**DOI:** https://doi.org/10.31073/mivg202401-375
Available at (PDF): https://mivg.iwpim.com.ua/index.php/mivg/article/view/375

UDC 631.67

# ANALYSIS OF THE CALCULATION OF REFERENCE EVAPOTRANSPIRATION ACCORDING TO THE DATA OF THE STATE METEOROLOGICAL STATION

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***Abstract.*** *Since direct measurement of reference evapotranspiration ($ET_0$) is a complex, time-consuming and expensive process, the most common procedure is to estimate $ET_0$ from climate data. The purpose of this study was to perform reference evapotranspiration calculations based on the data of the state meteorological station Askania-Nova and compare them with the actual $ET_0$ data obtained using an automatic Internet meteorological station. The data for the study were taken from the state meteorological station Askania-Nova (township Askania-Nova, Kakhovsky district, Kherson region, 46.45°N 33.88°E) and the automatic Internet meteorological station iMetos IMT 300 from the company "Pessl Instruments", which is located at the meteorological site of the Askaniysk DSDS (Tavrychanka village, Kakhovsky district, Kherson region, 46.55°N, 33.83°E). Standard evapotranspiration was calculated using the Penman-Monteith method (FAO56-RM). To assess the accuracy of $ET_0$ calculations, mean absolute percent error (MAPE), root mean square error (RMSE) and Standard Error of Estimate (SEE) were determined. According to the results of the comparison of indicators from two meteorological stations, it was found that the smallest errors are inherent in the daily average and maximum temperature and relative air humidity (MAPE<10 %), for the minimum temperature and relative air humidity, the MAPE errors are 18,1 and 13,7 %, respectively. The MAPE error for water vapor pressure deficit and solar radiation is 20,2 and 26,3 %, respectively. The largest MAPE error of 40,3 % was established for wind speed measurements. The average MAPE error between the calculated $ET_0$, based on the meteorological data of the Askania-Nova station, and the actual $ET_0$ data obtained from the automatic Internet meteorological station iMetos is 16,8 %, RMSE – 0,65 mm, SEE – 0,56 mm. Applying a coefficient of 0,92 when calculating $ET_0$ reduces the errors of MAPE, RMSE, and SEE by 3,2 %, 0,15 mm, and 0,05 mm, respectively, for all calculation periods. For the May-August period, the MAPE error was 10,7 %, which brings the calculations close to high accuracy (MAPE <10 %). Based on the results of the calculations, it was established that on average over the years of research, the actual $ET_0$ was 68 mm less than the calculated one. The absolute errors of determination of ETc depended on the crop and the average over the years of research ranged from 33 mm (winter wheat) to 68 mm (early tomatoes). The application of the refined value of $ET_0$ in calculations reduces the absolute errors in the determination of c over the years of research, this error did not exceed 6 mm (early tomato). Research results confirm the possibility of using meteorological indicators obtained from state meteorological stations to calculate $ET_0$. To increase the accuracy of calculations, it is necessary to use a refinement coefficient.*

***Key words:*** *reference evapotranspiration, Penman-Monteith method, meteorological stations, meteorological parameters, errors*

**Relevance of research.** Evapotranspiration (ET) plays an important role in the formation of the water balance of the field, which is the main expenditure item of the balance, and determines the need for irrigation. Despite the huge role of ET in the vital activity of plants, it is not always measured directly. The complexity of methods of direct measurement of ET, as well as the need for a detailed study of the variability of ET in time and area, contributed to the development of many calculation methods for determining potential evapotranspiration, one of which is the Penman-Monteith method [1]. Quantification of reference surface evapotranspiration ($ET_0$) used in the Penman-Monteith method is necessary in the context of many issues, such as crop production, water management, irrigation planning. Since the direct measurement of ET0 is a complex, time-consuming and expensive process, the most common procedure is to estimate $ET_0$ from climatic data, such as solar radiation, temperature and relative humidity, wind speed [2, 3]. The Food and Agriculture Organization of the United Nations (FAO) recommends the Penman-Monteith method (FAO56-PM) for $ET_0$ calculation, which can be used as a standard method for $ET_0$ estimation [4–7]. Any calculation of $ET_0$ should provide consistent and reliable results, use only commonly available meteorological data and a minimum of calculations. The FAO56-PM equation requires solar radiation, wind speed, temperature and humidity data. The quality of meteorological data and the difficulties in collecting them can be serious limitations. Although meteorological parameters are measured regularly and widely presented on weather sites on the Internet, they must be checked for reliability.

The FAO56-PM method requires a large amount of data, so it is desirable to check which factors influence evaporation and consider only such factors to determine evapotranspiration. The accuracy of the calculation depends on this. One of the methods for calculating the Penman-Monteith formula is to use a constant wind speed (2 m/s), as recommended by Allen [6]. Another option is to ignore the wind speed data. In the climatic conditions of Hungary, the method with a constant wind speed was recognized as the best [8].

**Analysis of recent research and publications**. Calculation of $ET_0$ requires data on radiation, air temperature, atmospheric humidity and wind speed, which limits its application in regions where these data are not available; therefore, new alternatives are needed. In a semi-arid region of Mexico, the accuracy of ET0 calculated by the Blaney-Criddle (BC) and Hargreaves-Samani (HS) methods was compared with that of FAO56-PM using information from the Automated Weather Station (AWS) and the NASA-POWER platform (NP) over different periods. Information on maximum and minimum temperatures from the NP platform was suitable for estimating $ET_0$ using the HS equation. This data source is a suitable alternative, especially in semi-arid regions with limited climatological data from weather stations [9]. In the Andean highlands, meteorological monitoring is limited and high-quality data is lacking. Therefore, the FAO 56-PM equation can only be applied using an alternative method. A study was conducted on the feasibility of effectively using the FAO 56-PM method to estimate missing data for Páramo landscapes in the high Andes of Southern Ecuador. The researchers found that using estimated wind speed data had no significant effect on estimated $ET_0$, but when solar radiation data were evaluated, $ET_0$ estimates could be in error by as much as 24 %; if relative humidity data is evaluated, the error can reach 14 %; and if all data except temperature are evaluated, errors exceeding 30 % may occur. Methods of estimation of solar radiation, water vapor pressure deficit calculated based on average temperature, and taking the minimum temperature as a dew point to estimate the actual vapor pressure have been successful. The study demonstrates the importance of using high-quality meteorological data to calculate $ET_0$ in humid Páramo landscapes in southern Ecuador [10, 11]. Reference evapotranspiration can be estimated using various methods, for example: Penman-Monteith, Blaney-Criddle, Hargreaves, ANN and WNN, regression and fuzzy logic. Humidity, temperature, wind speed, and solar radiation are factors that have a significant impact on $ET_0$ estimates. In general, traditional methods are cumbersome because the determination of $ET_0$ requires experimental setups and additional climate data, which are not available in many developing countries. So, in this case, non-traditional techniques can give more accurate results [12].

Modern technologies enable agricultural producers to minimize the time and effort previously required to monitor evapotranspiration, especially in large fields. Modern meteorological stations help to monitor and forecast the status of $ET_0$ effectively. Thus, instead of doing the calculations themselves, farmers can use ready-made solutions from meteorological service providers [13]. However, due to the high cost of existing technologies, it is difficult for small farms to obtain accurate data on evapotranspiration. The most economically efficient solution for them is the calculation of $ET_0$ based on meteorological data [14, 15].

**The purpose of the research** was to calculate reference evapotranspiration based on the data of the Askania-Nova state meteorological station and compare them with the actual $ET_0$ data obtained using an automatic Internet meteorological station.

**Materials and methods of research.** Meteorological data for this study were obtained from the state meteorological station Askania-Nova (WMO_ID 33915 town of Askania-Nova, Kakhovsky district, Kherson region. 46.45°N 33.88°E) [16] for the period from the 1st of April 2013 to 30th October 2018 and from the automatic Internet meteorological station iMetos IMT 300 from the company “Pessl Instruments” [17], which is located at the meteorological site of the Askaniysk SARS (Tavrychanka village, Kakhovsky district, Kherson region. 46.55° N. 33.83°E). The distance between the meteorological stations is 12,5 km, which does not significantly affect the climatic indicators for the selected points, so the comparison of the calculated ET0 is correct [18, 19].

Average daily meteorological data were used to analyze and calculate the reference evapotranspiration ($ET_0$): maximum, minimum temperature and relative air humidity, wind speed, dew point temperature, cloudiness, solar radiation.

The reference evapotranspiration, according to the meteorological data of the Askania-Nova state weather station, was calculated using the Penman-Monteith method FAO56-RM [6]:

$$ET_0 = \frac{0,408\Delta\left(R_n - G\right) + \gamma \dfrac{900}{T+273} u_2 \left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0,34u_2\right)} \qquad (1)$$

where $ET_0$ – reference evapotranspiration, mm/day; $Rn$ – net radiation on the surface of plants, MJ/m$^2$·day; $G$ – soil heat flow density, MJ/$^{m2}$·day; $T$ – average daily air temperature at a height of 2 m, °C; $u_2$ – wind speed at a height of 2 m, m/s; $e_s$ – saturated vapor pressure, kPa; $e_a$ – actual pressure, kPa; Δ – gradient of the vapor pressure curve, kPa/°C; γ – psychometric constant, kPa/C.

To calculate $e_s$ and $e_a$, the measured values of maximum and minimum air temperature and dew point temperature were used, respectively. The daily wind speed measured at the weather station (10 m above the ground) was calculated for a height of 2 m.

In the absence of observations of total solar radiation at the Askania-Nova meteorological station, it was calculated using the Savinov-Ongström formula [20]:

$$R_s = R_{so}\left[1 - \left(1 - k\right)n\right], \qquad (2)$$

where $Rs$ – total solar radiation, MJ/m$^2$·day; $Rso$ – solar radiation in the absence of clouds, MJ/m$^2$·day; $k$ – the coefficient that determines what part of the possible is the actual radiation under full cloud cover (k = 0,35 for 46.5° N); $n$ – average cloudiness in fractions of one.

Other parameters included in formulas (1) and (2) were calculated according to the FAO56-RM method [6]. The calculated reference evapotranspiration was compared with the actual $ET_o$ obtained from the Internet weather station iMetos IMT 300.

The evapotranspiration of crops was calculated according to the formula [6]:

$$ET_C = ET_0 \cdot K_C \qquad (3)$$

where $ET_C$ is evapotranspiration, mm/day; $K_C$ is the crop’s coefficient [21].

To assess the accuracy of reference evapotranspiration calculations, mean absolute percent error (MAPE), root mean square error (RMSE), and standard error of estimate (SEE) were determined [22, 23] (Table 1):

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{x-y}{x}\right| \cdot 100\,\%, \qquad (4)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(x-y\right)^2}, \qquad (5)$$

$$SEE = \sqrt{\frac{1}{(n-2)}\left[\left(y-\bar{y}\right)^2 - \frac{\left[\Sigma\left(x-\bar{x}\right)\left(y-\bar{y}\right)\right]^2}{\Sigma\left(x-\bar{x}\right)^2}\right]}, \qquad (6)$$

where $x$ – is $ET_0$ by the data of the Internet weather station iMetos; y – $ET_0$ calculated according to the FAO56-RM method; $n$ – the size of the sample.

1. The value of the MAPE error and its interpretation [23]

| MAPE, % | Interpretation |
|---|---|
| < 10 | High accuracy |
| 10–20 | Good accuracy |
| 20–50 | Satisfactory accuracy |
| >50 | Unsatisfactory accuracy |

**Research results and their discussion.** To verify the calculations according to equation (1), we calculated $ET_0$ from the data received from the iMetos meteorological station and compared them with those calculated automatically. The years 2013, 2015, and 2018 were selected for analysis. The average errors of MAPE, RMSE, and SEE, respectively, were 3,20; 0,13 and 0,13 (Table 2). The MAPE error over the years varied from 2.85 % (2018) to 3,58 % (2015).

2. Errors of $ET_0$ calculation according to the Penman-Monteith method (FAO56-PM) and according to the data of the meteorological station iMetos

| Error | 2013 | 2015 | 2018 | Average |
|---|---|---|---|---|
| MAPE | 3,15 | 3,58 | 2,85 | 3,20 |
| RMSE | 0,11 | 0,15 | 0,15 | 0,13 |
| SEE | 0,11 | 0,14 | 0,14 | 0,13 |

To evaluate the efficiency of the calculations, the average daily $ET_0$ values obtained from the weather station are plotted in the form of a graph depending on the calculated values according to FAO56-PM. As can be seen from the graph, the obtained linear dependence almost coincides with the 1:1 line, the coefficient of determination $R^2$=0,9949 for the sample series n = 642 (Fig. 1).

The obtained results of the calculations confirm their reliability and provide an opportunity for further analysis of $ET_0$ calculated from the data of the meteorological station Askania-Nova.

According to the results of the comparison of the air temperature measured at the iMetos and Askania-Nova meteorological stations, it was found out that the MAPE (Table 3) for the average daily and maximum air temperature on average over the years of research was 3,6 and 3,3 %, respectively (high accuracy), and RMSE (Table 3) – 0,73 and 1,26 °C. Checking the minimum air temperature showed that the MAPE between the two weather stations was 18,1 % (good accuracy) and the RMSE was 1,49 °C. The analysis of relative air humidity indicated that the MAPE for average daily, maximum, and minimum relative air humidity was 7,7, respectively; 9,1 % (high accuracy) and 13,7 % (good accuracy), and RMSE is 6,44; 10,14; 6,63 %, respectively. The MAPE error for water vapor pressure deficit and solar radiation was 20,2 and 26,3 % (satisfactory accuracy), respectively, and the RMSE error was 0,17 kPa and 3,89 MJ/m$^2$, respectively. The greatest MAPE error of 40,3 % (satisfactory accuracy) was established for wind speed measurements, the RMSE error was 0,77 m/s.

Despite the errors of the meteorological data included in the Penman-Monteith formula, the average MAPE between the calculated ET0, according to the weather station Askania-Nova and iMetos, was 16,8 % (good accuracy), RMSE – 0,65 mm, SEE – 0,56 mmThe largest MAPE and RMSE for ET0 were observed in 2015 and were 22,4 % and 0,89 mm, respectively. It is worth noting that this year was characterized by the largest errors of MAPE and RMSE among all measured meteorological parameters. As an example, MAPE and RMSE for wind speed were 101 % and 1,45 m/s, respectively, and for maximum air temperature were 5,2 % and 2,10 °C, respectively.

The analysis of errors by calendar months (Table 4) revealed that the largest errors of MAPE for air temperature are inherent in April and October. By reducing the observation period from April to October to May-September, MAPE errors for average daily and maximum air temperature are reduced by 1,3 and 0,8 %, respectively. The greatest decrease in MAPE by 9.9 % was observed for the minimum air temperature. MAPE for relative air humidity almost did not change, but for wind speed, on the contrary, it increased by 3,7 %. For the deficit of water vapor pressure and solar radiation, MAPE decreased by 5 %.

During the observation period (April-October), MAPE ET0 was 16,8 %, which is 2,5 % more than in May-September. The RMSE errors for all meteorological indicators almost did not change.

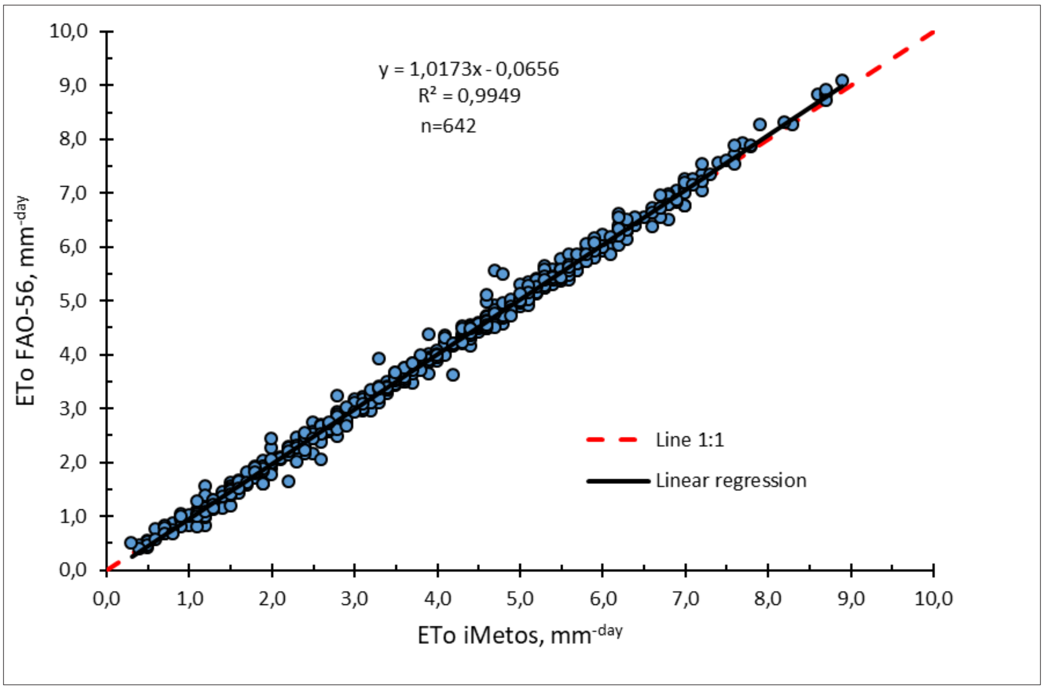


Fig. 1. Regression analysis to verify $ET_0$ calculations based on data from the iMetos meteorological station

3. MAPE and RMSE errors for iMetos and Askania-Nova weather stations (by year)

| **Year of research** | **Air temperature, °C** | | | **Relative air humidity, %** | | | **Wind speed, m/s** | **DWVP *, kPa** | **Solar radiation, MJ/m$^2$** | **ET$_0$, mm/day** |
|---|---|---|---|---|---|---|---|---|---|---|
| | **aver.** | **max.** | **min.** | **aver.** | **max.** | **min.** | | | | |
| MAPE error | | | | | | | | | | |
| 2013 | 2,8 | 2,7 | 13,7 | 6,0 | 6,3 | 9,2 | 22,2 | 17,7 | 24,5 | 12,3 |
| 2014 | 3,6 | 2,9 | 16,7 | 7,8 | 10,4 | 9,9 | 16,6 | 20,1 | 24,9 | 13,3 |
| 2015 | 7,0 | 5,2 | 24,6 | 11,2 | 11,2 | 22,4 | 101,0 | 20,0 | 26,2 | 22,4 |
| 2016 | 2,6 | 2,6 | 17,2 | 6,7 | 8,6 | 15,5 | 27,0 | 22,2 | 29,4 | 15,6 |
| 2017 | 3,0 | 2,8 | 19,5 | 7,8 | 9,7 | 11,2 | 52,0 | 28,6 | 28,3 | 19,5 |
| 2018 | 2,6 | 3,4 | 16,6 | 6,6 | 8,4 | 14,2 | 22,8 | 12,7 | 24,6 | 10,5 |
| Average | 3,6 | 3,3 | 18,1 | 7,7 | 9,1 | 13,7 | 40,3 | 20,2 | 26,3 | 16,8 |
| RMSE error | | | | | | | | | | |
| 2013 | 0,65 | 0,96 | 1,28 | 5,44 | 6,88 | 5,31 | 0,63 | 0,18 | 3,44 | 0,58 |
| 2014 | 0,52 | 0,88 | 1,30 | 6,11 | 10,88 | 4,57 | 0,47 | 0,17 | 3,83 | 0,60 |
| 2015 | 1,41 | 2,10 | 1,85 | 9,73 | 12,85 | 10,06 | 1,45 | 0,19 | 4,47 | 0,89 |
| 2016 | 0,63 | 0,70 | 1,68 | 5,97 | 10,56 | 8,10 | 0,67 | 0,15 | 3,80 | 0,60 |
| 2017 | 0,63 | 1,83 | 1,52 | 6,38 | 10,69 | 6,51 | 0,77 | 0,20 | 3,98 | 0,72 |
| 2018 | 0,56 | 1,06 | 1,28 | 4,97 | 9,00 | 5,22 | 0,61 | 0,15 | 3,82 | 0,50 |
| Average | 0,73 | 1,26 | 1,49 | 6,44 | 10,14 | 6,63 | 0,77 | 0,17 | 3,89 | 0,65 |

*DWVP – deficiency of water vapor pressure.

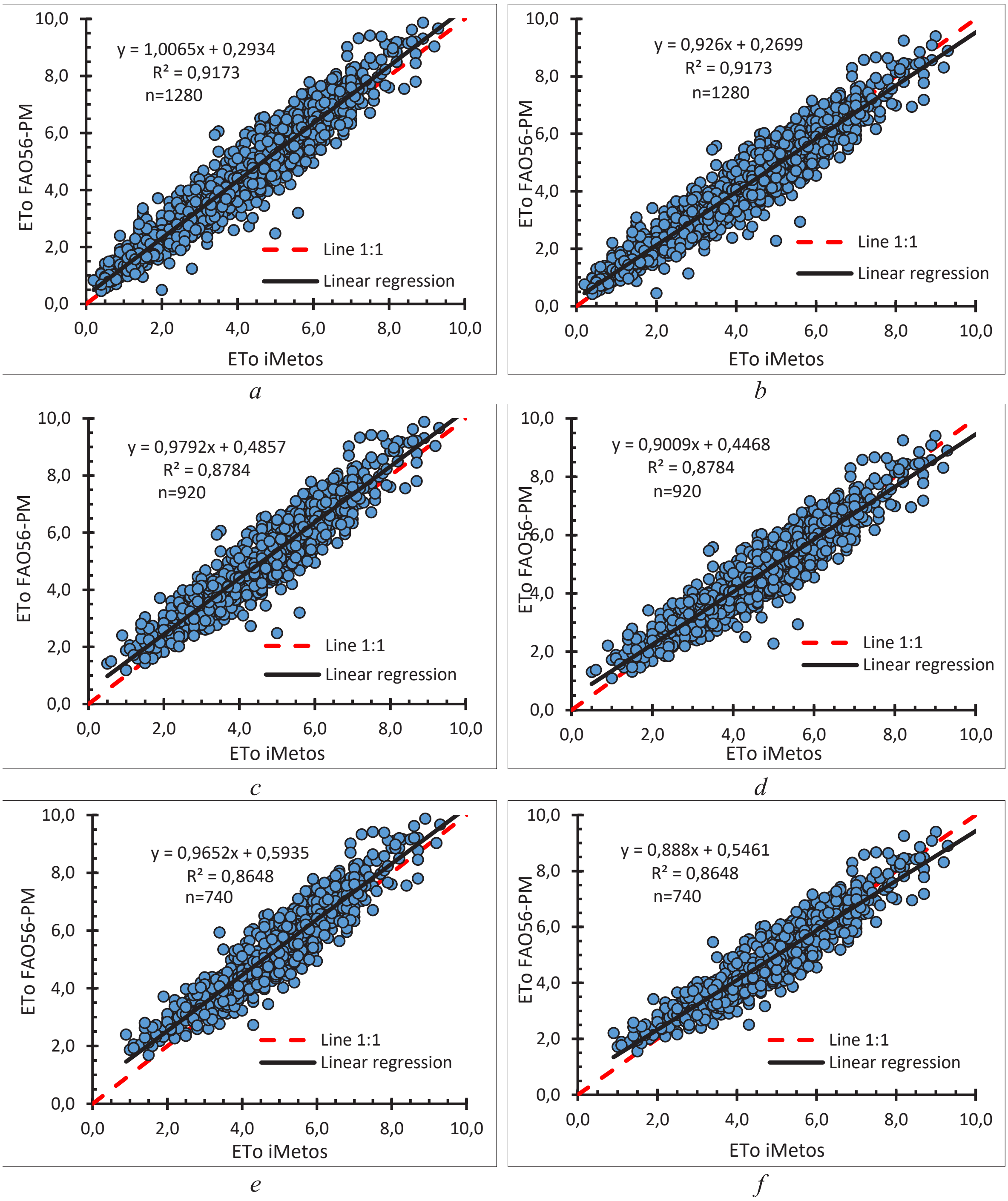
4. MAPE and RMSE errors for iMetos and Askania-Nova weather stations (by month)

| **Month of research** | **Air temperature, °C** | | | **Relative air humidity, %** | | | **Wind speed, m/s** | **DWVP, kPa** | **Solar radiation, MJ/m$^2$** | **ETo, mm/day** |
|---|---|---|---|---|---|---|---|---|---|---|
| | **aver.** | **max.** | **min.** | **aver.** | **max.** | **min.** | | | | |
| MAPE error | | | | | | | | | | |
| April | 4,1 | 3,9 | 45,5 | 7,3 | 7,3 | 14,0 | 27,8 | 28,5 | 26,2 | 15,6 |
| May | 2,7 | 2,9 | 9,8 | 8,7 | 8,6 | 11,5 | 59,4 | 21,1 | 20,9 | 14,5 |
| June | 2,1 | 2,4 | 7,9 | 8,7 | 10,6 | 11,2 | 84,4 | 18,2 | 18,9 | 16,2 |
| July | 2,0 | 2,2 | 5,9 | 7,2 | 10,3 | 13,7 | 35,8 | 12,5 | 18,4 | 13,1 |
| August | 2,0 | 1,8 | 5,0 | 6,9 | 10,5 | 14,4 | 18,7 | 9,0 | 22,1 | 10,3 |
| September | 2,6 | 3,1 | 12,3 | 7,1 | 8,6 | 17,7 | 21,9 | 15,2 | 26,8 | 14,0 |
| October | 10,4 | 7,0 | 44,8 | 8,2 | 7,8 | 12,9 | 42,5 | 39,3 | 53,0 | 26,9 |
| April-Oct. | 3,6 | 3,3 | 18,1 | 7,7 | 9,1 | 13,7 | 40,3 | 20,2 | 26,3 | 16,8 |
| May-Sept. | 2,3 | 2,5 | 8,2 | 7,7 | 9,7 | 13,7 | 44,0 | 15,2 | 21,4 | 14,3 |
| RMSE error | | | | | | | | | | |
| April | 0,52 | 0,97 | 1,30 | 6,88 | 8,36 | 7,50 | 0,70 | 0,11 | 3,88 | 0,46 |
| May | 0,68 | 2,06 | 1,05 | 7,35 | 10,01 | 7,36 | 0,88 | 0,16 | 4,12 | 0,65 |
| June | 0,60 | 0,89 | 1,84 | 6,82 | 11,64 | 5,39 | 0,94 | 0,19 | 4,03 | 0,79 |
| July | 0,64 | 0,94 | 1,20 | 5,65 | 11,40 | 7,06 | 0,60 | 0,21 | 4,01 | 0,77 |
| August | 0,66 | 0,73 | 1,12 | 4,57 | 10,30 | 4,49 | 0,59 | 0,19 | 3,90 | 0,67 |
| September | 0,67 | 1,20 | 1,61 | 6,69 | 9,62 | 6,96 | 0,76 | 0,20 | 3,72 | 0,63 |
| October | 1,42 | 2,02 | 2,11 | 7,87 | 10,45 | 8,70 | 1,19 | 0,13 | 3,61 | 0,60 |
| April-Oct. | 0,73 | 1,26 | 1,49 | 6,44 | 10,14 | 6,63 | 0,77 | 0,17 | 3,89 | 0,65 |
| May-Sept. | 0,65 | 1,16 | 1,36 | 6,22 | 10,60 | 6,25 | 0,75 | 0,19 | 3,96 | 0,71 |

According to the results of ET0 calculations according to the FAO56-PM formula, according to the data of the Askania-Nova meteorological station, it was established that the errors of MAPE, RMSE and SEE (Table 5) between the calculated and actual values for the period April-October (Fig. 2a, n=1280) are 16,8 %, respectively; 0,65 mm and 0,56 mm, coefficient of determination $R^2=0.92$. As can be seen from Figure 2a, the regression line of estimated ET$_0$ values passes above the 1:1 line, which means that the actual values are less than the estimated. The ratio of actual ET0 values to estimated values is 0,92. The coefficient of 0,92 in ET0 calculations reduces MAPE, RMSE, and

5. Errors between calculated and actual $ET_0$ values

| Observation period | iMetos – Askania-Nova | | | | iMetos – Askania-Nova (specified) | | | |
|---|---|---|---|---|---|---|---|---|
| | MAPE | RMSE | SEE | $R^2$ | MAPE | RMSE | SEE | $R^2$ |
| April – October | 16,8 | 0,65 | 0,56 | 0,92 | 13,6 | 0,53 | 0,52 | 0,92 |
| May – September | 14,3 | 0,71 | 0,59 | 0,88 | 11,1 | 0,56 | 0,54 | 0,88 |
| May – August | 13,9 | 0,72 | 0,59 | 0,86 | 10,7 | 0,56 | 0,54 | 0,86 |



*a* *b*

*c* *d*

*e* *f*

Fig. 2. Regression analysis for verification of ET0 calculations based on data from the Askania-Nova meteorological station for the period: April-October (*a*, *b*); May-September (*c*, *d*); May-August (*e*, *f*)

SEE errors by 3,2 %, respectively; 0,12 mm and 0,04 mm. The regression line and the 1:1 line intersect at point 4.0 (Fig. 2b). Up to ET0 values of 4,0 mm, the actual values are less than the calculated values, and then they begin to exceed them.

By reducing the observation period to May-September (Fig. 2c, $n = 920$), the MAPE error and the coefficient of determination $R^2$ decreased to 14,3 % and 0,88, respectively, and the RMSE and SEE increased and amounted to 0,71 mm and 0,59 mm, respectively. Application of the 0,92 factor in $ET_0$ calculations reduces MAPE, RMSE and SEE errors by 3,2 %, respectively; 0,17 mm and 0,05 mm for this calculation period. The regression line and the 1:1 line cross at point 4,5 (Fig. 2d). Up to $ET_0$ values of 4,5 mm, the actual values are less than the calculated values, and then they begin to exceed them. For the May-August period (Fig. 2d, $n = 740$), the MAPE error and the coefficient of determination $R^2$ between the calculated and actual ET0 values decreased to 13,9 % and 0,86, respectively, and the RMSE and SEE almost did not change to the May-September period and were 0,72 mm and 0,59 mm, respectively. The inclusion of the coefficient 0,92 in the $ET_0$ calculations reduces the MAPE, RMSE, and SEE errors by 3,2 %, respectively; 0,16 mm and 0,05 mm. The regression line and the 1:1 line intersect at point 5,0 (Fig. 2e). Up to $ET_0$ values of 5,0 mm, the actual values are less than the calculated values, and then they begin to exceed them.

To establish the errors of evapotranspiration ($ET_C$) of crops, which may arise when using $ET_0$ calculated according to the FAO56-PM formula, appropriate calculations were carried out for some crops. The $K_C$, specified in previous studies, were used to calculate the *ETS* [21]. $ET_C$ were calculated for each day for each year of research. On average, over the years of the study, the actual $ET_0$ was 68 mm less than the calculated one (tabl. 6), by year this difference ranged from 26 (2018) to 109 mm (2017). As a result, $ET_C$ for all cultures, when using the calculated $ET_0$ according to the data of the meteorological station Askania-Nova, also exceeded the actual values. The absolute error of $ET_C$ determination

6. Evapotranspiration of crops and its error, according to the data of meteorological stations iMetos and Askania-Nova

| **Date / year** | **$ET_0$** | **Winter wheat** | **Corn** | **Medium ripe soybeans** | **Late ripe soybeans** | **Early onions** | **Medium ripe onion** | **Early tomato** | **Medium ripe tomato** |
|---|---|---|---|---|---|---|---|---|---|
| Evapotranspiration, according to the data of the meteorological station iMetos | | | | | | | | | |
| 2013 | 831 | 395 | 573 | 544 | 687 | 372 | 476 | 743 | 772 |
| 2014 | 887 | 347 | 602 | 563 | 726 | 399 | 493 | 755 | 788 |
| 2015 | 811 | 303 | 526 | 492 | 649 | 329 | 442 | 630 | 705 |
| 2016 | 790 | 315 | 539 | 498 | 642 | 349 | 445 | 677 | 707 |
| 2017 | 845 | 326 | 584 | 545 | 701 | 364 | 497 | 709 | 790 |
| 2018 | 948 | 407 | 581 | 541 | 719 | 364 | 482 | 727 | 776 |
| Average | 852 | 349 | 567 | 531 | 687 | 363 | 472 | 707 | 756 |
| Evapotranspiration, according to the data of the meteorological station Askania-Nova | | | | | | | | | |
| 2013 | 892 | 431 | 616 | 587 | 738 | 400 | 511 | 806 | 829 |
| 2014 | 956 | 361 | 655 | 611 | 789 | 433 | 537 | 818 | 857 |
| 2015 | 889 | 348 | 583 | 548 | 716 | 365 | 487 | 702 | 778 |
| 2016 | 855 | 346 | 589 | 546 | 700 | 385 | 484 | 749 | 770 |
| 2017 | 954 | 380 | 648 | 609 | 778 | 410 | 546 | 805 | 871 |
| 2018 | 974 | 422 | 610 | 571 | 752 | 386 | 503 | 771 | 813 |
| Average | 920 | 381 | 617 | 579 | 745 | 396 | 511 | 775 | 820 |
| Absolute evapotranspiration error (iMetos – Askania-Nova) | | | | | | | | | |
| 2013 | –61 | –36 | –43 | –43 | –52 | –28 | –34 | –63 | –57 |
| 2014 | –69 | –14 | –53 | –48 | –62 | –35 | –45 | –63 | –69 |
| 2015 | –78 | –45 | –57 | –56 | –68 | –36 | –45 | –72 | –73 |
| 2016 | –65 | –31 | –50 | –48 | –58 | –35 | –39 | –72 | –64 |
| 2017 | –109 | –54 | –64 | –64 | –77 | –46 | –49 | –96 | –82 |
| 2018 | –26 | –15 | –29 | –30 | –32 | –22 | –22 | –44 | –36 |
| Average | –68 | –33 | –49 | –48 | –58 | –34 | –39 | –68 | –63 |

depended on the culture and the average over the years of research ranged from 33 (winter wheat) to 68 mm (early tomatoes). The highest $ET_C$ determination errors were recorded in 2017 – 46 mm for early onion and 96 mm for early tomato.

The application of the refined value of $ET_0$ in the calculations reduces the absolute errors in the determination of $ET_C$ (Table 7). So, over the years of research, this error did not exceed 6 mm (early tomatoes). In 2017, the absolute error of determination of $ET_C$ for early onions decreased by 32 mm, and for early tomatoes by 64 mm, and in 2018, the corrected values of $ET_C$, on the contrary, became smaller than the actual ones. Thus, for early onions, the absolute error was 9 mm, and for medium-ripe tomatoes – 29 mm.

Based on the results of the analysis of the absolute errors of determining ETs by month (Table 8), it was found that the reduction of the calculation period to May-September did not affect the errors for most crops, only for winter wheat this error decreased by 6 mm. The distribution of errors by month depended on the crop. Thus, for mid-ripe tomatoes and late-ripe soybeans, the absolute error was –10 mm in June, and +12 and +9 mm in August, respectively.

**Conclusions.** The results of $ET_0$ calculations based on meteorological data obtained from the iMetos station confirm their reliability. The errors of MAPE, RMSE, and SEE between our calculated and actual values of $ET_0$ were 3,2 %, respectively; 0,13, 0,13 mm.

According to the results of the comparison of meteorological indicators, it was found that the minimal errors are inherent in the daily average, maximum temperature and relative air humidity (MAPE<10 %), for the minimum temperature and relative air humidity, the MAPE errors were 18,1 and 13,7 %, respectively. The MAPE error for the deficit of water vapor pressure and solar radiation was 20,2 and 26,3 %, correspondently. The maximal MAPE error of 40,3 % was for wind speed measurements. By shortening the observation period from April to October to May-September, MAPE errors are reduced by 1–10 %, depending on the meteorological indicator.

7. Refined evapotranspiration of crops and its error, according to the data of meteorological stations iMetos and Askania-Nova

| **Date / year** | **$ET_0$** | **Winter wheat** | **Corn** | **Medium ripe soybeans** | **Late ripe soybeans** | **Early onions** | **Medium ripe onion** | **Early tomato** | **Medium ripe tomato** |
|---|---|---|---|---|---|---|---|---|---|
| Evapotranspiration, according to the data of the meteorological station iMetos | | | | | | | | | |
| 2013 | 831 | 395 | 573 | 544 | 687 | 372 | 476 | 743 | 772 |
| 2014 | 887 | 347 | 602 | 563 | 726 | 399 | 493 | 755 | 788 |
| 2015 | 811 | 303 | 526 | 492 | 649 | 329 | 442 | 630 | 705 |
| 2016 | 790 | 315 | 539 | 498 | 642 | 349 | 445 | 677 | 707 |
| 2017 | 845 | 326 | 584 | 545 | 701 | 364 | 497 | 709 | 790 |
| 2018 | 948 | 407 | 581 | 541 | 719 | 364 | 482 | 727 | 776 |
| Average | 852 | 349 | 567 | 531 | 687 | 363 | 472 | 707 | 756 |
| Evapotranspiration, according to the data of the meteorological station Askania-Nova | | | | | | | | | |
| 2013 | 821 | 397 | 567 | 540 | 679 | 368 | 470 | 742 | 763 |
| 2014 | 880 | 332 | 602 | 563 | 725 | 399 | 494 | 753 | 789 |
| 2015 | 818 | 320 | 536 | 504 | 659 | 336 | 448 | 646 | 715 |
| 2016 | 786 | 318 | 542 | 503 | 644 | 354 | 445 | 689 | 709 |
| 2017 | 877 | 350 | 597 | 560 | 715 | 377 | 502 | 741 | 802 |
| 2018 | 896 | 388 | 561 | 525 | 692 | 355 | 463 | 709 | 748 |
| Average | 846 | 351 | 567 | 533 | 686 | 365 | 470 | 713 | 754 |
| Absolute evapotranspiration error (iMetos – Askania-Nova) | | | | | | | | | |
| 2013 | 10 | –2 | 6 | 4 | 7 | 4 | 7 | 1 | 9 |
| 2014 | 8 | 15 | –1 | 1 | 1 | 0 | –2 | 2 | 0 |
| 2015 | –7 | –17 | –10 | –12 | –10 | –7 | –6 | –15 | –11 |
| 2016 | 3 | –3 | –3 | –4 | –2 | –5 | 0 | –12 | –2 |
| 2017 | –33 | –24 | –12 | –15 | –15 | –14 | –5 | –32 | –12 |
| 2018 | 51 | 19 | 20 | 16 | 28 | 9 | 18 | 18 | 29 |
| Average | 6 | –2 | 0 | –2 | 1 | –2 | 2 | –6 | 2 |

8. Evapotranspiration of crops and its error, according to the data of meteorological stations iMetos and Askania-Nova, by month (using as the example 2017)

| **Date / month** | **$ET_0$** | **Winter wheat** | **Corn** | **Medium ripe soybeans** | **Late ripe soybeans** | **Early onions** | **Medium ripe onion** | **Early tomato** | **Medium ripe tomato** |
|---|---|---|---|---|---|---|---|---|---|
| Evapotranspiration, according to the data of the meteorological station iMetos | | | | | | | | | |
| April | 69 | 66 | 0 | 0 | 0 | 0 | 0 | 0 | 7 |
| May | 113 | 134 | 47 | 64 | 68 | 38 | 30 | 104 | 76 |
| June | 152 | 123 | 172 | 178 | 192 | 125 | 121 | 288 | 197 |
| July | 163 | 3 | 216 | 192 | 211 | 178 | 171 | 310 | 260 |
| August | 194 | 0 | 146 | 112 | 206 | 23 | 174 | 6 | 251 |
| September | 111 | 0 | 2 | 0 | 24 | 0 | 0 | 0 | 0 |
| October | 43 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| April-Oct. | 845 | 326 | 584 | 545 | 701 | 364 | 497 | 709 | 790 |
| May-Sept. | 732 | 260 | 584 | 545 | 701 | 364 | 497 | 709 | 783 |
| Evapotranspiration, according to the data of the meteorological station Askania-Nova (refined) | | | | | | | | | |
| April | 75 | 71 | 0 | 0 | 0 | 0 | 0 | 0 | 7 |
| May | 123 | 145 | 53 | 71 | 75 | 42 | 34 | 116 | 83 |
| June | 159 | 130 | 181 | 187 | 202 | 132 | 127 | 303 | 207 |
| July | 166 | 4 | 221 | 196 | 216 | 181 | 175 | 316 | 266 |
| August | 186 | 0 | 139 | 106 | 197 | 22 | 166 | 6 | 238 |
| September | 118 | 0 | 3 | 0 | 25 | 0 | 0 | 0 | 0 |
| October | 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| April-Oct. | 877 | 350 | 597 | 560 | 715 | 377 | 502 | 741 | 802 |
| May-Sept. | 752 | 279 | 597 | 560 | 715 | 377 | 502 | 741 | 795 |
| Absolute evapotranspiration error (iMetos – Askania-Nova) | | | | | | | | | |
| April | –6 | –5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| May | –9 | –11 | –6 | –7 | –8 | –4 | –4 | –11 | –8 |
| June | –8 | –7 | –9 | –9 | –10 | –6 | –6 | –14 | –10 |
| July | –4 | 0 | –5 | –4 | –5 | –3 | –4 | –6 | –6 |
| August | 8 | 0 | 7 | 6 | 9 | 0 | 9 | 0 | 12 |
| September | –7 | 0 | 0 | 0 | –1 | 0 | 0 | 0 | 0 |
| October | –7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| April-Oct. | –33 | –24 | –12 | –15 | –15 | –14 | –5 | –32 | –12 |
| May-Sept. | –20 | –18 | –12 | –15 | –15 | –14 | –5 | –32 | –12 |

It was found, that the average error of MAPE between the calculated $ET_0$ based on the meteorological data of the Askania-Nova station and the actual data of $ET_0$ obtained from the automatic Internet meteorological station iMetos is 16,8 %, RMSE – 0,65 mm, SEE – 0,56 mm. Shortening the calculation period from April-October to May-August reduces the MAPE error for $ET_0$ by 2,9 %.

The use of a coefficient of 0,92 when calculating $ET_0$ reduces the errors of MAPE, RMSE, and SEE by 3,2 %, respectively; 0,15 and 0,05 mm for all calculation periods. For the May-August period, the MAPE error was 10,7 %, which brings the calculations close to high accuracy (MAPE <10 %).

Based on the results of calculations, it was found that on average over the years of research, the actual $ET_0$ was 68 mm less than the calculated one. The absolute errors of determination of *ETs* depended on the culture and on average over the years of research ranged from 33 (winter wheat) to 68 mm (early tomatoes). The maximal errors of $ET_C$ determination were recorded in 2017, which were 46 mm for early onion and 96 mm for early tomato.

Application of the refined $ET_0$ value in the calculations reduces the absolute errors of $ET_C$ determination, over the years of research this error did not exceed 6 mm (early tomato). In 2017, the absolute error of $ET_C$ determination for early onion decreased by 32 mm, and for early tomato – by 64 mm.

So, the research results confirm the possibility of using meteorological indicators obtained from state weather stations to calculate $ET_0$. To increase the accuracy of calculations, it is recommended to use a refinement coefficient.

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УДК 631.67

# АНАЛІЗ РОЗРАХУНКУ ЕТАЛОННОЇ ЕВАПОТРАНСПІРАЦІЇ ЗА ДАНИМИ ДЕРЖАВНОЇ МЕТЕОРОЛОГІЧНОЇ СТАНЦІЇ

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***Анотація.*** *Оскільки пряме вимірювання еталонної евапотранспірації (ET*$_0$*) є складним, трудомістким і дорогим процесом, найпоширенішою процедурою є оцінювання ETo за кліматичними даними. Метою проведення цього дослідження було виконати розрахунки еталонної евапотранспірації за даними державної метеостанції Асканія-Нова та порівняти їх з фактичними даними ET*$_0$*, отриманими за допомогою автоматичної інтернет-метеорологічної станції. Дані для дослідження були взяті з державної метеорологічної станції Асканія-Нова (смт Асканія-Нова, Каховський р-н, Херсонська обл., 46.45° п.ш. 33.88° сх.д.) та з автоматичної інтернет-метеорологічної станції iMetos IMT 300 від компанії "Pessl Instruments", яка розташована на метеомайданчику Асканійської ДСДС (с. Тавричанка, Каховський р-н, Херсонська обл. 46.55° п.ш. 33.83° сх.д.). Еталону евапотранспірацію розраховували за методом Пенмана-Монтейта (FAO56-PM). Для оцінювання точності розрахунків ET*$_0$ *визначали середню абсолютну відсоткову помилку MAPE (Mean Absolute Percent Error), середньоквадратичну похибку RMSE (Root Mean Square Error) та стандартну похибку SEE (Standard Error of Estimate). За результатами порівняння показників з двох метеорологічних станцій встановлено, що найменші похибки притаманні для середньодобової та максимальної температури та відносної вологості повітря (MAPE<10 %), для мінімальної температури та відносної вологості повітря похибки MAPE відповідно становлять 18,1 і 13,7 %. Похибка MAPE для дефіциту тиску водяної пари та сонячної радіації відповідно становить 20,2 і 26,3 %. Найбільшу похибку MAPE 40,3 % встановлено для вимірювань швидкості вітру. Середня похибка MAPE між розрахованою ET*$_0$*, за метеорологічними даними станції Асканія-Нова, та фактичними даними ET*$_0$*, отриманими з автоматичної інтернет-метеорологічної станції iMetos, становить 16,8 %, RMSE – 0,65 мм, SEE – 0,56 мм. Застосування коефіцієнта 0,92 при* *розрахунку $ET_0$ зменшує похибки MAPE, RMSE та SEE відповідно на 3,2 %, 0,15 мм та 0,05 мм для всіх розрахункових періодів. За період травень-серпень похибка MAPE становила 10,7 %, що наближує розрахунки майже до високої точності (MAPE <10 %). За результатами розрахунків встановлено, що в середньому за роки досліджень фактична $ET_0$ була на 68 мм менша, ніж розрахована. Абсолютні похибки визначення ETc залежали від культури і в середньому за роки досліджень становили від 33 мм (пшениця озима) до 68 мм (томати ранні). Застосування в розрахунках уточненого значення $ET_0$ зменшують абсолютні похибки визначення ETc, за роки досліджень ця похибка не перевищувала 6 мм (томат ранній).Результати досліджень підтверджують можливість використання метеорологічних показників, отриманих з державних метеостанцій, для розрахунку $ET_0$. Для підвищення точності розрахунків необхідно використовувати уточнювальний коефіцієнт.*

***Ключові слова:*** *еталонна евапотранспірація, метод Пенмана-Монтейта, метеорологічні станції, метеопараметри, похибки*