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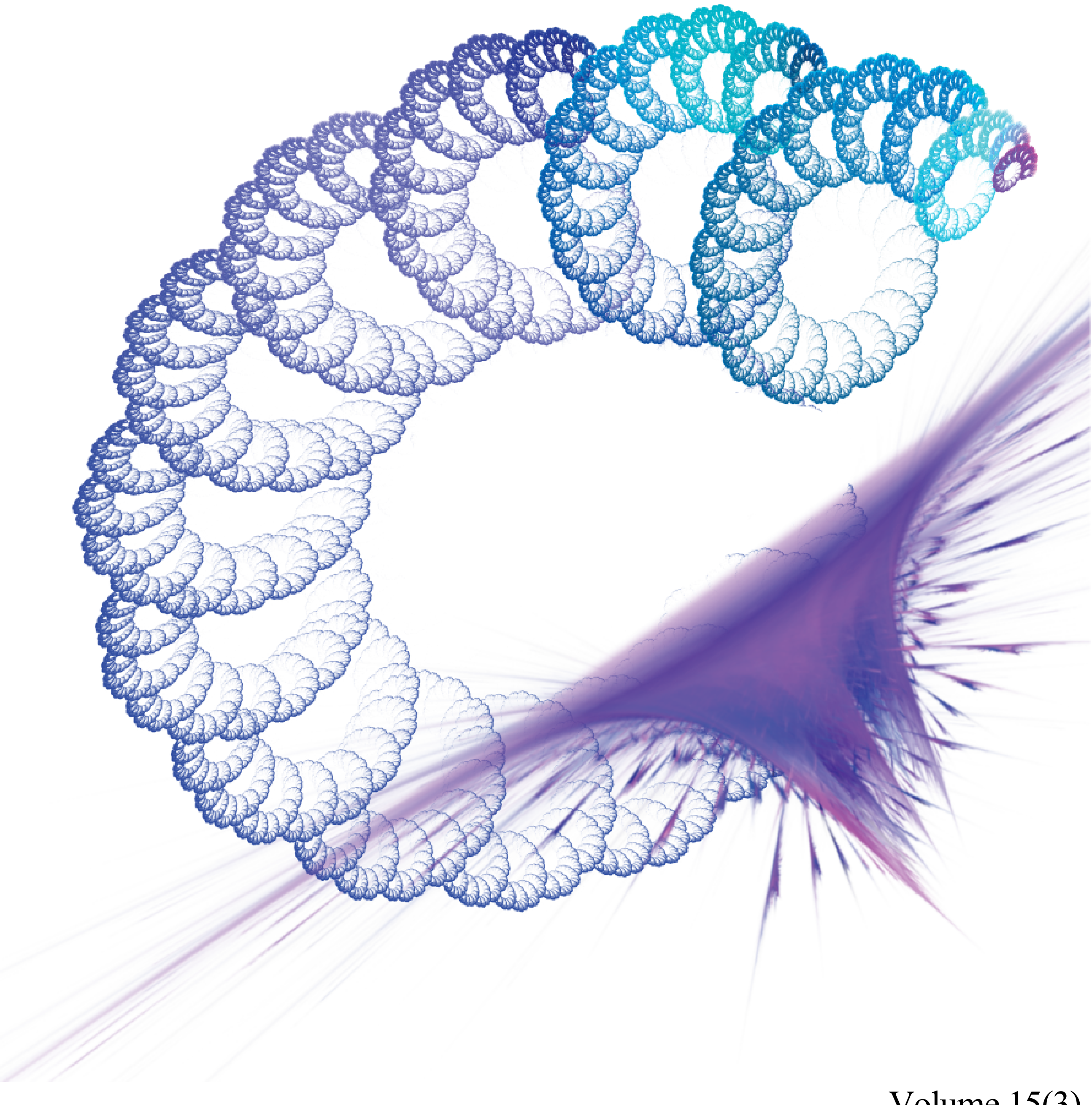
Regulatory Mechanisms in Biosystems



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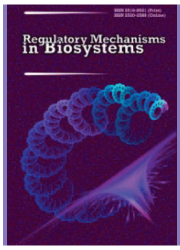

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Aims and scope. *Regulatory Mechanisms in Biosystems* publishes peer-reviewed original research and review articles across all aspects of regulatory mechanisms in biological systems from the molecular level of organisation to the level of the organism. This journal mostly focuses on physiological mechanisms of regulation of metabolic processes, biochemical and physiological features of any species including human beings. This journal covers a wide range of regulatory mechanisms in biological systems that are associated both with natural processes and those transformed under the influence of chemicals and drugs, and any other man-made factors. We will publish papers concerned solely with clinical case studies and clinical trials if such articles address important questions in regulatory mechanisms in biosystems. *Regulatory Mechanisms in Biosystems* focuses on good-quality research, reporting scientifically sound observations and valid conclusions, which bring new and important information to the attention of the wider international scientific community. The journal publishes contributions in the following basic areas: biochemistry, bioinformatics, biophysics, cell biology, endocrinology, genetics, immunology, microbiology, molecular biology, physiology, neuroscience, pharmacology, toxicology.

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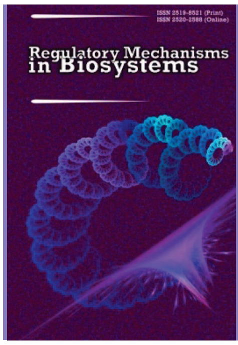

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Evaluation of different methods for reference evapotranspiration assessment: A case study for Ukraine

P. V. Lykhovyd*, O. V. Averchev**, I. O. Bidnyna***, N. O. Avercheva**, M. Nikitenko**

*Institute of Climate-Smart Agriculture of NAAS, Odesa, Ukraine
**Kherson State Agrarian and Economic University, Kropyvnytskyi, Ukraine
***National Academy of Agrarian Sciences of Ukraine, Kyiv, Ukraine

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Institute of Climate-Smart Agriculture of NAAS, Mayakska Doroha st., 24, Odesa, 67667, Ukraine. Tel.: +38-066-062-98-97. E-mail: pavel.likhovid@gmail.com

Kherson State Agrarian and Economic University, Universytetskyi av., 5/2, Kropyvnytskyi, 25013, Ukraine. Tel.: +38-050-521-80-00. E-mail: averchev1966@gmail.com

National Academy of Agrarian Sciences of Ukraine, Mykhaila Omelianovycha-Pavlenka st., 9, Kyiv, 01010, Ukraine. Tel. +38-066-000-64-12. E-mail: irinabidnina@ukr.net

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The paper presents the results of the study devoted to the examination of the accuracy and reliability of the temperature-based approach of the 'Evapotranspiration Calculator (Ukraine)' application for the reference evapotranspiration assessment in Ukraine. The objective of the study was to determine the level of reliability and accuracy of modern alternative temperature-based algorithms for the reference evapotranspiration assessment in Ukraine compared to internationally recognized methods. The study was carried out for the territories of Ukraine, based on the meteorological data for the period 2021–2023. The basic methodology was compared to the standard Penman-Monteith method and the method of Hargreaves. The comparison was performed using the values of MAPE, RMSE, and correlation coefficient. Statistical analysis testified that there is a strong correlation and subtle difference between the Hargreaves method and the 'Evapotranspiration Calculator (Ukraine)' application, with an average MAPE of 30.3%, the correlation coefficient of 0.92, and RMSE of 1.46 mm. The difference between the Penman-Monteith method and the studied methodology was greater, as the MAPE averaged 41.0%, the correlation coefficient was 0.87, and the RMSE value was 2.05 mm. However, the high variation of the results by the regions of the country and the years of the study did not allow us to draw solid conclusions on whether the methodology embedded in the 'Evapotranspiration Calculator (Ukraine)' application is inferior to the method of Penman-Monteith. Further studies are required to clarify this issue through the improvement in the dataset, involvement of in-field reference evapotranspiration measurements, and application of adjustment guidelines for the 'Evapotranspiration Calculator (Ukraine)' application.

Keywords: evapotranspiration calculator; Hargreaves method; irrigation scheduling; modeling; Penman-Monteith method.

Introduction

Reference evapotranspiration (ETo) is the most widely implemented agrometeorological index for establishment of irrigation rates and irrigation scheduling (Hargreaves, 1994). The best accurate ETo assessment is provided by lysimetric measurements. However, lysimeters are expensive, require trained staff for maintenance, and are more of scientific rather than practical use. Therefore, in practice, reference evapotranspiration is mainly estimated through indirect calculation methods. There are different approaches to ETo estimation using different meteorological and climatic parameters, but the most widespread in practice are methods developed by Penman-Monteith and Hargreaves (Tabari et al., 2013). The former method is more complicated and requires numerous inputs for the best performance in reference to evapotranspiration assessment. If an incomplete dataset is used, the accuracy and reliability of this method are reduced (Trajkovic, 2005). The Hargreaves method is less complicated and requires a smaller number of inputs, thus, it is frequently preferred over the Penman-Monteith method by practitioners and scientists. Although both quoted methods for reference evapotranspiration belong to the most used ones, the fact of the great difference in their accuracy in different environments cannot be neglected. Sometimes, these methods, especially Hargreaves, cannot be applied without previous calibration because of the great discrepancy between actual (measured in the field using a lysimeter or at the hydrometeorological station) and calculated reference evapotranspiration. This makes it risky to use the calculated values of ETo in irrigation scheduling (Jung et al., 2016). To overcome the mentioned problem, regional models for ETo evaluation, based on lysimetric measurements or the Penman-Monteith equation, were developed. One of the most recent developments in this direction is 'Evapotranspiration Calculator (Ukraine)' application, developed to estimate reference evapotranspiration in the regions of Ukraine (Lykhovyd, 2022). This application is available for Android-based devices free of charge. It was developed as a result of the mathematical approximation of the complete Penman-Monteith equation to the simplified one, which uses average air temperature as the only input for the ETo estimation. In total, more than 10,000 data inputs from the period 1971–2020 were analysed and put into the basis of the simplified methodology. The interesting thing about the application is that there are 23 different mathematical models for 23 regions of Ukraine to estimate reference evapotranspiration because there are major differences in the patterns of how the estimated index reacts to the increase or decrease in the air temperature between the regions of the country. The developed models of reference evapotranspiration could be adjusted using the data on windspeed and relative air humidity if needed. The models' testing showed their reasonable accuracy and adequacy to the input dataset, and the mean absolute percentage error (MAPE) fluctuated within 20–30%, while the values of the predicted coefficient of determination were within 0.96–0.98, and mean square errors fluctuated between 0.31–1.62 mm (Lykhovyd, 2020a, 2020b). However, these results were received for the tested time span (the period 1971–2020), and there was no validation using the dataset, which is different from the testing one. Thus, the goal of this study was to determine whether 'Evapotranspiration Calculator (Ukraine)' application and its basic methodology are reliable and accurate for the assessment of reference evapotranspiration in Ukraine and to compare its performance with the standard methodology of the Penman-Monteith method, edited by FAO, and the closest temperature-based methodology of Hargreaves.

Materials and methods

The study was conducted for the period 2021–2023. Meteorological data from the regional hydrometeorological stations were used to conduct the calculations of reference evapotranspiration by the methods of Penman-Monteith, Hargreaves, and by means of the application 'Evapotranspiration Calculator (Ukraine)'. The calculations of the ETo were carried out during the warm period of the year (the average air temperature is above zero) on a monthly basis, using standard calculation procedures for the named methods (Hargreaves & Samani, 1985; Allen et al., 1998). The equations for the Hargreaves (1) and Penman-Monteith (2) methods are also presented below.

$$ETo = 0.408 \times 0.030 \times (T_a + 20) \times (T_{max} - T_{min})0.4 \times R \quad (1)$$

where: ETo – reference evapotranspiration (mm); T_a, T_{max}, T_{min} – average, maximum and minimum air temperature, correspondingly (ºC); R – solar radiation ($MJ/m^2/day$).

$$ETo = (0.408\Delta(R - G) + \gamma(900/(T + 273))U(es - ea))/(\Delta + \gamma(1 + 0.34U)) \quad (2)$$

where: ETo – reference evapotranspiration (mm); R – solar radiation ($MJ/m^2/day$); G – heat balance of the soil ($MJ/m^2/day$); γ – psychrometric constant; es – saturation of vapor (kPa); ea – pressure of vapor (kPa); Δ – the slope of the curve 'vapor pressure – air temperature' (kPa/ºC); T – average air temperature (ºC); U – windspeed at the height of 2 m.

Table 1
Mathematical algorithms, used in the 'Evapotranspiration calculator (Ukraine)' application for reference evapotranspiration calculation (T is an average air temperature, ºC)

Region of Ukraine	Mathematical model
Cherkasy	0.2413×T
Chernivtsi	0.2438×T
Chernihiv	0.2461×T
Dnipropetrovsk	0.2609×T
Ivano-Frankivsk	0.2534×T
Kharkiv	0.2401×T
Kherson	0.2473×T
Khmelnytskyi	0.2537×T
Kirovohrad	0.2654×T
Kyiv	0.2262×T
Lviv	0.2466×T
Mykolaiv	0.2424×T
Odesa	0.2138×T
Poltava	0.2388×T
Rivne	0.3023×T
Sumy	0.2540×T
Ternopil	0.2562×T
Vinnytsia	0.2573×T
Volyn	0.2212×T
Zakarpattia	0.2248×T
Zaporizhzhia	0.2499×T
Zhytomyr	0.2362×T
Crimea	0.2711×T

The accuracy of the calculations was evaluated using the values of mean absolute percentage error (MAPE), root mean square error (RMSE), and Pearson's correlation coefficient both on regional and country scales. Statistical calculations were conducted by common methodologies in Microsoft Excel 365 (Khair et al., 2017; Jebarathinam et al., 2020; Hodson, 2022). The interpretation of MAPE was performed using the guidance by Moreno et al. (2013), while the interpretation of the correlation coefficient was performed using the guidelines by Taylor (1990). Thus, MAPE values of <10% were considered as very accurate predictions of the ETo; 10–20% – good prediction; 20–50% – reasonable prediction; >50% – inaccurate prediction. As for the correlation coefficient, the values of <0.35 testify about weak correlation; 0.36–0.67 – moderate correlation; 0.68–1.00 – strong correlation (>0.90 – very strong correlation). The values of RMSE were evaluated according to their relation to the minimal and maximal single irrigation rates in Ukraine, which are 5 and 60 mm, respectively (Ushkarenko, 1994). The general methodological flow is presented in Figure 1.

The best prediction, reliability, and accuracy are associated with the highest values of correlation coefficient, the least MAPE, and RMSE. Considering the average irrigation rate in Ukraine of 150 mm for winter wheat, 240 mm for grain corn, and 388 mm for alfalfa, respectively, RMSE values that fall below 1.5 mm are considered very good, and those within the range of 1.5–2.5 mm are reasonably good.

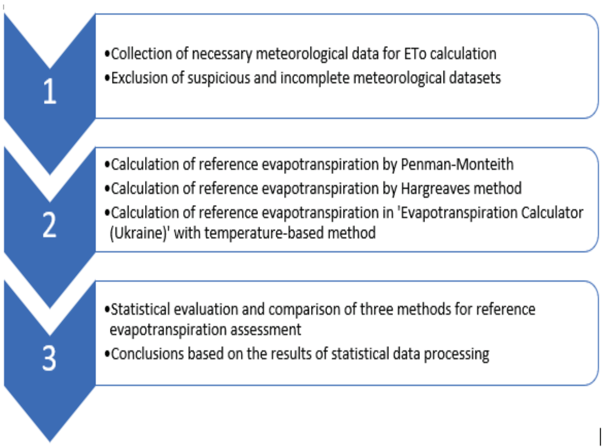

Fig. 1. Methodology flow chart of the study

Results

In the course of the study, major regularities for reference evapotranspiration assessment in Ukraine using alternative methodology were established. First of all, it should be stressed that the accuracy of the tested temperature-based methodology, realized within the shell of the 'Evapotranspiration Calculator (Ukraine)' application, was strongly dependent on the year of the study. The more typical the meteorological relations of the year of the study, the better the accuracy and reliability of the methodology. The most typical year from the climatological point of view for most territories of Ukraine was 2023, thus, the best average accuracy and reliability of the evaluation were achieved for that year.

At the same time, the year 2022 was characterized not only as slightly atypical but there also were gaps in meteorological data because of military activities in most territories of Ukraine. Therefore, the general number of inputs was less than in 2021 and 2023, resulting in less accuracy of the ETo prediction and less representability this year (Tables 2–4).

It was established that the temperature-based methodology, embedded in the 'Evapotranspiration Calculator (Ukraine)' application, corresponded much more strongly to the methodology of Hargreaves than Penman-Monteith. On average, it was 10% more accurate and provided a much stronger correlation (0.92 vs 0.87) resulting in a 0.59 mm less average RMSE value. In some regions, the discrepancy between the methods was even more evident and strong, e.g., for the Crimea, Ternopil, Mykolaiv, Chernivtsi regions. However, in Zhytomyr and Zakarpattia regions of Ukraine lower RMSE values were recorded in the comparison to the Penman-Monteith method. But this is more of an exception than a rule as far as in other regions the tendency to greater closeness between the Hargreaves and the 'Evapotranspiration Calculator (Ukraine)' methodology is obvious (Table 5).

Generally, the adequacy of the 'Evapotranspiration Calculator (Ukraine)' application is reasonably good in case of comparison with the method of Hargreaves using the MAPE values as guidance (Moreno et al., 2013); there is a strong correlation between these two methods of the ETo assessment (Taylor, 1990), and the average RMSE value of 1.46 mm testifies to a very good performance in terms of accuracy. However, in case of comparison with the standard FAO-recommended method of Penman-Monteith, the accuracy of the method is suspicious, as the average MAPE greatly exceeds 30% (Moreno et al., 2013). The correlation is strong (R = 0.87) (Taylor, 1990), but the average RMSE value of

2.05 mm testifies that the method should be used with caution in irrigation scheduling.

Table 2
Statistical evaluation of 'Evapotranspiration Calculator (Ukraine)' application for reference evapotranspiration calculation in comparison to standard Penman-Monteith and Hargreaves methods (the data of the year 2021)

Region of Ukraine	Comparison with Penman-Monteith method			Comparison with Hargreaves method		
	MAPE, %	R	RMSE, mm	MAPE, %	R	RMSE,mm
Cherkasy	44.40	0.90	2.57	30.77	0.93	1.60
Chernivtsi	37.83	0.89	2.03	26.39	0.91	1.36
Chernihiv	39.87	0.88	2.20	31.27	0.94	1.63
Dnipropetrovsk	42.97	0.90	2.74	25.30	0.91	1.41
Ivano-Frankivsk	39.63	0.86	2.15	32.43	0.92	1.65
Kharkiv	44.33	0.90	2.68	33.60	0.79	1.65
Kherson	41.88	0.94	2.27	26.47	0.94	1.37
Khmelnytskyi	40.34	0.87	2.19	27.01	0.91	1.37
Kirovohrad	40.08	0.91	2.41	23.99	0.92	1.34
Kyiv	30.22	0.86	1.58	31.36	0.91	1.62
Lviv	38.47	0.84	2.01	33.74	0.88	1.72
Mykolaiv	45.59	0.94	2.72	26.40	0.93	1.38
Odesa	36.72	0.88	1.65	31.08	0.92	1.28
Poltava	31.63	0.89	1.72	27.08	0.92	1.46
Rivne	36.24	0.89	2.23	21.71	0.92	1.16
Sumy	41.86	0.87	2.46	28.57	0.93	1.53
Ternopil	42.71	0.89	2.35	27.80	0.92	1.37
Vinnytsia	41.24	0.89	2.31	25.45	0.91	1.32
Volyn	44.91	0.88	2.41	37.91	0.50	1.93
Zakarpattia	37.34	0.87	1.67	37.33	0.94	1.68
Zaporizhzhia	40.34	0.90	2.31	24.76	0.93	1.30
Zhytomyr	23.21	0.86	1.13	29.99	0.92	1.51
Crimea	44.43	0.90	2.75	20.76	0.92	1.03
Average	39.40	0.89	2.20	28.75	0.90	1.46

Notes: MAPE – mean absolute percentage error; R – correlation coefficient; RMSE – root-mean-square error.

Table 3
Statistical evaluation of 'Evapotranspiration Calculator (Ukraine)' application for reference evapotranspiration calculation in comparison to standard Penman-Monteith and Hargreaves methods (the data of the year 2022)

Region of Ukraine	Comparison with Penman-Monteith method			Comparison with Hargreaves method		
	MAPE, %	R	RMSE, mm	MAPE, %	R	RMSE, mm
Cherkasy	87.92	0.99	1.53	80.36	0.99	0.59
Chernivtsi	43.46	0.82	2.49	30.37	0.92	1.47
Chernihiv	30.06	0.92	1.54	25.06	0.95	1.35
Dnipropetrovsk	33.63	0.91	1.90	21.97	0.92	1.04
Ivano-Frankivsk	41.08	0.83	2.37	33.65	0.91	1.74
Kharkiv	87.77	-0.04	1.10	51.35	0.96	0.58
Kherson	42.84	0.69	1.68	34.87	0.60	0.96
Khmelnytskyi	43.59	0.79	2.61	31.65	0.87	1.58
Kirovohrad	43.81	0.92	2.51	25.38	0.95	1.22
Kyiv	36.37	0.79	1.89	34.13	0.87	1.76
Lviv	40.07	0.88	1.92	33.05	0.93	1.55
Mykolaiv	61.65	0.98	1.43	26.81	0.94	0.44
Odesa	32.64	0.91	1.49	28.10	0.94	1.20
Poltava	38.44	0.84	2.02	30.27	0.90	1.43
Rivne	34.61	0.77	2.27	28.85	0.86	1.31
Sumy	32.57	0.86	1.86	23.54	0.87	1.23
Ternopil	41.89	0.83	2.43	29.73	0.90	1.38
Vinnytsia	81.89	0.99	1.23	67.38	0.99	0.53
Volyn	72.28	0.99	1.33	48.48	0.99	0.48
Zakarpattia	20.97	0.94	0.53	24.76	0.95	0.55
Zaporizhzhia	31.15	0.71	1.69	28.91	0.76	1.53
Zhytomyr	33.52	0.76	1.57	32.90	0.87	1.71
Crimea	43.69	0.79	2.85	26.80	0.87	1.30
Average	45.91	0.82	1.84	34.71	0.90	1.17

Note: see Table 2.

However, taking a closer look at the figures, it should be noted that the 'Evapotranspiration Calculator (Ukraine)' application's performance was quite different between the regions of Ukraine, and in some geographical zones, it provided relatively good and reasonable accuracy for practical use even in comparison with the robust Penman-Monteith method, e.g., in Kyiv, Odesa, Zakarpattia, Zhytomyr regions. Besides, the accuracy greatly fluctuated over the years of the study, therefore, it should be emphasized that the accuracy will be strongly dependent on the typicality of the meteorological conditions of the year.

Table 4
Statistical evaluation of 'Evapotranspiration Calculator (Ukraine)' application for reference evapotranspiration calculation in comparison to standard Penman-Monteith and Hargreaves methods (the data of the year 2023)

Region of Ukraine	Comparison with Penman-Monteith method			Comparison with Hargreaves method		
	MAPE, %	R	RMSE, mm	MAPE, %	R	RMSE, mm
Cherkasy	N/A	N/A	N/A	N/A	N/A	N/A
Chernivtsi	41.65	0.86	2.16	29.80	0.92	1.35
Chernihiv	35.69	0.82	1.98	26.54	0.91	1.42
Dnipropetrovsk	32.35	0.91	1.76	21.08	0.92	1.01
Ivano-Frankivsk	42.39	0.85	2.11	30.68	0.92	1.43
Kharkiv	24.90	0.87	1.13	22.53	0.93	1.24
Kherson	36.17	0.92	1.97	25.39	0.94	1.22
Khmelnytskyi	44.20	0.91	2.30	29.96	0.92	1.26
Kirovohrad	41.21	0.85	2.75	24.41	0.90	1.21
Kyiv	30.50	0.84	1.38	29.07	0.91	1.35
Lviv	37.10	0.88	1.66	29.76	0.92	1.33
Mykolaiv	34.96	0.94	1.88	26.45	0.93	1.28
Odesa	32.90	0.94	1.52	26.22	0.93	1.20
Poltava	34.19	0.92	1.69	24.98	0.93	1.16
Rivne	39.33	0.91	2.11	24.43	0.92	1.03
Sumy	39.48	0.85	2.26	25.23	0.92	1.32
Ternopil	44.83	0.88	2.28	29.18	0.92	1.19
Vinnytsia	38.20	0.91	1.74	29.94	0.94	1.31
Volyn	44.69	0.91	2.03	34.75	0.93	1.58
Zakarpattia	30.46	0.85	1.30	31.37	0.91	1.42
Zaporizhzhia	24.70	0.83	1.32	19.05	0.84	1.44
Zhytomyr	32.49	0.84	1.24	29.49	0.93	1.28
Crimea	41.20	0.93	2.61	21.57	0.91	0.95
Average	36.53	0.88	1.87	26.90	0.92	1.27

Note: see Table 2.

Table 5
Statistical evaluation of 'Evapotranspiration Calculator (Ukraine)' application for reference evapotranspiration calculation in comparison to standard Penman-Monteith and Hargreaves methods (the data for the generalized period 2021-2023)

Region of Ukraine	Comparison with Penman-Monteith method			Comparison with Hargreaves method		
	MAPE, %	R	RMSE, mm	MAPE, %	R	RMSE, mm
Cherkasy	66.16	0.92	2.41	55.56	0.95	3.47
Chernivtsi	40.98	0.85	2.24	28.85	0.92	1.39
Chernihiv	35.21	0.87	1.94	27.62	0.93	1.48
Dnipropetrovsk	36.32	0.89	2.14	22.78	0.91	1.15
Ivano-Frankivsk	41.04	0.84	2.18	32.25	0.91	1.58
Kharkiv	52.33	0.85	1.92	35.83	0.90	1.34
Kherson	40.30	0.92	2.07	28.91	0.93	1.26
Khmelnytskyi	42.71	0.86	2.37	29.54	0.90	1.40
Kirovohrad	41.70	0.90	2.56	24.59	0.92	1.25
Kyiv	32.36	0.82	1.62	31.52	0.90	1.58
Lviv	38.55	0.87	1.86	32.18	0.91	1.52
Mykolaiv	47.40	0.93	2.21	26.55	0.94	1.25
Odesa	34.09	0.91	1.55	28.47	0.93	1.23
Poltava	34.75	0.88	1.82	27.44	0.92	1.35
Rivne	36.73	0.86	2.24	25.00	0.90	1.16
Sumy	37.97	0.85	2.22	25.78	0.91	1.37
Ternopil	43.14	0.86	2.35	28.90	0.91	1.31
Vinnytsia	53.78	0.90	1.95	40.92	0.94	1.27
Volyn	53.96	0.90	2.22	40.38	0.92	1.67
Zakarpattia	29.59	0.86	1.34	31.15	0.92	1.39
Zaporizhzhia	32.06	0.77	1.86	24.24	0.88	1.55
Zhytomyr	29.74	0.82	1.32	30.79	0.91	1.50
Crimea	43.11	0.86	2.74	23.04	0.90	1.10
Average	41.04	0.87	2.05	30.53	0.92	1.46

Note: see Table 2.

In addition, it must be stressed that average ETo values, calculated by the 'Evapotranspiration Calculator (Ukraine)' application, were used in this study as a reference. There was no adjustment of the calculated values to the windspeed and relative air humidity parameters. However, the application guidelines state that in the case of strong winds or calm, as well as extremely high or low relative air humidity, the smaller or the higher estimated ETo values should be taken. Therefore, there is an option for better in-app calibration of the reference evapotranspiration calculation, which was not enrolled in this study.

Discussion

In recent decades, numerous indirect calculation methods for the reference evapotranspiration assessment have been developed and introduced in agricultural science and practice. Most of the developed methods were created and tested in specific environmental conditions, and they were found not to be equally accurate and relevant globally because of the great differences in climate of different regions of the planet.

The Penman-Monteith equation, edited by FAO, was internationally accepted as a standard methodology for the ETo assessment in different environments. Its accuracy is the best among the calculation methodologies, although, in some cases, it also fails to provide accurate reference evapotranspiration predictions. The huge number of meteorological inputs are another impediment for the practical application of this method, as not all the hydrometeorological stations can provide access to specific meteorological indices, required to complete the calculation. Thus, alternative simplified methodologies are still in great demand by agricultural producers, mainly those providing calculations based on limited meteorological inputs (Rodrigues & Braga, 2021).

Special attention is paid to the automation of ETo assessment. In this regard, numerous applications were developed to facilitate the most simple and intuitive way of reference evapotranspiration calculation. For example, Rodrigues & Braga (2021) proposed a simple Microsoft Excel-based application to help agricultural producers estimate reference evapotranspiration using different methods considering the availability of meteorological inputs. The application was promising but received little attention from the international scientific community.

An interesting approach to reference evapotranspiration assessment and simultaneous mapping was proposed by Dimitriadou & Nikolakopoulos (2021), who utilized the remote sensing data for automated computation of the ETo within the ArcGIS shell. The methodological approach is quite promising, but it still lacks practical adaptation and versatility.

Brazilian scientists developed one of the most popular mobile applications for the automated ETo assessment – EVAPO. This application allows one to estimate the reference evapotranspiration on a daily basis by the geolocation of the field. The meteorological data are downloaded from NASA-POWER cloud services and then used in the Penman-Monteith equation. The application showed good results in Brazil, with an RMSE of 0.95 mm and a correlation coefficient of 0.85, compared to the standard methodology (Júnior et al., 2019). However, its performance requires robust calibration for different climate conditions, as it was proved in the work by Vozhehova & Lykhovyd (2021). Another similar application is AgSAT. This application utilizes satellite imagery from NASA and ESA services to estimate the water requirements for crops, or reference evapotranspiration (if grass is used as a crop). However, the results of the calculation are far from perfection and require even more robust calibration than the results obtained in the EVAPO application, notwithstanding the fact that in some agroecological zones, it provides acceptable results (Jaafar et al., 2022). Thus, there is a need for the development of a locally adapted reference evapotranspiration model for every agricultural zone.

The application 'Evapotranspiration Calculator (Ukraine)' provides a zonal approach to the estimation of reference evapotranspiration in the country. Based on robust perennial research, it requires air temperature as the only input for the index calculation. The results of the initial testing were good (Lykhovyd, 2022), but the testing lacked validation on the dataset, which was not included in the training. Besides, it should be stressed that the pilot testing of the algorithms, embedded in the application 'Evapotranspiration Calculator (Ukraine)' was performed for a limited number of the regions of Ukraine, namely, Kherson, Mykolaiv, Dnipropetrovsk, Cherkasy, Chernihiv, and Zakarpattia regions, while other territories of Ukraine remained out of the evaluation. The current study presents the results of a more robust and comprehensive validation of the application algorithms. Considering that the previous research did not include the latest meteorological data, the presented study fills two gaps, namely, it covers the full area of the country and provides the results of the three-year study including an absolutely novel meteorological dataset. Moreover, the results are not limited to the comparison with the Penman-Monteith method only, but the Hargreaves method is also added. The results of current research are somewhat inconclusive, as it was determined that related to the Hargreaves method, the 'Evapotranspiration Calculator (Ukraine)' temperature-based methodology provides reasonably good estimation of the agrometeorological index, especially for southern and central parts of Ukraine (Crimea, Kherson, Mykolaiv, Odesa, Dnipropetrovsk, Kirovohrad, Zaporizhzhia regions), while the comparison with the Penman-Monteith method showed that lack of accuracy in the reference evapotranspiration assessment, especially, in the years with the weather conditions, are not typical. But it should be pointed out that regardless of relatively high average MAPE values for the comparison with the Penman-Monteith method, the estimations of the reference evapotranspiration are in generally strong agreement, as is proved by the values of the coefficients of correlation (R = 0.77–0.93). Besides, RMSE values are reasonably good for almost all the regions of Ukraine, except for the Crimea, Cherkasy, and Kirovohrad regions, because they do not exceed the stipulated limit of 2.5 mm. In addition, some discrepancy was previously detected for the Penman-Monteith and Hargreaves methods themselves, especially for the conditions of the semi-arid climate, which is predominant in Ukraine, and under the missing meteorological data (Koudahe et al., 2018; Djaman et al., 2019; Bakhsh et al., 2020). Therefore, it is difficult to tell whether the discrepancy, which was found in our study, between the methodology of the 'Evapotranspiration Calculator (Ukraine)' and the mentioned above referent methods testifies its inferiority to them (Hua et al., 2020; Hadria et al., 2021). Besides, a calibration study with lysimeters or in-field meteorological stations is required to draw the final conclusion on the accuracy of the application in certain environmental conditions. This research work is going to be conducted in the near future.

Conclusion

The current study provides the results of statistical evaluation of the accuracy of the 'Evapotranspiration Calculator (Ukraine)' application in the reference evapotranspiration assessment in Ukraine in comparison to the standard Penman-Monteith method and the method of Hargreaves. As a result, it was established that the application provides good performance and reliability compared with the Hargreaves method (R = 0.92, RMSE = 1.46 mm, MAPE = 30.5%), while the results of comparison with the Penman-Monteith methodology are inconclusive, as they are inconsistent by the years and the regions of the country. The limitations of this study are mainly due to the absence of the control direct measurements of the reference evapotranspiration using lysimeters and in-field meteorological stations. Besides, in-app calibration guidelines were not implemented. Further research work will be conducted to cover the gaps related to the above-mentioned limitations of the current study and to provide more details on the performance of the 'Evapotranspiration Calculator (Ukraine)' application.

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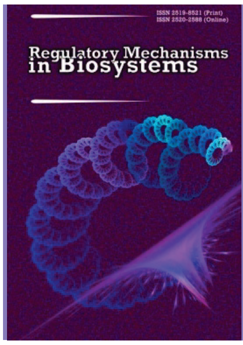

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