *A* coefficient was determined to be 0.0029 [–], the value of the *B* coefficient of 19.7[–] and the *C* coefficient of 0.4 [–] (Fig. 3).

Using these generalized coefficient values in $ET_{0,\ MODIF.1}$ equation with daily data for a station with an altitude lower than 1000 m a.s.l., model reached a mean *WAPE* of 16.6%, ranging from 14 .5 to 19.1% through the stations. The mean *WAPE* of the original Hargreaves model for stations with an altitude lower than 1000 m a.s.l. was 17.3%; however, the maximum *WAPE* of the station was 21.7%. Mean $ET_{0,\ MODIF.1}$ WAPE for all the stations (independently in their altitude) is 17.9%, ranging between 14.5 and 46.3%. The deviations of purposed modified equation are in strong positive linear relationship with altitude of the station, i.e., *R* = 0.92. These findings also indicate that the Hargreaves model's coefficients modified for local conditions, don't provide good performance across various altitudes. The results indicated, that the deviations are reduced by considering the altitude in the model.

Several modifications of the Hargreaves considering the altitude of the station have been proposed in past. Results from one of them are also used in the comparison of Hargreaves modifications accuracy (Fig. 5); however, this method does not provide sufficient accuracy for the stations selected in our case study.

Calibration of the regional Hargreaves model using elevation dependence

We have proposed a new modification considering the impact of the changing climatological conditions with the altitude of a station. We expressed a linear relationship between the daily values of FAO56 P-M ET_0 and $ET_{0,\ MODIF.1}$ values modelled using our proposed coefficients by slope and intercept individually for each station; the results of the methods shown strong linear relationship with a mean *R* of 0.91. The station mean of the regression intercept is 0.224. We also identified a linear relationship between altitude of the station and the slopes of the linear relationship between the station-specific mean Penman-Monteith ET_0 and Hargreaves ET_0 values. This positive relationship is characterized by a very small slope of –0.0002 and an intercept of 0.977 (Fig. 4).

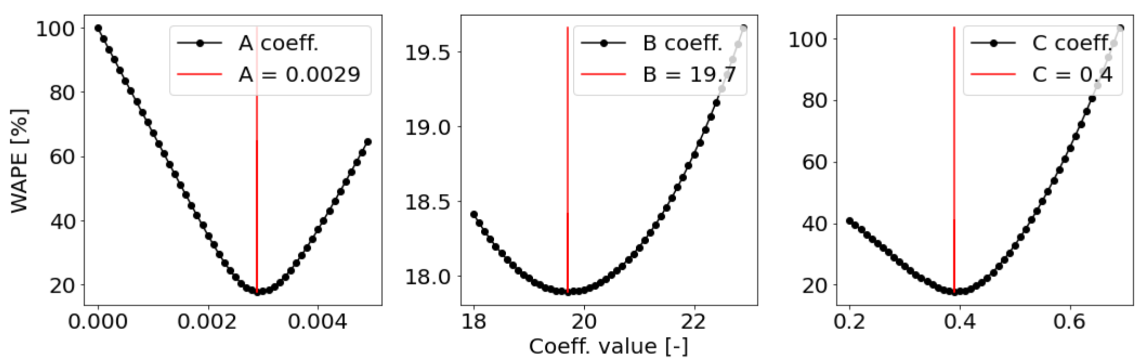

Fig. 3. Calibration of the general Hargreaves model (Variant 2) for 60 climate stations in Slovakia.

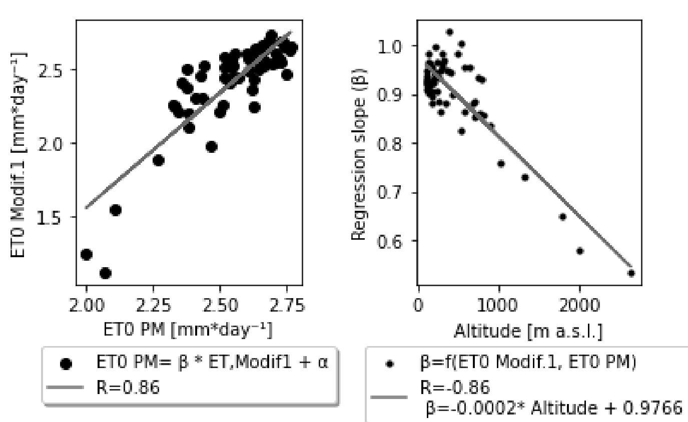

Fig. 4. The left panel shows agreement between FAO56 $ET_{0,PM}$ (Eq. 2) and the results from the modified $ET_{0,\ MODIF.1}$ equation (Variant 2). The right panel displays the linear relationship between the slope of the regression at the stations and the altitude of the climate stations.

Hinshaw (2002) noted, that a linear equation can be used as a calibration equation in a case, when the calibration curves have a relatively narrow range, which was also detected in our results. The FAO56 methodology recommends calibrating the Hargreaves equation using a linear relationship, either through regression analysis or visual fitting. We therefore used this characteristic of linear relationships presented above for the calibration of our first proposed Hargreaves modification and examined the impact of the new coefficient values to the accuracy of the method at various altitudes. The coefficients, which did not provide a better performance of the model were excluded from the equation; the coefficients which had a positive impact on the model's performance (including *B* and *C* coefficients) were calibrated separately by curve fitting method.

Our new proposed modification of the Hargreaves model, which also considers the altitude of the station, has the form:

$$ET_{0,\ MODIF.2} = 0.0029\left(\frac{T_{max}+T_{min}}{2}+21.27\right)\left(T_{max}-T_{min}\right)^{0.39} \times R_a 0.408\left(0.00014H+0.97\right) \quad (6)$$

where H is the altitude of the station [m a.s.l.].

Our proposed modification of the Hargreaves equation $ET_{0,\ MODIF.2}$ brings a significant improvement in the amplitude of *WAPE* values over stations (Fig. 7), where the standard deviation of *WAPE* in the model without considering altitude was 5.29 mm day^{-1} (Fig. 5), our proposed model $ET_{0,\ MODIF.2}$ provides standard deviation of *WAPE* values in stations 2.45 mm day^{-1}. The proposed model *WAPE* values ranged from 14.3% to 27.4% and also provide a decrease in the station's mean WAPE (17.4%). This is a very important improvement for future use of the model in hydrological or climatological modelling, because this model provides a consistent level of accuracy across all the climatological stations of Slovakia, regardless of their location and altitude.

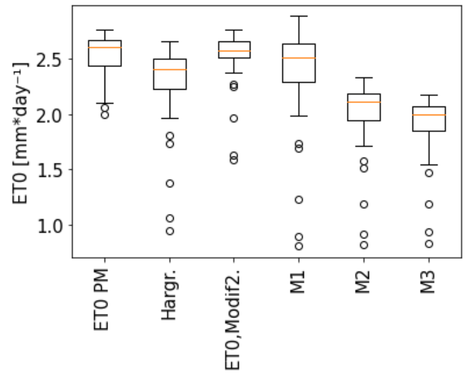

Fig. 5. Distribution of the mean stational ET_0 values estimated by various methodology [mm day^{-1}].

The Pearson correlation coefficient between the reference ET_0 FAO56 P-M dataset and the results of our proposed Hargreaves modification $ET_{0,\ MODIF.2}$ indicate a good linear correlation (Fig. 6), with R of 0.96 [–] for the daily data, R = 0.99 [–] in a monthly totals and R of 0.89 [–] in yearly totals.

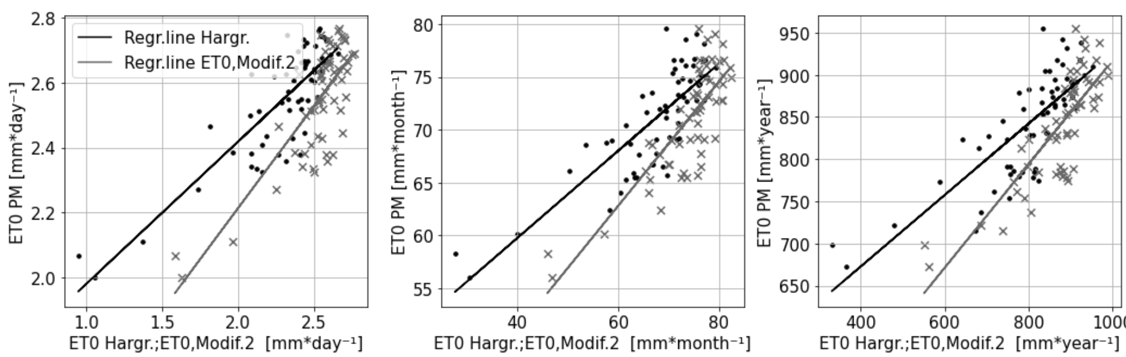

Fig. 6. Linear correlation between the reference $ET_{0,PM}$ results and the original Hargreaves (Hargr., marked with o) and modified Hargreaves $ET_{0,\ MODIF.2}$ (marked with x) results, shown for daily, monthly, and yearly temporal resolutions.

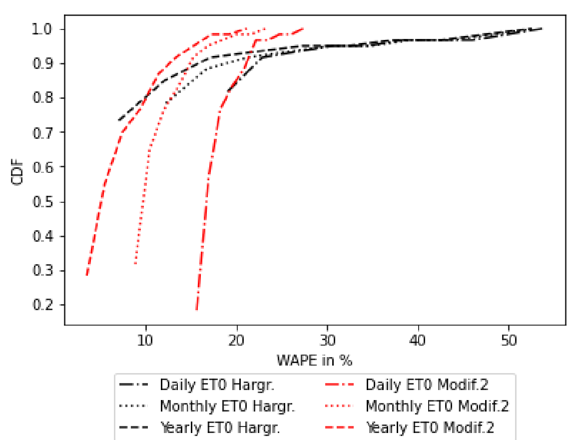

Fig. 7. Cumulative distribution function of the original Hargreaves and modified Hargreaves equation *WAPE* [%] in daily, monthly and yearly temporal resolutions.

The yearly distribution of the mean $ET_{0,PM}$, Hargreaves (Hargr.), and modified Hargreaves $ET_{0,\ MODIF.2}$ values (Fig. 8) show that the proposed modification of Hargreaves equation tends to underestimate ET_0 values in the spring and overestimate ET values from July to December.

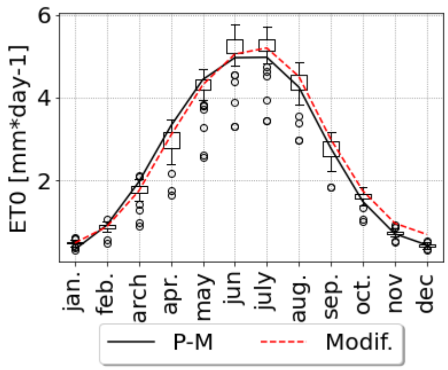

Fig. 8. Yearly distribution of mean $ET_{0,PM}$ and modified Hargreaves $ET_{0,\ MODIF.2}$ values

Validation of the model

For validation of the proposed method's accuracy, we used data from nine climatological stations (Fig. 1). We compared the accuracy of the Hargreaves equation, our proposed modification of the Hargreaves equation (Eq. 6), and also three selected Hargreaves modifications. We selected these equations based on previous research, where these methods were commonly used. The analyses also include previous versions of Hargreaves modifications that consider the altitude of the stations and precipitation totals.

The results of the validation show, that the modified Hargreaves model $ET_{0,\ MODIF.2}$ involving the altitude, provides consistent accuracy across the various altitude of the stations (Fig. 9). Nevertheless, the original Hargreaves model and also the other models compared show a huge deviation in stations with higher altitude, the results of our proposed Hargreaves modification (Eq. 6) are consistent over various altitudes. Also, the mean values of $ET_{0,\ MODIF.2}$ in stations showed a good correlation with the reference FAO56 values.

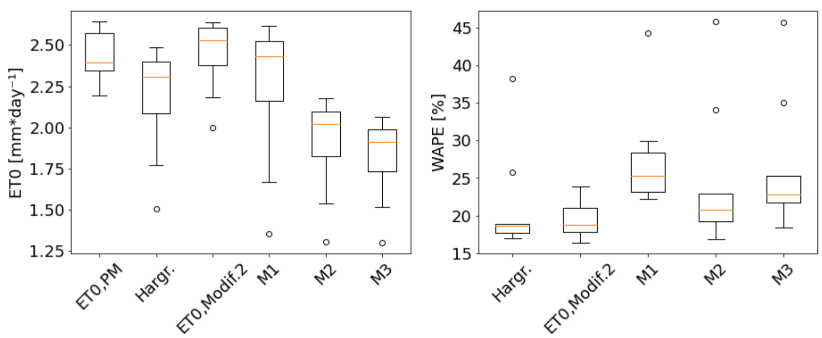

Fig. 9. Distribution of the mean daily ET_0 [mm day^{-1}] values and *WAPE* [%] of methods compared for calculating the ET_0 values including the proposed Hargreaves modification involving altitude $ET_{0,\ MODIF2}$.

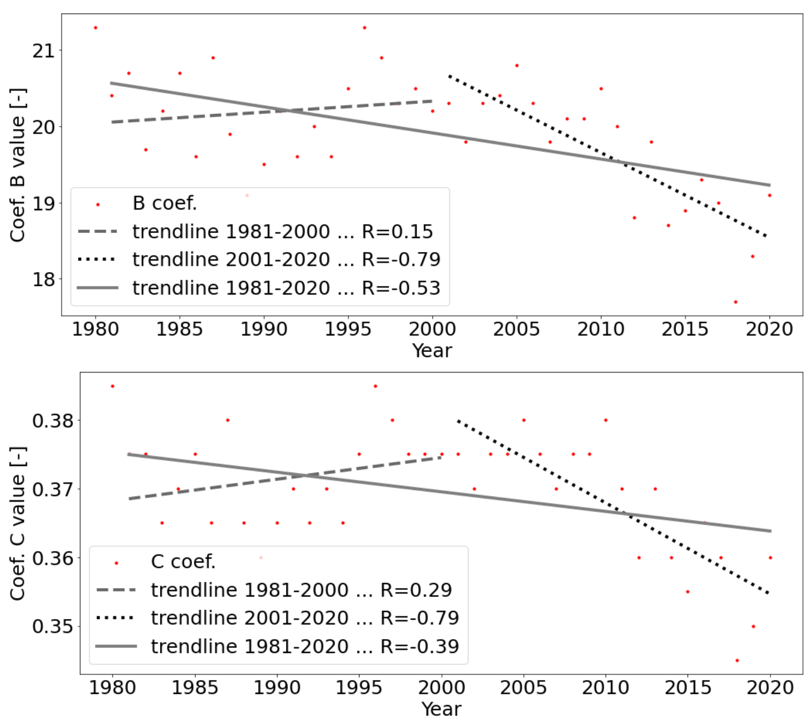

Fig. 10. Temporal stability of Hargreaves model parameters *B* and *C*.

Assessment of temporal stability of the Hargreaves model

We also focused on determining the Hargreaves coefficient values over time, for the period 1981–2020. We determined the optimal values of the model coefficients separately for each year, in $ET_{0, MODIF.2}$ equation (Eq. 6). Parameter *A* is stabile over time, the optimal value has not changed. The value of the *B* parameter revealed negative linear trend with an *R* value of –0.53 in the period 1981–2020 (Fig. 10); however, the slope of this negative trend has increase in the recent period (2001–2020). We observed a significant change in the trend of the *B* value after the year 2000. In the previous period (1981–2000), the trend was insignificant, but in the recent period, the trend of the *B* parameter became significant, with a p-value of 0.0007 and a magnitude of –1[–] per 10 years. These results are very important for future research, as they suggest the necessity of validating Hargreaves equations on a regular basis.

The assumption of very similar behaviour in the *B* and *C* parameter values, as observed in Figure 10, was confirmed by linear regression analyses. The *B* and *C* coefficient values exhibit a strong positive linear relationship with an *R* value of approximately 0.97.

Therefore, we calibrated the method coefficients separately for two periods: 1981–2000 and 2001–2020 (Fig. 11). The results show that the optimal *B* coefficient value changed by –0.5 [–] between the periods (from 20.2 to 19.7 [–]). Using the general "B" coefficient value of 21.27 [–] for the recent period resulted in a decrease in the model's precision to a *WAPE* of 17.4%, compared to a *WAPE* of 16.9% when using a *B* coefficient of 19.7 calibrated for the recent period (Fig. 12).

Figure 12 shows a heatmap of mean station *WAPE* [%] using various *B* and *C* coefficient values for 1981–2020. You can see, that the values of the coefficients are changeable over time. Specially using specific *B* coefficient value in modelling does not reach the same level of accuracy over years. Although the generally best fitting value of the coefficients for all the stations could bring sufficient level of accuracy in long-term period, but this method could bring large errors for specific year. Therefore, for a short period we recommended validation of model on reference dataset, to ensure a sufficient level of accuracy of the model.

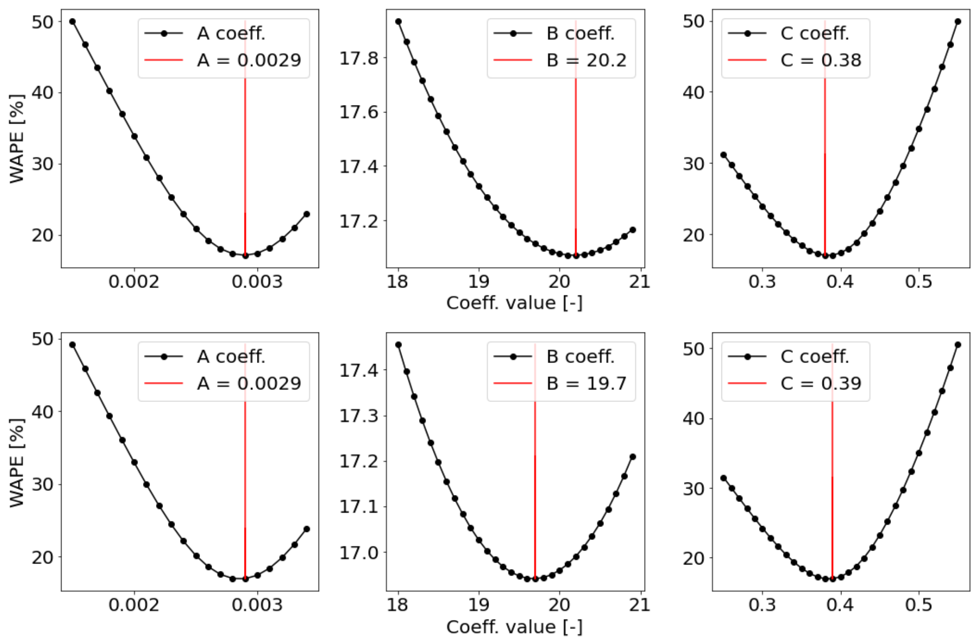

Fig. 11. Difference in in the optimal parameters (*A*, *B*, *C*) of Hargreaves model (variant 3) estimated in the two periods examined (top panels: 1981–2000; bottom panels: 2001–2020).

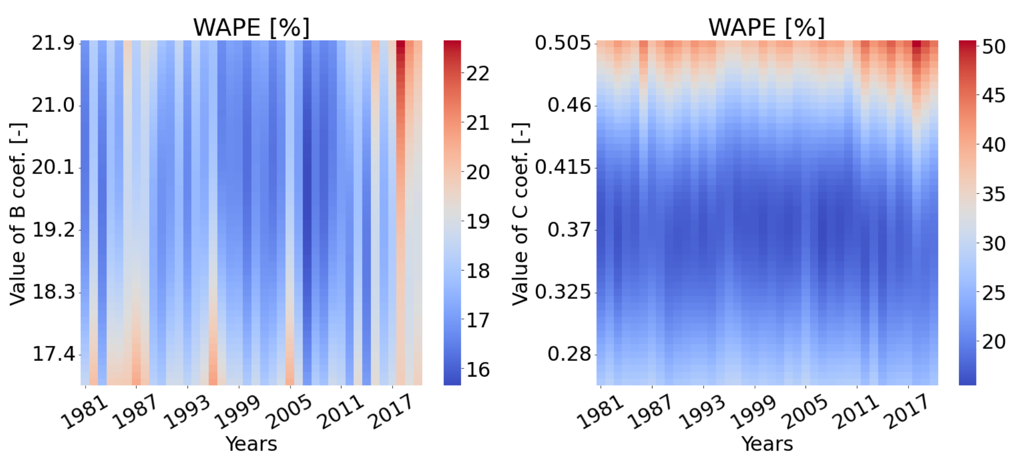

Fig. 12. Heat map of the *WAPE* (%) estimated for Hargreaves model parameters *B* (left panel) and *C* (right panel) in the period 1981–2020.

DISCUSSION

Previous modifications of the Hargreaves method by adjusting coefficients bring improvements in model accuracy under the conditions of the country of research. These results usually have limited applicability outside the country of origin. In the context of Central and Eastern Europe, the modifications of the Hargreaves method proposed by Trajkovic (2007) and Ravazzani et al. (2012) are the most commonly cited.

Trajkovic (2007) modified the Hargreaves coefficients for the Western Balkan region. The results showed that the Hargreaves method overestimates Penman-Monteith reference evapotranspiration values, with overestimation across the whole region varying from 12% to 28%. In our study, the original Hargreaves model consistently underestimates the FAO results, and this underestimation becomes more pronounced with increasing altitude (R = 0.88). Although Trajkovic (2007) reported that the ratio of his proposed modification results to the FAO-Penman-Monteith model ranged from 0.95 to 1.07, our results show that for our region, this ratio ranges from 0.82 to 0.88. In contrast, our method provides $ET_{0,Modif2}/ET_{0,FAO}$ ratios ranging from 1.03 to 1.17.

Trajkovic's method was derived only for stations at lower altitudes (42–630 m a.s.l.), and as our results indicate, its application at various altitudes is limited. Therefore, the method considering altitude suggested by Ravazzani et al. (2012) seems promising for application in complex studies. However, our results show that this modification, proposed for alpine regions in Italy (the Upper Po River) and Switzerland (the Rhone River), consistently underestimates reference evapotranspiration values in our region, and the magnitude of error increases with decreasing altitude. This method is therefore more suitable for stations at higher altitudes, for which it was primarily adjusted, but less suitable for stations at lower altitudes.

Our proposed method (Eq. 6) achieves similar accuracy regardless of station altitude, providing a reliable method for complex regional studies. Although previous research noted that the seasonal variability of Hargreaves coefficients is important to consider (Martí et al., 2015), our results bring a new finding indicating that mean coefficient values also vary over time. Therefore, it is necessary to regularly verify the accuracy of previously presented methods.

CONCLUSIONS

Evapotranspiration, which is a fundamental process in the hydrological cycle, profoundly influences various hydrological and meteorological variables, and plays a pivotal role in water storage (Keszeliová et al., 2022), runoff dynamics, and overall climatic conditions. Despite its significance, the estimation of evapotranspiration remains a challenge, as it lacks a universally recognized methodology. Reference evapotranspiration, which is vital for numerous agricultural and engineering applications, including irrigation design and water resource management, demands accurate estimation techniques.

This study addresses the pressing need for a reliable method to estimate the reference evapotranspiration, particularly in regions with limited meteorological data available. By optimizing coefficients in the Hargreaves method through curve fitting analyses tailored to local conditions in Slovakia, we aimed to enhance the accuracy of the evapotranspiration estimates.

Many authors have implemented continuous meteorological measurements into the Hargreaves equation to increase its accuracy, this also increases the complexity of the HS model, leading to greater resource requirements and more intricate simulations (Ishak et al., 2010). Although the optimal values of the Hargreaves coefficients do not directly relate to the altitude of the station, the deviation of ET_0 values from the reference FAO56 $ET_{0,}$ values shows a strong linear relationship with the altitude. The results show that modifying the Hargreaves coefficients alone is not sufficient to ensure a good performance of the model across various altitudes.

The inclusion of station altitude as a variable in the model is a significant step toward guaranteeing consistent model deviation across the research area. Modifying the Hargreaves model to include altitude (Eq. 6) provides consistent model performance across various altitudes.

Although determining the general coefficient values is necessary for implementing the model in research, it is important to note that model coefficient values vary over time. This variability in the model's deviation is smoothed by averaging over long research periods. However, when implementing the model for short research periods, it is essential to validate the model's performance and calibrate the model coefficients for the selected periods to achieve the expected accuracy of the model. The research has provided new insights indicating that the optimal Hargreaves coefficient not only varies on a seasonal or monthly basis (Maestre-Valero et al., 2013) but also changes over the years. Furthermore, the climate changes have had a significant impact on the trend of these coefficient variations in recent decades.

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