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Simulation of irrigation in southern Ukraine incorporating soil moisture state in evapotranspiration assessments

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Abstract

The paper studies the accuracy of modeling moisture transport under the conditions of sprinkler irrigation using evapotranspiration assessment methods that take into account the soil moisture conditions. Appropriate modifications of the Penman-Monteith and the Priestley-Taylor models are considered. Moisture transport modeling is performed using the Richards equation in its integer- and fractional-order forms. Parameters identification is performed by the particle swarm optimization algorithm based on the readings of suction pressure sensors. Results for the two periods of 11 and 50 days demonstrate the possibility of up to ~20% increase in the simulation accuracy by using a modified Priestley-Taylor model when the maintained range of moisture content in the root layer is 70%-100% of field capacity. When irrigation maintained the range of 80%-100% of field capacity, moisture content consideration within evapotranspiration assessment models did not enhance simulation accuracy. This confirms the independence of evapotranspiration from soil moisture content at its levels above 80% of field capacity as in this case actual evapotranspiration reaches a level close to the potential one. Scenario modeling of the entire growing season with the subsequent estimation of crop (maize) yield showed that irrigation regimes generated using evapotranspiration models, which take into account soil moisture data, potentially provide higher yields at lower water supply.

Keywords: Evapotranspiration, Richards equation, soil moisture, corn productivity.

Introduction

The accuracy of evapotranspiration estimates is one of the determining factors for performing forecasts of soil moisture state in the irrigation management process (Wanniarachchi and Sarukkalige, 2022). In the areas of agricultural production, evapotranspiration can be considered as consisting of three components: evaporation of intercepted moisture, transpiration, and evaporation from the soil surface (Savenije, 2004).

Changes in the corresponding fluxes are mutually influenced by fluctuations in meteorological parameters, vegetation dynamics, and soil moisture (Rodriguez-Iturbe, 2000; Shao et al., 2017). Thus, to quantify the intensity of evapotranspiration for more accurate modeling of moisture transport in the "soil-plant-atmosphere" system, integrated models that consider soil and atmospheric physics along with plant physiology are needed (Overgaard et al., 2006).

A widely used evapotranspiration model based on the Penman–Monteith equation (Monteith, 1965) successfully estimates it in the case of closed vegetation for various weather and soil conditions (see, e.g., Shao et al., 2022). In it, the processes of transpiration and evaporation from the bare soil, which are different intrinsically, are not considered separately. One of the first models in which the description of these processes was separated was the Shuttleworth-Wallace model (Shuttleworth and Wallace, 1985). Among the disadvantages of this model, the need to determine the values of numerous parameters that limits its

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application can be singled out (Gharsallah et al., 2013). The compromise between the model's complexity and prediction accuracy is provided, in particular, by the Priestley-Taylor energy balance model (Priestley and Taylor, 1972). The modified Priestley–Taylor model can also effectively evaluate evaporation and transpiration separately using the data on the downward energy flux (Qiu et al., 2019), which can be considered as the main factor determining the intensity of crops evapotranspiration (Gong et al., 2021).

In the studies of irrigated crops' growing processes, the best strategy according to Faybishenko (2007) is to choose the methods that take into account the highest number of input parameters. At the same time, the problem of determining the accuracy of evapotranspiration estimates remains urgent in each specific situation and such approaches as the usage of different methods' linear combination with fittable coefficients (Romashchenko et al., 2020) or machine-learning-related approaches (Elbeltagi et al., 2023) are used. The need for scenario modeling here stems from the fact that under irrigation the maintained ranges of moisture content in soil's root layer significantly influence the availability of moisture for plants. Hence, the processes that have a decisive influence on evapotranspiration and the parameters that quantify their intensity may change.

In this paper, evapotranspiration estimates are used as input to the models of moisture transport based on the Richards differential equation. The study of their accuracy is carried out by assessing the compliance of the simulated dynamics with sensor readings. The model parameters were identified using the readings in the initial part of the growing season. Then, to assess the accuracy, we perform extrapolation modeling over longer time ranges including the entire growing season.

Material and Methods

We investigate two models for evapotranspiration assessment - the Priestley-Taylor and Penman-Monteith methods - along with their modifications that consider the current state of soil moisture.

The Penman-Monteith method

Having a weather station equipped with sensors of temperature and relative humidity of air along with solar radiation and wind speed, estimation of potential evapotranspiration by the Penman-Monteith method can be performed the following way (Cannata, 2006). The soil component of evapotranspiration is calculated as (Cannata, 2006)

$$ET_{rad} = \frac{\Delta}{\Delta+\gamma^*}\frac{R_n-G}{\lambda}$$

where $\Delta = \frac{4098e_a}{(237.3+T)^2}$, $e_a = 0.61078e^{\frac{17.27T}{T+237.3}}$ is the coefficient of the dependency between the saturated vapor pressure and temperature T (*kPa K*$^{-1}$); $\lambda = 2.501 - 0.002361T$ is the heat of water evaporation (*J kg*$^{-1}$); $\gamma = 0.001\frac{c_p P}{\varepsilon\lambda}$ is the psychrometric constant (*kPa K*$^{-1}$), $P = P_0\left(\frac{T_{ko}-\eta(Z-A_0)}{T_{ko}}\right)^{\frac{g}{\eta R}}$ is the atmospheric pressure (in the absence of an appropriate sensor), $c_p = 1.013$ (*kJ kg*$^{-1}$ *°C*) is the specific heat of air, $\varepsilon = 0.622$ is the ratio of molecular weight of water and dry air, $T_{ko} = 293.16$ K is the temperature at the sea level, $P_0 = 101.3$ kPa is the atmospheric pressure at the sea level, $A_0 = 0$ m is the altitude at the sea level, $\eta = 0.0065$ $K\,m^{-1}$ is the constant vertical temperature gradient, $g = 9.81$ $m\,s^{-2}$ is the acceleration of gravity, $R = 287$ is the universal gas constant; $d = \frac{2}{3}h_c, Z_{om} = 0.123h_c, Z_{oh} = 0.1Z_{om}$, h_c is the height of plants (m); $u_{10} = u_2\log(67.8*10-5.42)/4.87$ is the assessment of wind speed ($m\,s^{-1}$) at the height of 10 m, u_2 is the wind speed at the height of 2 m; $\gamma^* = \gamma(1+\frac{r_s}{r_a})$ is the modified psychrometric constant, $r_s = \frac{100}{12h_c}$,

$r_a = \begin{cases} \frac{\log \frac{Z_w - d}{Z_{om}} \log \frac{Z_h - d}{Z_{oh}}}{k^2 u_2}, h_c < 2 \\ 94 / u_{10}, h_c \geq 2 \end{cases}$, $Z_w = 2$ m is the height of wind speed measurement, $Z_h = 2$ m is the height of air humidity measurement, $k = 0.41$ is the von Karmann's constant.

Soil heat flux G is set to be linearly dependent on the flux of solar radiation R_n ($mJ\ m^{-2} s^{-1}$).

The atmospheric component of evapotranspiration is calculated as (Cannata, 2006)

$$ET_{aero} = \frac{3.6}{\lambda(\Delta + \gamma^*)} \frac{\rho c_p (e_a - e_d)}{r_a},$$

$$\rho = \frac{100P}{T_{kv} R},\ T_{kv} = \frac{T + 273.15}{1 - 0.378 e_d / P},\ e_d = R_h e_a / 100.$$

Total potential evapotranspiration is then obtained in the form

$$ET_0 = ET_{rad} + ET_{aero}.$$

Soil surface resistance r_s can be estimated based on the so-called "relative soil moisture index" R_{sm2} (Sellers et al., 1992; Kustas et al, 1998), which is defined as the ratio between the volumetric moisture content on the soil surface (SM_2, $m^3 m^{-3}$) and the saturation moisture content (S_p, $m^3 m^{-3}$) in the form

$$r_s = e^{a - bR_{sm2}},\ R_{sm2} = SM_2 / S_p \quad (1)$$

where a and b are empirical constants.

The Priestley-Taylor method

The Priestly-Taylor method can be considered as a simplified form of the Penman-Monteith method (Priestly and Taylor, 1972; Gong et al., 2021) and its computation formula is

$$\lambda ET = a_e \frac{\Delta}{\Delta + \gamma}(R_n - G)$$

where λET is the heat flux ($W\ m^{-2}$), α_e is the volume coefficient.

The heat flux λET can be divided into λE_s (evaporation in the form of energy flux) and λT_r (transpiration in the form of energy flux), which are calculated as (Gong et al., 2021)

$$\lambda E_s = a_s \frac{\Delta}{\Delta + \gamma}(R_{ns} - G),\ \lambda T_r = a_c \frac{\Delta}{\Delta + \gamma} R_{nc}$$

where R_{ns} and R_{nc} are the energy ($W\ m^{-2}$) received by soil and vegetation surfaces; α_s and α_c are the coefficients for λE_s and λT_r. R_{ns}, R_{nc}, α_s, and α_c can be defined as (Gong et al., 2021)

$$R_{ns} = R_n \tau, R_{nc} = R_n - R_{ns}, \tau = e^{-kLAI},\ a_s = f_{sw} a_{s0}, a_c = (1 - f_s) f_t a_{c0}$$

where τ is the fraction of radiation that reaches the surface of soil; LAI is the Leaf Area Index; α_{s0} and α_{c0} are the coefficients for soil and vegetation defined as (Gong et al., 2021)

$$a_{s0} = \begin{cases} 1.0, \tau \leq \tau_c, \\ a_0 - \frac{(a_0 - 1)(1 - \tau)}{1 - \tau_c}, \tau > \tau_c, \end{cases}\quad a_{c0} = \frac{a_0 - a_{s0}\tau}{1 - \tau}$$

where α_0 is the reference coefficient (*1.26*), τ_c is the critical value of τ when the closure of vegetation is maximal.

Leaf aging coefficient f_s can be determined as (Gong et al., 2021) $f_s = 0.05 e^{\frac{CDC}{0.98} t - 1}$ where t is the time from the beginning of leaf aging and CDC is the aging factor. The limiting factor f_t for plant temperature is defined as (Ershadi et al., 2014) $f_t = e^{-\left(\frac{T_a}{T_{opt}} - 1\right)^2}$ where T_{opt} is the optimal temperature for crop growth (°C).

The soil moisture stress index f_{sw} is used to combine the data on soil and atmospheric conditions and can be determined according to the model presented in Deardorff (1978) as (Gong et al., 2021):

$$f_{sw} = \begin{cases} 1.0, S_e \geq 0.75, \\ S_e, S_e < 0.75 \end{cases}$$

where $S_e = (\theta - \theta_w)/(\theta_s - \theta_w)$ is the effective moisture saturation in the upper soil layer with the depth of *0.1 m*; θ, θ_s, and θ_w are the actual volumetric moisture content, saturated moisture content, and wilting point, correspondingly.

To finally obtain the expression for α_e, G is described as a function of R_{ns} (Choudhury et al., 1987) in the form $G = f_G R_{ns}$ where f_G is the fraction of G in R_{ns}. Combining all the above mentioned, for α_e we have (Gong et al., 2021)

$$a_e = \frac{f_{sw} a_{s0} (1 - f_G) \mathrm{e}^{-kLAI} + (1 - f_s) f_t a_{c0} (1 - \mathrm{e}^{-kLAI})}{1 - \mathrm{e}^{-kLAI} f_G}.$$

The method described by Venturini and co-authors in Venturini et al. (2008) modifies the Priestley-Taylor method representing, in particular, Δ as $F\Delta$ where

$$F = \frac{SM}{SM_c} \tag{2}$$

SM is the volumetric moisture content in the soil, and SM_c is the field capacity.

Methods for modeling moisture transport

The main aim of our study is to experimentally test the effectiveness of the combined use of the above-mentioned evapotranspiration models and differential moisture transport models while simulating changes in moisture content in irrigated soil. For this purpose, considering the Penman-Monteith method, we determine the values of r_s according to (1) with *a=8.2*, *b=5.9* according to Kustas et al. (1998). The value of Δ is multiplied by F calculated according to (2).

As an alternative, we use the Priestley-Taylor model with similar modifications.

To model moisture content dynamics, we consider the classical integer-order one-dimensional head-based Richards equation according to the method described in Romashchenko et al. (2020). The corresponding equation has the form

$$\frac{\partial}{\partial t} H = C^{-1}(h) \left[\frac{\partial}{\partial z} (k(H) \frac{\partial H}{\partial z}) - S \right], 0 \leq z \leq L, \ t \geq 0 \tag{3}$$

where $h(z,t) = \frac{P(z,t)}{\rho g}$ is the water head (*m*), $H(z,t) = \frac{P(z,t)}{\rho g} + z$ is the full moisture potential (*m*), $P(z,t)$ is the suction pressure (*Pa*), ρ is the water density ($kg\ m^{-3}$), g is the acceleration of gravity ($m\ s^{-2}$), $C(h) = \frac{\partial \theta}{\partial h}$, $\theta(x,z,t)$ is the volumetric soil moisture content (*%*), $k(H)$ is the hydraulic conductivity ($m\ s^{-1}$).

In (3) the function S describes water uptake by root systems.

To the water head function H at the lower boundary $z = L$ of the simulation domain in the case of confining bed presence we set the condition $\frac{\partial H}{\partial z} = 0$. In the case of groundwater presence, the condition $H = H_L$ where H_L is the given function is set.

At the upper boundary $z = 0$, in the case when the soil is saturated, the Dirichlet boundary condition is set (van Dam and Feddes, 2020). In other cases the Neumann boundary condition is set in the form $k \frac{\partial H}{\partial z} = Q_e - Q_p - Q_i$ where Q_e, Q_p, Q_i are the flows ($m\ s^{-1}$), caused by evaporation, precipitation, and irrigation.

The function S that models water uptake by plant roots has the form (Molz and Remson, 1970) $S=\frac{TL(z)}{\int_0^v L(z)dz}$, where v is the depth of the root layer, $L(z)$ is the function of root length distribution density, T is the transpiration.

With the known value of actual evapotranspiration ET, it is subdivided on the components Q_e and T according to Gigante et al. (2009) the following way: $Q_e=e^{-\mu\cdot LAI}ET$, $T=(1-e^{-\mu\cdot LAI})\cdot ET$ where LAI is the leaf area index, μ is a given constant.

The finite difference method (Samarskii, 2001) is used to numerically solve the initial-boundary value problem for Equation 3 as described in Romashchenko et al. (2020).

Additionally, we consider the one-dimensional space-time-fractional equation of moisture transport in the form (Romashchenko et al., 2021)

$$D_t^{(\beta)}H=C^{-1}(h)\left[D_z^{(\alpha)}(k(H)\frac{\partial H}{\partial z})-S\right],0\le z\le L,\ t\ge 0$$

where $D_t^{(\beta)},D_z^{(\alpha)}$ are the Caputo derivatives of fractional order subject to time *t* and depth *z* (Podlubny, 1999). The numerical technique for the fractional-differential model is described in Romashchenko et al. (2021).

In computational experiments, soil's water retention curves are determined by selecting the parameters of the van Genuchten model (van Genuchten, 1980) considered to have the form $\theta(h)=\theta_0+\frac{\theta_1-\theta_0}{\left[1+\left(10\alpha|h|\right)^n\right]^m}$ (θ_0, θ_1, α, n, $m=1-1/n$ are the model parameters) the way to make the model best describe the laboratory analysis data on the dependency of soil moisture content on suction pressure. Hydraulic conductivity is represented in the form (Averianov, 1982) $k(H)=k_f\left(\frac{\theta(H-z)-\theta_0}{\theta_1-\theta_0}\right)^\beta$ where k_f is the saturated hydraulic conductivity (filtration coefficient), $\beta=3.5$ is the fixed power.

To compensate for the errors in the measurement of irrigation water flow, precipitation flow, and evapotranspiration estimates, the corresponding flows were multiplied by coefficients, the values of which are, similarly to the described in Romashchenko et al. (2020), fitted by the particle swarm optimization (PSO) algorithm (Zhang et al., 2015). These coefficients are fitted in a way to minimize the total sum of squares deviations of the simulated water head dynamics from the measured one. To compensate for the errors in laboratory determination of the saturated hydraulic conductivity, as well as errors arising from soil heterogeneity, the value of the saturated hydraulic conductivity was also determined by the PSO algorithm.

An approach for assessing the impact of evapotranspiration models' accuracy on the effectiveness of irrigation management

The use of the considered technique in irrigation management involves estimating the time and rate of subsequent watering by predictive modeling with evapotranspiration estimated using forecast weather data.

To estimate the seasonal irrigation rate and the volume of actual evapotranspiration the irrigation simulation is performed for the entire growing season with watering assigned to maintain in the given range the average water head in the root layer.

The seasonal effectiveness of irrigation can be assessed using the so-called relative yield function (Kovalchuk and Matiash, 2006), which simulates the decrease of yield due to not-optimal irrigation. In particular, according to Kovalchuk and Matiash (2006), for maize grown in southern Ukraine, such a function has the form

$$f(u,w,p)=-0.444+2.02\left(\frac{u+p}{w+p}\right)-0.556\left(\frac{u+p}{w+p}\right)^2 \tag{4}$$

where u is the actual seasonal irrigation rate (*mm*), w is the biologically optimal irrigation rate (*mm*) defined as an irrigation rate for a regime, in which evapotranspiration is maintained at the level close to the potential one, p is the precipitation (*mm*).

Given the close relationship between w and evapotranspiration, we transform (4) into

$$f(W,ET) = -0.444 + 2.02\frac{W}{ET} - 0.556\left(\frac{W}{ET}\right)^2 \quad (5)$$

where W is the actual seasonal water supply (*mm*), ET is the total potential evapotranspiration (*mm*).

After conducting a scenario modeling of irrigation assignments throughout the growing season and obtaining simulated values of W and ET, the effectiveness of the method of evapotranspiration assessment for irrigation management can be estimated by the value of $f(W,ET)$.

Input data

Two sets of the time series of monitoring data obtained during the 2018 and 2021 growing seasons were used for simulation.

The first data set was collected while growing soybeans under sprinkler irrigation in the fields of State Enterprise "Experimental Farm "Brylivske" (Privitne village, Kherson region, Ukraine) in 2018. The data set covers the time range from May 21 to August 22, 2018. Suction pressure measurements were performed using Irrometer 200SS-5 Watermark Soil Moisture Sensor using the Imetos® Pessl Instruments Internet Weather Station. The sensors were installed at the depths of 0.1 m, 0.25 m, 0.4 m, 0.55 m, 0.7 m, and 0.85 m.

A detailed description of the data set obtained in 2018 is given in Romashchenko et al. (2020). The values of the van Genuchten model's coefficients for the three-layer soil model are given in Romashchenko et al. (2020), Table 1.

The second data set was collected in 2021 in production conditions with pivot sprinkler irrigation in the fields of the LLC "Agrotechnology" (Bratske village, Kherson region, Ukraine). In the 2021, the "Tesla" variety of maize (UIPVE, 2019) was grown there. Data were collected using the same equipment as in 2018 located at 46°47'56.4"N 34°06'15.2"E. The sensors were installed at the depths of 0.2 m, 0.4 m, and 0.6 m. The actual yield was 13.8 *t/ha* with the total water supply equal to 439 *mm* for the active vegetation season from 19.05.2021 to 01.09.2021.

Data collected from 26.07.2021 to 14.09.2021 were used to model the dynamics of moisture content. The height of plants for the whole period was assumed to be equal to 1 *m*, and the depth of the root system was assumed to be 0.5 *m*.

In the scenario modeling of the entire growing season using the data collected in 2021, irrigation was applied when the average relative volumetric moisture content in the root layer of the soil decreased below 70% of field capacity that corresponds to the moisture content level of 24.8%. Irrigation was simulated until the corresponding level rises above 100% of field capacity (35.4%). The simulation was performed using the data acquired during the period of intensive irrigation from 25.07.2021 to 01.09.2021. In the period from 19.05.2021 to 25.07.2021 water supply to plants was provided mainly by precipitation. To test the sensitivity of computational procedures to inaccuracies in forecast meteorological data, modeling was also performed using the data on temperature, humidity, and wind speed, from the weather station located (46°51'N, 34°24'E) at a certain distance from the field. In the absence of predicted data on solar radiation, it was assumed that accurate measurements are performed once per 5 days, and then a constant value is used in the simulation.

The soil at the experimental sites corresponds to the southern low-humus heavy loam chernozem on loess. A single-layer soil model with the following values of the van Genuchten model's parameters was used for the data collected in 2021: θ_0=0.094, θ_1=0.5059, α=0.00919, n=1.475, m=0.3223. Parameters' values were obtained using Rosetta software based on soil particle size distribution data.

The actual irrigation regime, according to the data obtained in 2021, allowed the decrease of moisture content down to 68% of field capacity compared to the maximum reduction to 78% of field capacity according to the data collected in 2018. The minimum recorded value of suction pressure was *-132 kPa* compared to *-40 kPa* according to the data collected in 2018.

To identify the parameters of the models in the case of the data collected in 2018, a time interval of 11 days from the initial moment was used. For the data collected in 2021, we used a 7 days interval. For both cases, one watering was carried out within these intervals. An interval of 50 days was used to test the influence of different evapotranspiration assessment methods' usage on modeling accuracy.

The population size of the PSO algorithm was 20 particles, 20 iterations were performed with the following values of the parameters: $\omega=\varphi_r=\varphi_p=0.8$.

The smallest errors for the data set collected in 2018 were achieved when modeling a domain with the depth of *3 m* with the Dirichlet condition *H=-3.8 m* at its lower boundary on the finite-difference grid with 50 nodes. In the case of data collected in 2021, a *1 m* deep domain was used with the Neumann condition at the lower boundary on the finite-difference grid with 20 nodes.

Results and Discussion

The root-mean-squared error (RMSE) and average relative error ($\varepsilon_{rel}=\frac{1}{N}\sum_{i=1}^{N}\left|\frac{H_i-\bar{H}_i}{H_i}\right|$ where $H_i, \bar{H}_i, i=1,\ldots,N$ are the measured and the modeled water head values, N is the number of measurements) for the intervals of 11 and 50 days are given in Tables 1 and 2. The results show that for 2018 the differences between the modeling errors using different algorithms for estimating evapotranspiration are insignificant. Given the maintained high level of soil moisture content, its consideration has no significant impact on the obtained dynamics of evapotranspiration. Regarding the use of the model that contains the derivatives of fractional order, the results confirm the conclusions given in Romashchenko et al. (2021). Thus, the accuracy of the parameters' identification for the fractional-order model is ~10% higher, but when modeling for longer intervals it decreases faster than in the case of the classical model.

Table 1. Modeling errors for the model (3)

	Interval of 11 days		Interval of 50 days	
Data collected in 2018	RMSE, *kPa*	Average relative error, *%*	RMSE, *kPa*	Average relative error, *%*
Penman-Monteith method	1.750	30.66%	1.756	50.35%
Modified Penman-Monteith method	1.759	30.96%	1.783	52.75%
Priestley-Taylor method	1.751	30.67%	1.775	50.56%
Modified Priestley-Taylor method	1.747	30.38%	1.860	51.47%
Data collected in 2021				
Penman-Monteith method	11.086	41.07%	8.272	49.63%
Modified Penman-Monteith method	10.548	39.23%	7.894	47.57%
Priestley-Taylor method	10.474	39.22%	7.917	47.97%
Modified Priestley-Taylor method	10.528	38.08%	7.560	40.40%

Performing simulation based on the data collected in 2021 we observed up to ~10% reduction in RMSE using the modifications of the Penman-Monteith and the Priestley-Taylor methods that take the data on soil moisture content into account. This decrease can be explained by a larger range of water head changes than in the case of the data collected in 2018. Accuracy when using the Priestley-Taylor model was higher here and an additional increase in accuracy when using the fractional-differential model was observed for both considered intervals.

Table 2. Modeling errors for the fractional-differential model

	Interval of 11 days		Interval of 50 days	
Data collected in 2018	RMSE, *kPa*	Average relative error, *%*	RMSE, *kPa*	Average relative error, *%*
Penman-Monteith method	1.636	21.96%	2.729	60.56%
Modified Penman-Monteith method	1.635	21.96%	2.728	60.55%
Priestley-Taylor method	1.636	21.96%	2.731	60.59%
Modified Priestley-Taylor method	1.635	21.96%	2.728	60.54%
Data collected in 2021				
Penman-Monteith method	11.037	39.23%	8.313	50.99%
Modified Penman-Monteith method	10.360	38.54%	7.656	44.99%
Priestley-Taylor method	8.387	35.32%	6.292	35.04%
Modified Priestley-Taylor method	10.448	37.50%	7.389	38.41%

Thus, in regard of RMSE and average relative errors when modeling one or several irrigation cycles in two cases of different average moisture content and corresponding pressures we confirmed that, even when input data are collected in production condition, the incorporation of soil moisture assessments into the considered evapotranspiration models allows obtaining the increase in simulation accuracy in accordance with experimental results (see, e.g. Ding et al., 2013; Gong et al., 2021) on the importance of soil moisture factor.

Some of the obtained results on the dynamics of water heads are shown in Figure 1, 3 and 4. The dynamics of average volumetric moisture content in the 0.5 *m* layer of the soil is given in Figure 2 and 5. The results show that taking into account soil moisture in the Penman-Monteith method leads to an overall increase in the simulated moisture content level compared to the basic version of the method (Figure 2 and 5). When using the Priestley-Taylor model, the opposite trend was observed. The reasons for the latter could be the error accumulation in the performed long-range simulations that, in turn, could be caused by lower accuracy of the Priestley-Taylor model in water stress condition as reported in Shao et al. (2022).

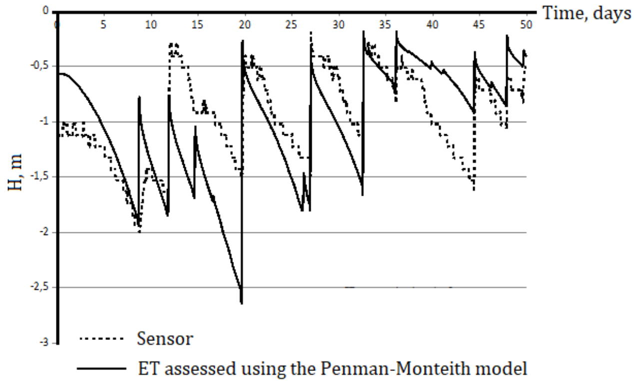

Figure 1. Dynamics of water head at the depth of 0.25 m for the data collected in 2018

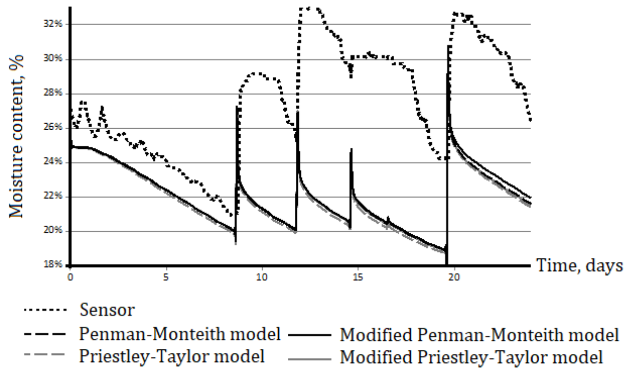

Figure 2. Average moisture content in the 0.5 m layer for the data collected in 2018

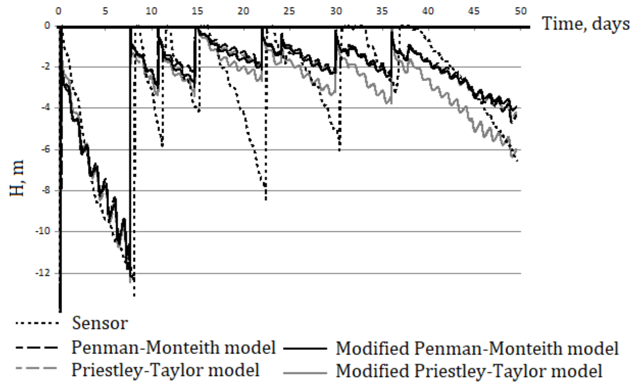

Figure 3. Dynamics of water head at the depth of 0.2 m for the data collected in 2021

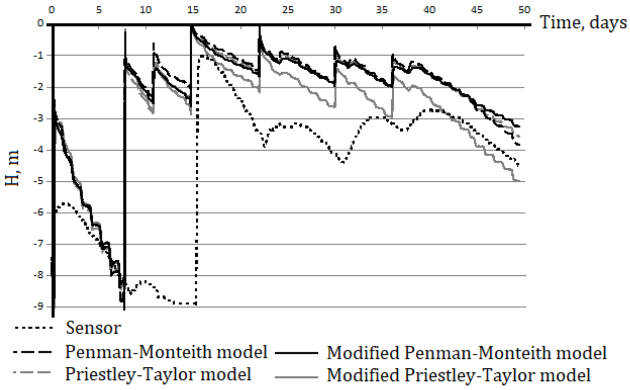

Figure 4. Dynamics of water head at the depth of 0.4 m for the data collected in 2021

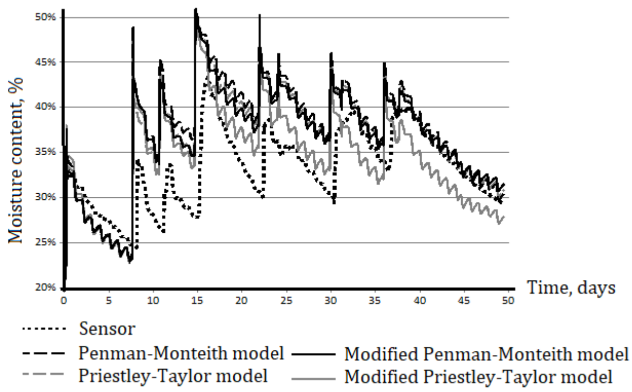

Figure 5. Average moisture content in the 0.5 m layer for the data collected in 2021

In the case of the data collected in 2018, there was an overestimation of water intake according to the data of the two upper sensors located at depths of 0.1 m and 0.25 m (Figure 1). Another reason for significant errors in predictive modeling here is the delayed or elongated in-time response of sensors to irrigation. RMSE values when modeling the data collected in 2018 were significantly lower compared to the RMSE values for the year 2021 which can be explained by the fact that average values of water heads in 2018 were to the same level lower when compared to 2021. It is confirmed by the same order of relative errors for the data collected in 2018 and 2021.

In the case of the data collected in 2021, there was an underestimation of water intake in computational experiments while performing predictive modeling. This is the main reason for the greater efficiency in this case of the modified Priestley-Taylor model. As can be seen from Figure 4, the reason for the high modeling errors is the lack of response of the sensor located at the depth of 0.4 *m* to the second and third irrigation. A similar trend was observed for the sensor located at the depth of 0.6 *m*. The simulation results were consistent with the data of the sensor located at the depth of 0.2 *m* (Figure 3) and with subsequent dynamics of water head changes according to the other two sensors. Thus, the used modeling procedure has stable response to inaccuracies in input data subject to the change of evapotranspiration assessment method similarly to the reported about other factors in Bohaienko et al. (2022).

Influence of evapotranspiration models' accuracy on the efficiency of irrigation management

The values of total water supply, total actual evapotranspiration, and the relative crop yield function (5) in the scenario modeling of the 2021 growing season are given in Table 3.

Table 3. Total water inflow W (*mm*), actual evapotranspiration ET (*mm*), and the relative crop yield $f(W,ET)$ in the scenario modeling of the 2021 growing season

Evapotranspiration assessment method	Actual meteorological data			Forecast meteorological data		
	W	ET	$f(W,ET)$	W	ET	$f(W,ET)$
Penman-Monteith	395	465	0.87	405	482	0.86
Modified Penman-Monteith	382	315	1.18	348	202	1.38
Priestley-Taylor	399	420	0.97	391	383	1.04
Modified Priestley-Taylor	457	367	1.21	364	188	1.38

At the maximum maize yield equal to 14.5 t/ha (UIPVE, 2019); total evapotranspiration, calculated from the actual meteorological data according to the Penman-Monteith equation; and the actual measured water supply, the expected yield according to Equation (5) differs from the actual one by 1.5%, which confirms its applicability in the considered case. The simulation technique's sensitivity to the meteorological data when using the Penman-Monteith method was low (not more than 4% deviation in the seasonal parameters between the cases of actual and forecast meteorological data). When using the Priestley-Taylor method, it increases (deviation <9%). The use of the considered modifications of evapotranspiration assessment methods leads to seasonally simulated scenarios with lower levels of both water supply and evapotranspiration compared to the usage of original methods. This decrease is more significant when using forecast meteorological data, to which the modified formulas are more sensitive (average deviations of parameter values equal to ~14%). The values of the relative crop yield function when using modified methods are 24-61% higher.

Conclusion

The results of water head dynamics modeling under sprinkler irrigation according to the two data sets collected growing different crops in different meteorological conditions demonstrate the possibility to increase modeling accuracy by ~20% using the Priestley-Taylor method modified to take into account the data on soil moisture content when compared with the classical Penman-Monteith method. The efficiency of this scheme increases with the increase of the range in which moisture content changes. For the data set collected under the irrigation regime aimed at maintaining moisture content in the root layer in the range of 80%-100% of field capacity, modified methods did not improve the accuracy of modeling. These results confirm the well-known conclusion that using such irrigation regimes, moisture content level is optimal for the grown crops, and evapotranspiration is maintained at the level close to the potential one. The results of scenario modeling for the entire growing season and the estimation of yield under the formed water regime showed that, according to the used yield model, the application of evapotranspiration estimates that incorporate moisture content data generates irrigation regimes with lower water supply.

References

Averianov, S.F., 1982. Filtration from canals and its influence on groundwater regime. Kolos, Moscow, USSR. 238p. [in Russian].

Bohaienko, V., Romashchenko, M., Sardak, A., Gladky, A., 2022. Mathematical modelling technique to mitigate soil moisture measurement inaccuracies under the conditions of drip irrigation. *Irrigation Science* (in Press)

Cannata, M., 2006. GIS embedded approach for Free & Open Source Hydrological Modelling. PhD thesis, Department of Geodesy and Geomatics, Polytechnic of Milan, Italy.

Choudhury, B.J., Idso, S.B., Reginato, R.J., 1987. Analysis of an empirical model for soil heat flux under a growing wheat crop for estimating evaporation by an infraredtemperature based energy balance equation. *Agricultural and Forest Meteorology* 39 (4): 283–297.

Deardorff, J.W., 1978. Efficient prediction of ground surface temperature and moisture, with inclusion of a layer of vegetation. *Journal of Geophysical Research* 83: 1889-1903.

Ding, R., Kang, Sh., Li, F., Zhang, Y., Tong, L., 2013. Evapotranspiration measurement and estimation using modified Priestley–Taylor model in an irrigated maize field with mulching. *Agricultural and Forest Meteorology* 168:140-148.

Elbeltagi, A., Srivastava, A., Al-Saeedi, A.H., Raza, A., Abd-Elaty, I., El-Rawy, M., 2023. Forecasting long-series daily reference evapotranspiration based on best subset regression and machine learning in Egypt. *Water* 15(6): 1149.

Ershadi, A., McCabe, M., Evans, J.P., Chaney, N.W., Wood, E.F., 2014. Multi-site evaluation of terrestrial evaporation models using FLUXNET data. *Agricultural and Forest Meteorology* 187: 46–61.

Faybishenko, B., 2007. Climatic forecasting of net ınfiltration at Yucca Mountain using analogue meteorological data. *Vadose Zone Journal* 6: 77–92.

Gharsallah, O., Facchi, A., Gandolfi, C., 2013. Comparison of six evapotranspiration models for a surface irrigated maize agro-ecosystem in Northern Italy. *Agricultural Water Management* 130: 119–130.

Gigante, V., Iacobellis, V., Manfreda, S., Milella, P., Portoghese, I., 2009. Influences of Leaf Area Index estimations on water balance modeling in a Mediterranean semi-arid basin. *Natural Hazards and Earth System Sciences* 9: 979–991.

Gong, X., Qiu, R., Ge, J., Bo, G., Ping, Y., Xin, Q., Wang, Sh. 2021. Evapotranspiration partitioning of greenhouse grown tomato using a modified Priestley–Taylor model. *Agricultural Water Management* 247: 106709.

Kovalchuk, P.I., Matiash, T.V., 2006. Optimization of yearly water use planning in the conditions of resources deficit. *Melioratsija i vodne hospodarstvo* 93-94: 210-218. [in Ukrainian].

Kustas, W.P., Zhan, X., Schmugge, T.J., 1998. Combining optical and microwave remote sensing for mapping energy fluxes in a semiarid watershed. *Remote Sensing of Environment* 64(2): 116–131.

Molz, F. J., Remson, I., 1970. Extraction term models of soil moisture use by transpiring plants. *Water Resources Research* 6(5): 1346-1356.

Monteith, J.L., 1965. Evaporation and environment. In: The State and Movement of Water in Living Organisms. 19th Symposium of the Society for Experimental Biology. Fogg, G.E. (Ed.). 8–12 September 1964, Swansea. The Company of Biologists: Cambridge. pp.205–234.

Overgaard, J., Rosbjerg, D., Butts, M.B., 2006. Land-surface modelling in hydrological perspective – a review. *Biogeosciences* 3(2): 229–241.

Podlubny, I., 1999. Fractional differential equations: An introduction to fractional derivatives, fractional differential equations, to methods of their solution and some of their applications. Academic Press, USA. 340p.

Priestley, C.H.B., Taylor, R.J., 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. *Monthly Weather Review* 100: 81–92.

Qiu, R.J., Liu, C.W., Cui, N.B., Wu, Y.J., Wang, Z.C., Li, G., 2019. Evapotranspiration estimation using a modified Priestley-Taylor model in a rice-wheat rotation system. *Agricultural Water Management* 224: 105755.

Rodriguez-Iturbe, I., 2000. Ecohydrology: A hydrologic perspective of climate-soil-vegetation dynamies. *Water Resources Research* 36(1): 3–9.

Romashchenko, M.I., Bohaienko, V.O., Matiash, T.V., Kovalchuk, V.P., Danylenko, I.I., 2020. Influence of evapotranspiration assessment on the accuracy of moisture transport modeling under the conditions of sprinkling irrigation in the south of Ukraine. *Archives of Agronomy and Soil Science* 66(10): 1424-1435.

Romashchenko, M.I., Bohaienko, V.O., Matiash, T.V., Kovalchuk, V.P., Krucheniuk, A.V., 2021. Numerical simulation of irrigation scheduling using fractional Richards equation. *Irrigation Science* 39(3): 385-396.

Samarskii, A.A., 2001. The Theory of Difference Schemes. CRC Press, USA. 786p.

Savenije, H.H.G., 2004. The importance of interception and why we should delete the term evapotranspiration from our vocabulary. *Hydrological Processes* 18(8): 1507–1511.

Sellers, P.J., Heiser, M.D., Hall, F.G., 1992. Relations between surface conductance and spectral vegetation indices at intermediate (100 m^2 to 15 km^2) length scales. *Journal of Geophysical Research* 97(D17): 19033–19059.

Shao, M., Liu, H., Yang, L., 2022. Estimating tomato transpiration cultivated in a sunken solar greenhouse with the penman-monteith, shuttleworth-wallace and priestley-taylor models in the North China Plain. *Agronomy* 12: 2382.

Shao, W., Su, Y., Langhammer, J., 2017. Simulations of coupled non-isothermal soil moisture transport and evaporation fluxes in a forest area. *Journal of Hydrology and Hydromechanics* 65: 410–425.

Shuttleworth, W.J., Wallace, J.S., 1985. Evaporation from sparse crops—an energy combination theory. *Quarterly Journal of the Royal Meteorological Society* 111: 839–855.

UIPVE, 2019. Ukrainian Institute of Plant Varieties Expertize. Protection of plant variety rights: Bulletin. Issue 1. 1088 p.

van Dam, J.C., Feddes, R.A., 2000. Numerical simulation of infiltration, evaporation and shallow groundwater levels with the Richards equation. *Journal of Hydrology* 233(1-4): 72-85.

van Genuchten, M.T., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal* 44(5): 892-898.

Venturini, V., Islam, S., Rodriguez, L., 2008. Estimation of evaporative fraction and evapotranspiration from MODIS products using a complementary based model. *Remote Sensing of Environment* 112: 132–141.

Wanniarachchi, S., Sarukkalige, R., 2022. A Review on evapotranspiration estimation in agricultural water management: Past, Present, and Future. *Hydrology* 9(7):123.

Zhang, Y.A., Wang, Sh.H., Ji, G.L., 2015. Comprehensive survey on particle swarm optimization algorithm and its applications. *Mathematical Problems in Engineering* Article ID: 931256.