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Research paper

COMPARISON OF EVAPOTRANSPIRATION METHODS IN NOVI SAD FROM 1980 TO 2015

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Abstract

Evapotranspiration (ET) is a key process in hydrology, agriculture, and managing water resources. It affects numerous processes, including irrigation planning and climate research. In this study, the temperature-based variation of Penman-Monteith (PMt) and the Hargreaves (HARG) equation were compared to the standard Penman-Monteith (PM) method for estimating ET. The data used for the calculation of evapotranspiration was collected from the meteorological station in Novi Sad during the time period from 1980 to 2015. ET results were statistically analyzed using Pearson's correlation coefficient (r), the coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE), index of agreement (d), root mean square error (RMSE), mean absolute error (MAE), relative squared residual (RSR), relative error (RE), and percent bias (PBIAS). Findings in this study showed r=0.99, r=0.99 for PMt and HARG, respectively. For PMt RMSE equaled 0.24, and for HARG RMSE=0.41. Moreover, findings showed MAE=0.17 for PMt and MAE=0.32 for HARG. A high r value and low RMSE and MAE values indicate that PMt is more reliable than HARG method. The temperature-based Penman-Monteith (PMt) method has proven to be a more accurate and reliable alternative to the reference method in data-limited conditions, while the Hargreaves method can be used with caution due to its slightly lower accuracy.

Keywords: *Evapotranspiration, Penman-Monteith, temperature-based Penman-Monteith, Hargreaves, statistical evaluation.*

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1. INTRODUCTION

Evapotranspiration (ET) is a prominent hydrological process that represents the basis for calculations in hydrology and water resource management, particularly in the context of agricultural water use and irrigation planning. This includes evaporation from soil and transpiration from plant canopies. Estimating ET is central to sustainable water resource management, especially where water availability is limited or varies seasonally [1]. To estimate ET, several models have been developed ranging in complexity and data requirements. These contain physical based methods, empirical models and hybrid approaches.

Three reference evapotranspiration (ET_0) estimation methods were analyzed in this study: the standard FAO-56 Penman–Monteith (PM), its temperature-based variant (PMt), and the empirical Hargreaves (HARG) method. The PM method is widely accepted as a physically based standard requiring comprehensive meteorological input, including solar radiation, air temperature, humidity, and wind speed [1]. In contrast, the PMt approach excludes wind speed and simplifies radiation estimation, allowing application in data-scarce environments while maintaining acceptable accuracy under various climatic conditions demonstrated in comparative evaluations of temperature-based ET methods [2]. The HARG method relies solely on air temperature and extraterrestrial radiation, offering a computationally simple alternative that is particularly useful in regions lacking detailed weather records [3].

The Penman–Monteith (PM) method was adopted as the reference model for estimating reference evapotranspiration (ET_0), due to its physical robustness and reliance on a full set of meteorological parameters [1]. The temperature-based variant of the Penman–Monteith method (PMt) and the empirical Hargreaves method (HARG) were evaluated by comparing their results against the reference values. The following statistical indicators were used to assess model performance: Pearson correlation coefficient (r), coefficient of determination (R^2), Nash–Sutcliffe efficiency (NSE), root mean square error (RMSE), mean absolute error (MAE), standard deviation (s), index of agreement (d), relative square residual (RSR), relative error (RE), and percent bias (PBIAS) [2, 4]. These metrics enable a comprehensive evaluation of the agreement between estimated and reference values under given climatic conditions and represent standard criteria for performance assessment in hydrometeorological modeling.

2. METHODOLOGY

In this analysis, three commonly used methods for estimating the reference evapotranspiration (ET_0) were used and compared: the FAO-56 Penman-Monteith (PM) [1], the simplified temperature-based version of it (PMt), and the empirical Hargreaves (HARG) [2] approach. These methods were selected based on their distinct data requirements and appropriateness across different climates and levels of data availability. The PM approach is, traditionally, the standard reference model as it is the most physically rigorous and makes use of more comprehensive meteorological variables. The equation, as provided by FAO-56, can be expressed as follows:

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

where R_n represents net radiation at the crop surface [MJ m^{-2} day^{-1}], G soil heat flux density [MJ m^{-2} day^{-1}], T air temperature at 2 m height [°C], u_2 wind speed at 2 m height [m s^{-1}], e_s saturation vapour pressure [kPa], e_a actual vapour pressure [kPa], e_s-e_a saturation vapour pressure deficit [kPa], Δ slope vapour pressure curve [kPa $°C^{-1}$], and γ psychrometric constant [kPa $°C^{-1}$].

This model requires solar radiation, air temperature, relative humidity, and wind speed, and is suitable for regions where comprehensive meteorological data is available.

The temperature-based Penman–Monteith (PMt) equation is a simplified version of the classical Penman–Monteith (PM) equation without wind speed and using net radiation calculated in an approximate or estimated way [4]:

$$ET_0 = \frac{0.408\Delta R_n + \gamma \frac{900}{(T+273)}(e_s - e_a)}{\Delta + \gamma} \quad (2)$$

It is specifically established for regions without a lot of data, demonstrating adequate accuracy when some of the meteorological elements are either missing or not reliable, due to the fact that it is being derived on "missing" or "incomplete" data.

The Hargreaves (HARG) equation is an empirical equation based only on temperature and extraterrestrial radiation and is expressed as:

$$ET_0 = 0.0023 * (T_{mean} + 17.8)(T_{max} - T_{min})^{0.5} * R_a \quad (3)$$

HARG is being used more widely because there can be minimal data to work with and the simplicity associated with the use of an average temperature (T_{mean}), maximum temperature (T_{max}) and minimum temperature (T_{min}). R_a represents extraterrestrial radiation [MJ m^{-2} day^{-1}].

All three methods were applied to the same long-term dataset (1980–2015) for the Novi Sad region, and compared to establish the accuracy and applicability of the simplified (PMt and HARG) to the Penman-Monteith (PM) in the context of continental climate.

To evaluate the performance of the temperature-based Penman–Monteith (PMt) and Hargreaves (HARG) methods in comparison to the reference Penman–Monteith (PM) model, a set of statistical indicators was applied to numerically assess the agreement between simulated and reference evapotranspiration (ET_0) values [3]. The following metrics were used:

- Pearson correlation coefficient (r):

$$r = \frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}\sqrt{\sum_{i=1}^{n}(P_i - \bar{P})^2}} \quad (1)$$

The Pearson correlation coefficient (r) quantifies the strength and direction of a linear relationship between observed and simulated values [3]. The coefficient ranges from -1 (perfect negative correlation) to +1 (perfect positive correlation). Pearson coefficients near zero indicate no linear correlation.

- Coefficient of determination (R^2):

$$R^2 = \left(\frac{\sum_{i=1}^{n}(O_i-\bar{O})(P_i-\bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i-\bar{O})^2} \cdot \sqrt{\sum_{i=1}^{n}(P_i-\bar{P})^2}} \right)^2 \tag{2}$$

The coefficient of determination (R^2) represents the proportion of the variance in the observed data explained by the model [3, 4, 5]. It is the square of the Pearson coefficient and ranges from 0 to 1, where higher values indicate a better fit.

- Nash-Sutcliffe efficiency (NSE):

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i-P_i)^2}{\sum_{i=1}^{n}(O_i-\bar{O})^2} \tag{3}$$

Nash-Sutcliffe efficiency (NSE) indicates how good model predictions are in comparison to the observed data, when comparing the predictions to using the mean of the observed values [3] [5]. A perfect prediction would have an NSE of 1, while any less than zero implies that the model prediction is worse than predicting the mean observed value.

- Root mean square error (RMSE):

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - P_i)^2} \tag{4}$$

RMSE gives the average magnitude of the observed and simulated values, and is presented in the same unit as the variable [3, 4, 5]. Smaller RMSE values indicate a better fitting model.

- Mean absolute error (MAE):

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|O_i - P_i| \tag{5}$$

MAE represents the average of the absolute differences between observed and predicted values [3, 5]. Unlike RMSE, MAE treats all errors equally, without emphasizing larger deviations.

- Standard deviation of model predictions (s):

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(P_i - \bar{P})^2} \tag{6}$$

The standard deviation of model predictions (s) quantifies the variation, or how dispersed the simulated values are in relation to their mean [3, 5, 6]. It is useful to see if the model overestimates or underestimates the variation of the data.

- Index of agreement (d):

$$d = 1 - \frac{\sum_{i=1}^{n}(O_i-P_i)^2}{\sum_{i=1}^{n}(|P_i-\bar{O}|+|O_i-\bar{O}|)^2} \tag{7}$$

The index of agreement (d) quantifies how well the predicted values fit with the observed data regarding both magnitude and trend [3]. Values approaching one imply very decent agreement, while values approaching zero imply weak or no agreement.

- Relative square residual (RSR):

$$RSR = \frac{RMSE}{s_O} \tag{8}$$

The RSR is the normalized RMSE, computed by dividing the RMSE by the standard deviation of the data [3]. Small RSR values indicate good performance of the model.

- Relative Error (RE):

$$RE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{O_i - P_i}{O_i}\right| \cdot 100\% \tag{9}$$

Quantifies the average observed and simulated value as a fraction of the observed values [3]. RE is helpful in comparing models when observed values span fairly large ranges of magnitudes.

- Percent Bias (PBIAS):

$$PBIAS = 100 \cdot \frac{\sum_{i=1}^{n}(O_i - P_i)}{\sum_{i=1}^{n} O_i} \tag{10}$$

PBIAS shows the average tendency of the model to either overestimate or underestimate the observed values (keeping track of the PBIAS's sign) [3]. Positive values indicate a tendency to underestimate while negative values indicate a tendency to overestimate.

These statistics enable a multidimensional evaluation and comparison of models in terms of accuracy, variability, and systematic deviations, providing a reliable analysis of the applicability of individual methods under conditions of limited meteorological data.

3. RESULTS AND DISCUSSION

The analysis was conducted in the study area of Novi Sad, which is situated in northern Serbia and features a continental climate with a significant seasonal variability, including hot summers and cold winters. Average annual maximum and minimum air temperatures during 1980–2015 were 16.5°C and 6.4°C, while relative humidity varied between 60% and 85%. The monthly mean precipitation ranged between 30 and 85 mm, with an average wind speed of about 1.9 m/s, these extreme climates are among the reasons that accurate estimation of reference evapotranspiration is essential for agricultural development and drought management in the local environment [5].

Statistical assessment of the simplified reference ET_0 methods — the temperature-based variation of Penman–Monteith (PMt) and the Hargreaves (HARG) method —was accomplished by comparing their monthly ET_0 values against the FAO-56 Penman–Monteith reference ET_0 method over a 36-year period. The evaluation consisted of ten performance measures: Pearson correlation coefficient (r), coefficient of determination (R^2), Nash–Sutcliffe efficiency (NSE), index of agreement (d), root mean square error (RMSE), mean absolute error (MAE), relative square residual (RSR), relative error (RE), percent bias (PBIAS), and standard deviation (Table 1).

Table 1. Statistical evaluation of PMt and HARG methods compared to PM reference.

Metric	PMt	HARG
r	0.995	0.989
R^2	0.99	0.978
NSE	0.982	0.927
d	0.995	0.982
RMSE	0.24	0.41
MAE	0.17	0.32
RSR	0.15	0.26
RE (%)	2.34	3.45
PBIAS	-0.86	-1.72
Standard Deviation	0.29	0.35

Both PMt and HARG showed linear correlation with the reference method ($r > 0.989$) which demonstrates the methods are capable of tracking seasonal trends. However, PMt was superior to HARG across all error type metrics. For example, PMt had a lower RMSE (0.24 vs. 0.41), MAE (0.17 vs. 0.32) and RSR (0.15 vs. 0.26) and had a better NSE (0.98 vs. 0.93). Both PMt and HARG had PBIAS near zero suggesting both methods are unbiased; however, PMt had slightly better agreement.

It was concluded that both methods could be used in climatological ET_0 estimation, but the PMt model would be considerably closer to the reference, especially when availability of radiation data is limited. While the HARG method is pragmatic under data-scarcity, it demonstrates increased uncertainty, especially during periods of extreme temperature or solar input. Thus, when wind or humidity data are not available, a PMt could be a more reliable alternative to PM in continental climates such as Novi Sad.

4. CONCLUSION

The results of this study indicated that the temperature-based Penman–Monteith (PMt) and Hargreaves (HARG) methods are valid alternatives to the standard FAO-56 Penman–Monteith (PM) model to estimate reference evapotranspiration (ET_0) in regions with limited meteorological data, but that PMt outperformed HARG in all statistical indicators and was in higher agreement with PM and had lower errors than HARG. Despite the aforementioned, PMt is a more valid substitute to the reference model in continental climates such as Novi Sad, on a physical basis and on the basis that PMt only uses the variables of precipitation and temperature, but when wind and humidity data are not available. HARG is a simpler method, but it did have a slightly lower accuracy and should be used with care under extreme climatic conditions. Overall, the findings of this study endorse simplified methods to be used in support of hydrological planning and agricultural water management, in data-scarce regions.

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