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Assessment of Reference Evapotranspiration in the South of Ukraine by Air Temperature

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ABSTRACT: Reference evapotranspiration is an important parameter for irrigation management. Freshwater scarcity requires careful approach to the water use in agriculture, and the maximum water use efficiency in irrigation might be achieved through reference evapotranspiration (ET_0) estimation. Modern methods for ET_0 assessment require great number of specific meteorological inputs, which include some indices of uncommon nature for most hydrometeorological stations in Ukraine, thus frequently it is difficult to provide the required amount of data to calculate ET_0. Therefore, modern irrigated agriculture must provide a solution for this challenge and work out methods for ET_0 estimation at the limited availability of meteorological inputs. The goal of the study was to develop simple equation for ET_0 calculation using air temperature as the only input. The starting point was the calculations of ET_0 by the complete Penman-Monteith equation using ET_0 Calculator software for Southern Steppe zone of Ukraine in general and by the regions, including Kherson, Mykolaiv, Odesa, and Zaporizhzhia oblasts. The simplified models for reference evapotranspiration computation were developed by the results of regression analysis between the average air temperature and calculated by the complete ET_0 equation. The test of their accuracy proved that it is reasonable to use the simplified models for fast and rough estimation of ET_0 in the studied regions, the mean average percentage errors of the models ranged within 30%.The method used in the study provides a solution for the challenge of ET_0 estimation using limited meteorological inputs, and the method will be implemented for other climatic zones and the territory of Ukraine overall.

Keywords: evapotranspiration calculation, irrigation management, Penman-Monteith method, regression evapotranspiration model, Southern Steppe of Ukraine.

Abbreviations:ET_0, reference evapotranspiration; FAO, Food and Agriculture Organization of the United Nations; MAPE, mean absolute percentage error; R, correlation coefficient; R^2, determination coefficient; RMSE, root mean square error.

I. INTRODUCTION

Global warming of climate is a great challenge for food security insurance. Warmth elongates the duration of growing season, allowing wider introduction of double cropping system, increasing yields of some crops (firstly, sugar beets and leafy vegetables) and introduction of southern species in the North [1]. To some extent, global warming might be beneficial for crop production due to the opportunities for the productivity increase [2]. But the fact is that, along with the mentioned benefits, an increase in global air temperature and CO_2 concentration in the atmosphere provide numerous difficulties for sustainable crop production in the regions with initially dry climate, such as Africa, Middle East and some regions of Asia, resulting in impossibility of obtaining good yields without intensive irrigation practices [3-5]. The problem is aggravated by freshwater scarcity in these regions, or poor water quality, which makes it impossible to use it for irrigation purposes [6]. Therefore, rational agricultural water management under water-saving irrigation schedule is a question of top priority for crop production in the current climate conditions, in particular, in the regions with semi-arid and arid climate [7].

Irrigation management is mainly based on the water balance, which is the difference between the income and expenditures of water for evaporation from the soil surface, plants respiration, runoff, etc. [8]. The main constituent in water balance expenditures is the sum of water evaporation from the field and plants respiration, so called evapotranspiration. It could be estimated as potential (evaporation from bare soil), reference (evapotranspiration from soil surface in the crop cover of 12 cm height, fixed surface resistance of 70 s m-1 and an albedo of 0.23), and crop's evapotranspiration (reference evapotranspiration multiplied by the crop's coefficient at the certain stage of its growth) [9]. Potential evaporation is of little interest for agriculture, while reference evapotranspiration (hereinafter referred as ET_0) is very important index being a starting point for further calculations of water requirements for a certain crop in the concrete time span, for example, using FAO CROPWAT, AquaCrop or other software [10].

At the moment, there are a number of methods used for estimation of reference or crop evapotranspiration. The best one is a field lysimetric method [11]. It provides the best accuracy and results in case of measuring water use in the field of a certain crop, allowing continuous monitoring of water dynamics and expenditures.

So, lysimetric method is recommended to be used for calibration of computation methods, for example, for adjustment of crop coefficients for CROPWAT and AquaCrop [12]. Notwithstanding the fact that lysimetric method for ET_0 assessment seems to be the best option, actually, it is not so. The method requires special technical equipment, it is laborious and expensive, it is not suitable for forecasting evapotranspiration on the basis of weather forecasts, and it cannot provide information on the parameter for large-scale arrays. Besides, lysimeters are not free from distortions and errors in the measurements, which are connected with their constructions, usage regularities, crop peculiarities, etc. [13]. That is why indirect computation methods have gained more popularity among scientists and practitioners. These methods cannot compete with direct on-field measurements; however, numerous studies have proved appropriate level of their accuracy, which also can be improved by calibration. There is a lot of various calculation methodologies for evapotranspiration assessment, however, the most popular among them are: Holdridge method, recommended for determination of potential evapotranspiration [14]; based on the huge weather data Penman-Monteith method for reference evapotranspiration estimation, which has received the greatest popularity and is considered as a standard by FAO although having proved drawbacks [15], special software (ET_0 Calculator) has been developed to make complicated calculations by this method easier [16]; Makkink, Abtew, Priestly-Tailor methods based on the radiation [17]; based on the air temperature and some additional inputs methods by Hargreaves-Samani, Thornthwaite, Hamon, Linacre, Blaney-Criddle, among which Hargreaves-Samani and Thornthwaite methods received the most popularity and has been proved to be the most close in accuracy to the standard, especially if calibrated [17, 18]. However, in arid conditions, Thornthwaite method is sometimes reported to fail [19]. All in all, the question of the most appropriate alternative for Penman-Monteith method remains open and debatable, because some scientists report that the best substitution for evapotranspiration on agricultural lands are Valiantzas-2 and Hargreaves□Makkink methods [20]. The only common thing is that scientists are striving to develop the simplest method for evapotranspiration estimation with the use of the minimum number of inputs and satisfactory accuracy.

The main aim of the study was to find a possibility to simplify standard method of Penmant-Monteith for the reference evapotranspiration estimation in the most arid zone of Ukraine [21-23], which is Southern Steppe zone, on the whole and by the individual regions (oblasts) within the zone using average air temperature as the only input for calculations. Southern Steppe of Ukraine is conditionally considered to be within the regions of Odesa, Mykolaiv, Kherson, Zaporizhzhia oblasts [24]. Reference evapotranspiration values obtained using simplified models were compared to the values, obtained through conventional computations in ET_0 Calculator software, in order to conclude whether such a diminishment of the weather inputs is reasonable.

II. MATERIALS AND METHODS

The study was based on the long-term meteorological data on monthly maximum, mean, minimum air temperature, mean relative humidity, wind speed, and hours of bright sunshine (where applicable) in the warm period (average air temperature ≥0°C), which were obtained from Kherson (for the period of January 1973 – July 2020), Mykolaiv (for the period of January 2000 – July 2020), Odesa (for the period of January 2000 – July 2020), Zaporizhzhia (for the period of January 1971 – July 2020) regional meteorological stations. The total number of data inputs, after the exclusion of the data pairs with the temperatures below zero, was: Kherson oblast – 477; Mykolaiv – 202; Odesa – 225; Zaporizhzhia – 447; Southern Steppe on the whole – 1351. All the meteorological data, used in the study, are available at the statistical web-database http://www.pogodaiklimat.ru/msummary. Weather data were used as the inputs for calculation of reference evapotranspiration by Penman-Monteith method in ET_0 Calculator. Cold periods of the studied years were excluded from the estimation because our study is mainly aimed to provide an instrument of fast and simple assessment of reference evapotranspiration for agricultural producers, who are not interested in ET_0 values out of the growing (warm) season of the year. Therefore, the pairs with air temperatures below zero were not taken into account and they were excluded from regression analysis. The values of the calculated reference evapotranspiration were linked to the corresponding values of average air temperature, and linear regression analysis (at $p<0.05$) was performed to develop simplified equations for reference evapotranspiration estimation. ET_0 prediction accuracy was evaluated by the values of mean absolute percentage error (MAPE) [Moreno et al., 2013]. Statistical processing of the data was performed in BioStat v7 software.

III. RESULTS AND DISCUSSION

Connection of monthly reference evapotranspiration, calculated in ET_0 Calculator by the standard Penman-Monteith method with full engagement of weather inputs, to the corresponding values of average air temperature resulted in determination of close correlation relationship between the indices (Table 1). Regression analysis pointed out that it is possible to derive reliable reference evapotranspiration using average air temperature as the only input that is proved by high values of the coefficients of determination R^2 for every studied region, which ranges from 0.95 to 0.97.

The models of reference evapotranspiration estimation by the average air temperature, developed for the warm period of year, are presented as simple equations in the Table 2 MAPE values are close to 30% (reasonable forecast according to Moreno *et al.,* [25]), therefore, the models can be considered reasonable and might be recommended to implementation in scientific and practical purposes. The highest accuracy, according to R^2 (0.9732) and MAPE (26.46<30%) values, is in the model for Zaporizhzhia oblast, although the number of inputs in this case was not the greatest (447). The least accuracy of estimation was recorded for Odesa oblast – R^2 of 0.9654 and MAPE of 32.96%.

Table 1: Regression analysis results on the relationship between average air temperature and Penman-Monteith reference evapotranspiration in the studied areas.

Criteria	Kherson oblast	Mykolaiv oblast	Odesa oblast	Zaporizhzhia oblast	Southern Steppe
R	0.9781	0.9864	0.9826	0.9865	0.9805
R^2	0.9568	0.9731	0.9654	0.9732	0.9614
Adjusted R^2	0.9568	0.9731	0.9654	0.9732	0.9614
Predicted R^2	0.9566	0.9728	0.9651	0.9730	0.9613
RMSE	0.6189	0.4454	0.3377	0.3962	0.5410
MAPE	31.13	29.02	32.96	26.46	30.71
Argument	0.2473	0.2551	0.2034	0.2499	0.2422

Table 2: Simplified equations for the ET_0 calculation in the studied areas based on the average air temperature (T).

Region	Equation
Kherson oblast	$ET_0 = 0.2473 \times T \pm 31.13\%$
Mykolaiv oblast	$ET_0 = 0.2551 \times T \pm 29.02\%$
Odesa oblast	$ET_0 = 0.2034 \times T \pm 32.96\%$
Zaporizhzhia oblast	$ET_0 = 0.2499 \times T \pm 26.46\%$
Southern Steppe	$ET_0 = 0.2422 \times T \pm 30.71\%$

Table 3: Range of reference evapotranspiration in the regions of Southern Steppe of Ukraine with accordance to the simplified models.

Air temperature (ºC)	Evapotranspiration (mm)				
	Kherson oblast	Mykolaiv oblast	Odesa oblast	Zaporizhzhia oblast	Southern Steppe
1	0.2	0.3	0.2	0.2	0.2
2	0.5	0.5	0.4	0.5	0.5
3	0.7	0.8	0.6	0.7	0.7
4	1.0	1.0	0.8	1.0	1.0
5	1.2	1.3	1.0	1.2	1.2
6	1.5	1.5	1.2	1.5	1.5
7	1.7	1.8	1.4	1.7	1.7
8	2.0	2.0	1.6	2.0	1.9
9	2.2	2.3	1.8	2.2	2.2
10	2.5	2.6	2.0	2.5	2.4
11	2.7	2.8	2.2	2.7	2.7
12	3.0	3.1	2.4	3.0	2.9
13	3.2	3.3	2.6	3.2	3.1
14	3.5	3.6	2.8	3.5	3.4
15	3.7	3.8	3.1	3.7	3.6
16	4.0	4.1	3.3	4.0	3.9
17	4.2	4.3	3.5	4.2	4.1
18	4.5	4.6	3.7	4.5	4.4
19	4.7	4.8	3.9	4.7	4.6
20	4.9	5.1	4.1	5.0	4.8
21	5.2	5.4	4.3	5.2	5.1
22	5.4	5.6	4.5	5.5	5.3
23	5.7	5.9	4.7	5.7	5.6
24	5.9	6.1	4.9	6.0	5.8
25	6.2	6.4	5.1	6.2	6.1
26	6.4	6.6	5.3	6.5	6.3
27	6.7	6.9	5.5	6.7	6.5
28	6.9	7.1	5.7	7.0	6.8
29	7.2	7.4	5.9	7.2	7.0
30	7.4	7.7	6.1	7.5	7.3
31	7.7	7.9	6.3	7.7	7.5
32	7.9	8.2	6.5	8.0	7.8
33	8.2	8.4	6.7	8.2	8.0
34	8.4	8.7	6.9	8.5	8.2
35	8.7	8.9	7.1	8.7	8.5

The range of average reference evapotranspiration by the studied areas depending on the air temperature is provided in the Table 3. It is obvious that the driestclimate is in Mykolaiv oblast, and the most humid one is in Odesa oblast, mainly due to the fact of the closet location to the open sea.

Work on simplification of Penman-Monteith equation for reference evapotranspiration assessment has been performing for several years by various approaches. Valiantzas [26] provided a new formula for air temperature – humidity and solar radiation. Besides, Valiantzas provided simple forms for ET_0 calculation without wind and humidity data [27]. There was a study devoted to the estimation of reference evapotranspiration by Penman-Monteith method using limited data sets (monthly maximum and minimum air temperature only) in comparison with several other temperature-based methods (Hargreaves and Turk). The study reports that their overestimation of reference evapotranspiration was recorded at the reduced Penman-Monteith method, while Turk equation provided the most accurate results [28]. Besides, it is evident that the best method is different for different conditions. For example, Djaman *et al.,* [29] claimed that the best performance in reference evapotranspiration assessment was achieved for Valiantzas, Trabert, Romanenko, Schendel and Mahringer methods in the conditions of Senegal River Valley. Penman-Monteith method with missing climate data was also studied by Jabloun and Sahli [30], who recorded little discrepancies (-0.4 to 0.2 mm day-1) between the full set and limited set estimation of ET_0 in the weather conditions of Tunisia. Similar studies were carried out in other parts of the world, for example, in China, where Turk and Valiantzas methods performed best in comparison to others [31]. Kra provided the solution for simplification of Penman-Monteith temperature-based model through the implementation of empirical computations for the tropics [32]. Highly accurate simplified statistical models for the estimation of reference evapotranspiration under the limited meteorological data were also proposed by ElNesr and Alazba [33]. The study performed in Mexico found out that the best RMSE of the temperature-based Penman-Monteith method for reference evapotranspiration assessment reached 0.70 mm day^{-1}, while other methods, including calibrated Hargreaves-Samani and Camargo methods showed worse performance with RMSE of 0.74 and 0.78 mm day^{-1}. Other methods, based on ET_0 estimation using air temperatures only, provided unsatisfactory level of accuracy with average RMSE of 1.56 mm day^{-1} [34]. In our study RMSE of the temperature-based ET_0 was much less and ranged from 0.34 to 0.62 mm day^{-1}. The advantage of air temperature based ET_0 calculation is also in wide opportunities for ET_0 forecasting using weather forecasts [35]. Notwithstanding the fact that some studies report about the worst performance of ET_0 models based on the air temperature only [36], we consider that such models are prospective and should be worked out and thoroughly tested and calibrated to provide the most convenient options for the reference evapotranspiration assessment [37].

The main difference between the mentioned studies and our work is in the methodological approaches used to the calculation simplification. While most scientists applied complicated empirical evaluations and computations to simplify and avoid excessive calculations in the Penman-Monteith equation, we developed the models based on statistical analysis of large data sets. Of course, the models developed through regression analysis are rough and have comparatively high rate of error, they are still reasonable and appropriate for fast and rough estimation of reference evapotranspiration in the regions they were developed for.

IV. CONCLUSION

Simplified models for reference evapotranspiration calculation by the average air temperature as the only input has been developed. The models are relevant both for Southern Steppe zone of Ukraine in general and for separate regions of the zone, namely, Kherson, Mykolaiv, Odesa, Zaporizhzhia oblasts. Statistical evaluation proves reasonable accuracy of the simplified evapotranspiration estimation method, which can be considered as an alternative to complicated calculations of a standard Penman-Monteith method, in particular, when some weather data are missing. The models provide fast rough assessment of reference evapotranspiration and allow the forecasting based on the air temperature forecasts.

V. FUTURE SCOPE

Further study will be targeted on the development of regression models for ET_0 estimation in the Forest-Steppe and Polissya zones of Ukraine, and in the country in general.

In addition to meteorological data, remote sensing data might be used for the improvement of ET_0 calculation models [38].

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