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DETERMINATION OF THE PARAMETERS OF SUBSURFACE DRIP IRRIGATION SYSTEMS ON THE BASE OF MOISTURE TRANSPORT MODELING

(Представлено членом редакційної колегії д-ром геол. наук, проф. О.Є. Кошляковим)

The paper considers the problem of determining the depth of drip pipelines installation and the distance between the pipelines within the design of subsurface drip irrigation systems along with the assessment of pulse irrigation regime efficiency. The corresponding optimization problem has an objective function that assesses costs of creating and operating the system and is solved by a genetic algorithm. For each set of system parameters' values the scheduling of irrigation during the growing season is modeled according to the specified pre-irrigation threshold. The simulation is based on the two-dimensional Richards equation approximated by a finite-difference scheme. The characteristics of crop development are determined according to the model based on the change of development stages with the accumulation of a given amount of active temperatures. To take into account the variability of weather conditions modeling is performed for a series of randomly generated weather scenarios.

Keywords: subsurface drip irrigation, pulse irrigation, moisture transport, modeling, optimization.

Introduction. The use of drip irrigation systems, especially subsurface ones, requires significant costs for their construction. The possibility of forming irrigation regimes that provide for the optimal distribution of moisture for crop development, and, accordingly, for highly efficient irrigation, depends on the quality of the choice of subsurface drip irrigation system's (SDIS) parameters.

Determination of design SDIS parameters' values can be carried out by an expert assessment or with the use of mathematical modeling. The background of such modeling is formed, on the one hand, by a description of moisture transport processes in soil, and, on the other hand, by a technological approach to the determination of irrigation schedules and rates on the base of crop development models.

The main approach to irrigation management is based on the control of moisture supply to the root-containing zone of soil (*Campbell et al., 1982; Muñoz-Carpena and Dukes, 2005*). In it, based on the concept of optimal range of moisture supply that maintains the level of water consumption by irrigated crops equal to or close to the maximal potential level (*Campbell et al., 1982*), irrigation is started when moisture content lowers down to some pre-irrigation threshold (*Campbell et al., 1982*) and is carried out until it is raised to the upper limit of optimal range, usually equal to field capacity (FC).

Moisture transport models for the conditions of drip irrigation (e.g., *Arbat et al., 2008; Romashchenko et al., 2016*) are mainly based on the Richards differential equation (*Richards, 1931*) in a two-dimensional approximation or are formed from experimentally determined contours of moistened zones (*Holzapfel et al., 1990*). Algorithms for automated selection of SDIS parameters are, in the majority of cases, optimization algorithms superposed on moisture transport models with objective functions based on economic assessment of irrigation efficiency with restrictions arising from the biological need to provide plants with moisture.

Among the papers investigating the algorithms of this class, we firstly highlight the paper of Kandelous et al. (*2012*). It proposes to carry out modeling throughout the growing season using a certain model of crop development to determine SDIS parameters considering one weather scenario. Irrigation here is modeled by such parameters as its frequency and duration. Optimization is performed by a meta-heuristic method with an objective function that contains only operating costs.

Further, Seidel et al. (*2015*) consider the set of generated weather scenarios and optimize profit by assessing the reliability of its receipt on this set. Three tasks are sequentially solved — determination of the duration of watering to achieve maximum uniformity of moistening; determination of such irrigation schedule that maximizes water productivity in accordance with certain models of yield and crop development; determination of optimal values of irrigation system's parameters that maximize profit for the fixed irrigation schedule. The cost of system construction is not considered.

In the paper of abd el Baki et al. (*2017*) authors consider single randomly generated weather scenario and a crop development model in which the parameters such as leaf area index (LAI), crop coefficient, and root system's depth depend exponentially on the accumulated transpiration during the season without division into separate development stages.

Among the papers on the application of empirical models in the problems of profit optimization we can highlight, e.g., the paper of Holzapfel et al. (*1990*) that study the modeling of the entire growing season. Although the assessment of the ability to meet the moisture needs of plants by irrigation system, without reducing the generality, can be carried out only in critical phases of crop development, from the best of our knowledge, the vast majority of studies consider optimization of drip irrigation systems' parameters using the modeling of the entire growing season. The reason for this can be the need to estimate seasonal water supply to calculate the values of objective functions that are based on economic criteria.

In general, the development of a model base in the direction of the fullest possible consideration of the factors influencing economic efficiency of irrigation is highly important for the development of decision support systems in the design of subsurface irrigation systems. Thus, we identify three major components of the studied optimization problem (models of moisture transport, irrigation scheduling, and crop development; weather scenarios; objective function of the problem) and in their context propose a novel technique for the solution of the problem.

Second main problem of design and operation of subsurface drip irrigation systems is choice and justification of the least water-consuming irrigation regime.

Pulse regime of drip irrigation (*Rank and Vishnu, 2021*) provides, in contrast to constant irrigation, the supply of water to the zones of maximum concentration of plants' root systems in the shortest possible cycles of fixed or variable duration in accordance with actual water demand. The use of pulse irrigation regime makes it possible to create moisture levels higher than field capacity in certain zones of moistened volume. In this way, moisture and nutrients become more available to plants in the corresponding zones than when other irrigation regimes are used. This, in turn, leads to a more intensive growth of plants' root systems in moistened zones (*Segal et al., 2006*), which is one of the main features of pulse drip irrigation regime.

Numerous papers are devoted to the modeling of moistening zones under drip irrigation, in particular, using pulsed water supply regime. They can be divided into three classes: papers based on regression analysis of experimental data (e.g., *Karimi et al., 2022*); papers that use soft computing techniques (*Shiri et al., 2020*); and papers in which differential mathematical models of moisture and salt transport are developed and applied (*Romashchenko et al., 2021a; Kim et al., 2021*). The construction of regression and soft computing models requires a large amount of experimental data on the behavior of a specific plant grown in specific conditions, and their extrapolative application can lead to high modeling errors. On the other hand, the models obtained this way are simple and effective in terms of simulation time.

Differential models of moisture transfer allow without significant corrections carrying out predictive modeling when irrigation regime, soil, or crop parameters change. At the same time, most of the studies on such modeling and its use in decision support in irrigation that are known to the authors (see, e.g., *Friedman et al., 2016; González Perea et al., 2020*) consider fixed root systems of plants and do not take into account the hypotheses regarding its dependency on the moistened zones when pulse drip irrigation regime is used. This study is also aimed at filling this gap of knowledge.

Materials and methods.

Moisture transport model and numerical solution scheme. We start from Richards equation (*Richards, 1931*) stated in terms of pressure in a two-dimensional setting in the form (*Romashchenko et al., 2021a*):

$$C(h)\frac{\partial H}{\partial t}=\frac{\partial}{\partial x}\left(k(H)\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial z}\left(k(H)\frac{\partial H}{\partial z}\right)-S, \quad 0\le x\le L_x,\ 0\le z\le L_z,\ t\ge 0 \qquad (1)$$

where $h(x,z,t)=\frac{P(x,z,t)}{\rho g}$ is the water head, *m*, $H(x,z,t)=\frac{P(x,z,t)}{\rho g}+z$ is the full moisture potential, *m*, $P(x,z,t)$ is the suction pressure, *Pa*, ρ is the density of water, *kg/m*^{3}, g is the acceleration of gravity, *m/s*^{2}, $C(h)=\frac{\partial\theta}{\partial h}$ is the differential soil moisture content, *%/m*, $\theta(x,z,t)$ is the volumetric soil moisture content, %, $k(H)$ is the hydraulic conductivity, *m/s*, $S(x,z,t)$ is the source function, *%/s*, that simulates the extraction of moisture by plants' roots and its supply by subsurface drip irrigation.

The two-dimensional Equation (1) is based on the assumption that the distance between emitters is sufficient to form a uniform wetted zone along irrigation pipelines.

Boundary and initial conditions for Equation (1) as well as the form of the source function are given in Romashchenko et al. (*2021a*). We assume that a fixed number of plants and irrigation pipelines placed at a given depth are located in the solution domain.

The parameters of subsurface drip irrigation system in the model are the depth of installation and the number of pipelines for a given distance (we consider the case of 10 m). The number, not the distance between the pipelines, was chosen as a parameter to have solution domains of the same size in all modeling scenarios.

Water retention curves of soils are described by van Genuchten's model (*van Genuchten, 1980*) in the form

$$\theta(h)=\theta_0+\frac{\theta_1-\theta_0}{\left[1+\left(10\alpha|h|\right)^n\right]^{1-1/n}} \qquad (2)$$

with coefficient values that vary from layer to layer and can be obtained on the base of laboratory studies' results (e.g., *Romashchenko et al., 2019*). The dependency between hydraulic conductivity and pressure is represented according to Averyanov's model (*Averyanov, 1982*) in the form

$$k(H)=k_f\left(\frac{\theta(H-z)-\theta_0}{\theta_1-\theta_0}\right)^{\beta}, \qquad (3)$$

where k_f is the filtration coefficient, β is the fixed exponent, the values of which is taken from experimentally obtained dependencies $k(H)$.

In the presented model irrigation starts at the time when the average moisture content of a root zone becomes less than the specified value (we consider first of all the scenarios where pre-irrigation threshold is at the level of 80% and 90% FC). Irrigation continues until the average moisture content reaches 95% or 100% FC. The value of 95% FC was used in the cases when uneven moistening under drip irrigation leads under certain conditions to significant overwetting or inability to reach high moisture content levels, especially near soil surface. Moisture content is averaged according to the function of root system density with higher weight coefficients for the areas where a root system is denser. The width of a root system depends linearly on its depth and its maximum width is a parameter of the model.

The numerical solution of the initial-boundary value problem for the model based on Equation (1) is performed according to the implicit finite-difference Crank-Nicholson scheme (*Samarskii, 2001*) on a uniform grid. The corresponding linear systems are solved by the TFQMR algorithm (*Freund, 1993*). The initial time step length is taken to be equal to 1 s and changes during the simulation according to the scheme based on the hypothesis about the correlation between time step and the condition number of a matrix along with the correlation of the condition number and the number of iterations of the solution algorithm – the step is multiplied on a given value (here equal to 1.25) when the number of iterations of the TFQMR algorithm exceeds a given maximum value (here 20). The solution at the appropriate time step is then repeated. If the number of iterations is less when 1/3 of the maximum value, the length of the next time step increases the same way.

The step with respect to the spatial variable is proposed to be found as follows. Starting from a certain value (here 3.3 cm) it decreases until the mean square of differences between the values of the average moisture content in a root zone during one day of simulation with the current number of grid nodes and the number greater on a given value does not decrease below a given value. The initial moisture content is taken close to the pre-irrigation threshold.

Determination of evapotranspiration and generation of weather scenarios. Random weather scenarios are generated by a stochastic weather generator software *weathergen* (https://github.com/ARVE-Research/gwgen). Its inputs are the average monthly minimum and maximum temperature, cloudiness, wind speed, total precipitation, and the number of days with precipitation. The output file contains daily values of the same parameters that are supplied as inputs. Because there is no humidity or radiation in this data set, the Hargreaves-Samani formula (*Hargreaves and Samani, 1985*), which is derived from the Penman-Monteith method, is used to estimate potential evapotranspiration as for calculations it requires only air temperature values and observation point coordinates. Further simulations used the average climatic data for Kherson, Ukraine, obtained from open sources. Our approach allows, in particular, to conduct modeling taking into account climate change by correcting input climatic data according to the scenarios of anticipated changes.

Model of crop development. The root system's depth together with the values of leaf area index (LAI) and crop coefficient are determined according to the model of crop development stages evolution upon accumulation of a certain sum of average daily temperatures (*Ritchie and Nesmith, 1991*). We assume that the corresponding parameters vary linearly from stage to stage. As an input parameter of the model we use the date of sawing, after which the duration of the growing season and the dynamics of LAI, root system depth, and crop coefficient is determined on the base of the generated weather scenario.

Peculiarities of pulse irrigation regime modeling. When modeling pulse irrigation, we proceed from the hypothesis that when using pulse irrigation regime, especially in the case when several waterings are performed within a day (high-frequency regime), root system is developing in the zones moistened by emitters and its size depends on the size of these zones (*Segal et al., 2006*). Let us state the modeling problem as follows: at a given irrigation rate, calculate the size of the root-containing zone that depends on the moistened zone created by watering with such a rate.

This problem can be solved by successive approximation according to the following algorithm:

1) Fix a certain initial zone where moisture content is maintained and that coincides with the root zone;

2) Perform simulation for a period of 1 day and determine the moistened zone as the maximum zone in the period from the beginning of a single watering to the beginning of the next one in which water head increases compared with the initial level by more than a given value, here and further, denoted as "a threshold for determining the moistened zone";

3) The obtained moistened zone is the next approximation of the zone where moisture content is maintained;

4) Perform modeling (step 2) until the moistened zone stops changing within a given accuracy threshold.

The question in which part of the moistened zone the root system grows most intensively must be solved experimentally. In the absence of experimental data, we determine the largest possible moistened zone for a given irrigation rate: such threshold for determining the moistened zone is chosen by successive changes at which it is possible to ensure the maintenance of the specified range of moisture content in the largest moistened zone that coincides with the root zone.

In the above-described procedure, the duration of watering is considered fixed and irrigation schedule is adapted to the changes in soil moisture, which is typical for automatic control of drip irrigation (see, e.g., *Obaideen et al., 2022*). At the same time, situations can emerge in which it is impossible to ensure the maintenance of the specified range of moisture content in the corresponding zone using the given rate. In such cases we assume that rate must be increased.

Input data. Input data described in Romashchenko et al. (*2021a, 2021b*) were used for computational experiments. A single-layered soil model with the filtration coefficient of 15 cm/day was considered.

Simulation domain was 10 m wide and 1 m deep. At its lower and lateral boundaries the free-flow boundary conditions were set. For modeling, without lowering the generality of the proposed technique, we assume that root systems of plants uniformly fill the corresponding layer of soil.

System parameters optimization procedure. We propose to use a procedure for optimizing the design parameters of SDIS that has the following features:

1) A given number of randomly generated weather scenarios is considered;

2) The procedure for calculating the objective function for the specific values of pipelines installation depth and the number of pipelines per 10 m is as follows. For each of weather scenarios, the simulation is performed for the entire growing season recording the volume of supplied irrigation water per 1 m of domain width by a given number of pipelines. Then, the seasonal volume of supplied irrigation water and the total length of pipelines per 1 ha are calculated. The price of 1 m^3 of water together with the costs of its supply and the price of 1 m of irrigation pipeline together with the costs of its installation are the parameters of the model. The objective function to be minimized is the average among all weather scenarios of the cost of constructing the system and water supply within a given period under constant growing conditions and crop. In the case when during 24 hours irrigation does not lead to the increase of root zone moisture content to the upper limit of the maintained range, the objective function is increased by a given substantially high "penalty value" – this way we cut off the scenarios under which the system cannot provide for the needed irrigation regime.

3) Minimization of the objective function is performed by a genetic algorithm (*Mitchell, 1996*). The discretization step with respect to the spatial variable is determined automatically for the scenario with the maximum number of pipelines and the minimum depth of their installation, which should ensure the fastest change in moisture content during irrigation.

Because modeling the entire growing season in multiple weather scenarios is a computationally complex problem, we propose to use a simplified model based on the assumption that SDIS is able to provide adequate moistening throughout the season if it is able to perform it during peak water consumption. In the optimization problem based on this assumption, the modeling of irrigation assignment is performed for a limited period (we used value of 10 days) and a fixed, the highest in the considered weather scenarios, evapotranspiration level with crop parameters at the time when this level is reached. Let us note that the level of potential errors in this case can be determined by the correlation between the dynamics of evapotranspiration and the state of crop development, and also by the correlation between water supply in the modeled period and total seasonal water supply.

Results and discussion.

Testing of system parameters optimization procedure. Testing of the proposed technique was carried out using monitoring data obtained in 2020 (*Romashchenko et al., 2021a, 2021b*) during the cultivation of corn in the State Enterprise "Experimental Farm Velyki Klyny" (Kherson region, Ukraine).

An example of the generated weather scenario together with the corresponding values of root system's depth, LAI, and the calculated actual evapotranspiration is shown in Fig. 1. The coefficients of linear dependencies in the crop development model were obtained from field observations.

The modeled distribution of water heads after 4 hours irrigation is shown in Fig. 2 for the case of the distance between pipelines equal to 1 m, the depth of their installation equal to 20 cm, the emitters' flow rate equal to 1.6 dm^3/h, and pre-irrigation threshold at the level of 85 % FC. The moistened zones obtained experimentally according to the observations are shown in Fig. 3 (*Romashchenko et al., 2021b*). The average accuracy of modeling the volumetric moisture content at the observation points here was ~1 % according to the results given in Romashchenko et al. (*2021a*). Visual comparison of the data shown in Fig. 2 and Fig. 3 also confirms sufficient accuracy of the simulation.

In the next stage of testing, the procedure of SDIS parameters optimization was executed for the case of modeling the range of 10 days at the highest water consumption level with maintainable moisture content ranges of 80–95 % FC and 90–95 % FC.

The population size of the genetic algorithm was 10 and 10 iterations were performed. The execution time of the algorithm on the SKIT-4 cluster of VM Glushkov Institute of Cybernetics with the use of one 8-core CPU was ~4 hours.

In the case of pre-irrigation threshold equal to 80 % FC, the best option based on the simulation results was to install irrigation pipelines at the distance of 66 cm from each other at the depth of 21.8 cm. The obtained dynamics of the average root zone moisture content, actual evapotranspiration, precipitation, and irrigation events for one of the considered weather scenarios and the full growing season is shown in Fig. 4.

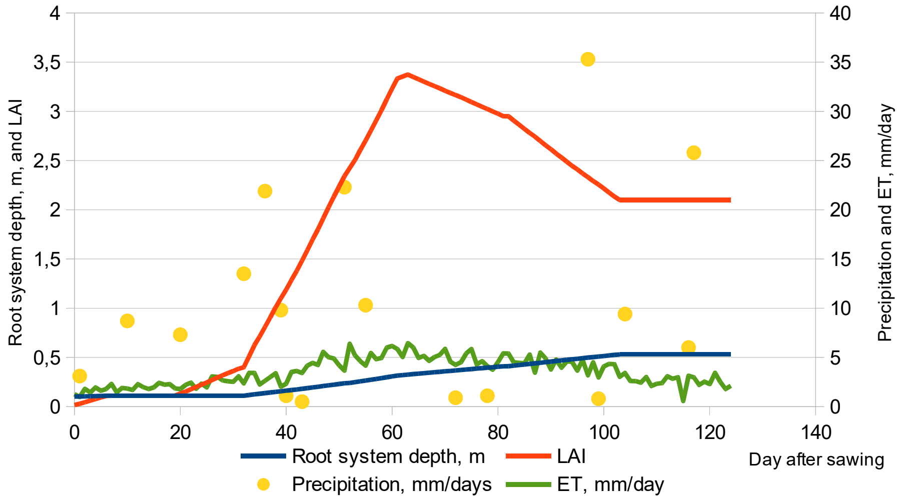

Fig. 1. Example of a weather scenario

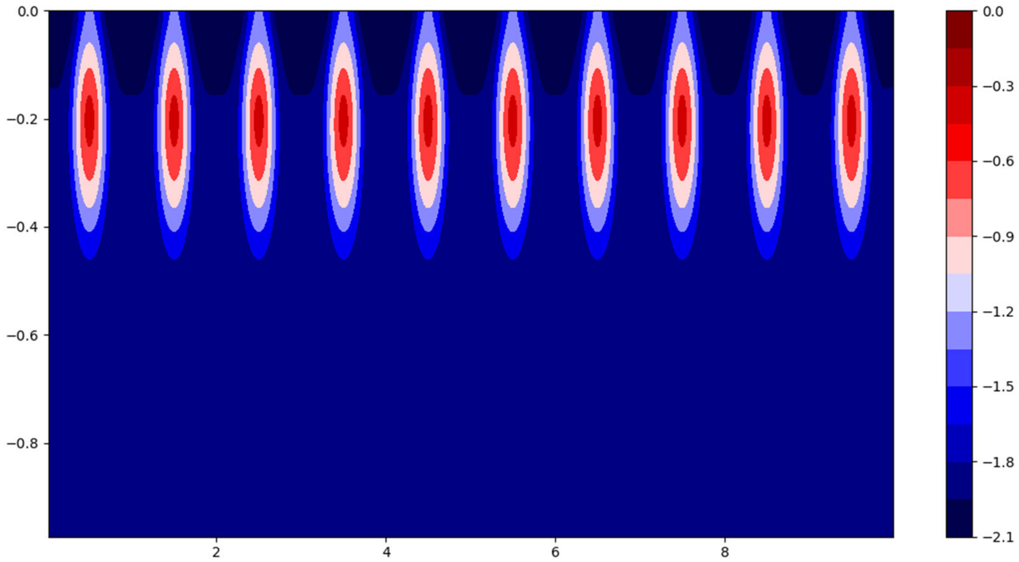

Fig. 2. Water heads, m, 4 hours after the start of irrigation

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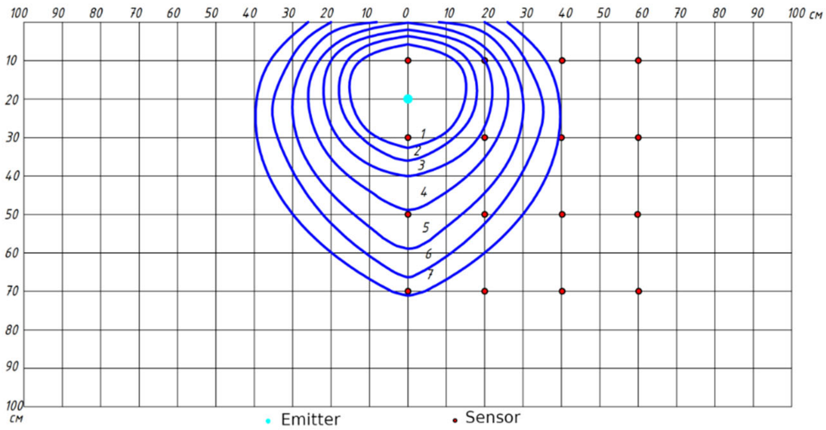

Fig. 3. Contours of the soil profile moistening zones depending on the duration of irrigation, *h*.
Source: *(Romashchenko et al., 2021b)*

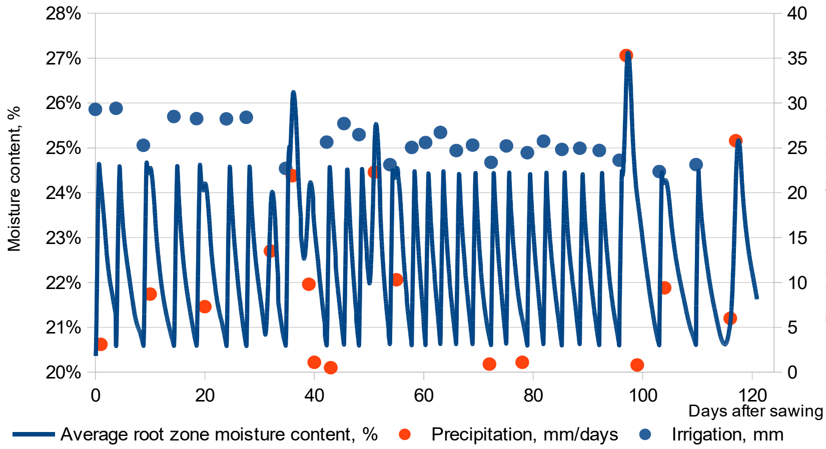

Fig. 4. Dynamics of the average moisture content in a root zone in the case of pre-irrigation threshold equal to 80% FC

The average seasonal water supply among 10 random weather scenarios was 701 mm (27 waterings with rates of 22–29 mm) with the coefficient of variation equal to 3 %; average seasonal evapotranspiration was equal to 465 mm, and total precipitation – to 168 mm. Thus, it can be stated that for a given value of hydraulic conductivity, range of maintained moisture content, and the dynamics of root system's depth, significant moisture losses are possible due infiltration into the layers below a root zone.

In the case of pre-irrigation threshold equal to 90 % FC the determined optimal parameters insignificantly differed from the case of 80 % FC: the distance between pipelines was equal to 62 cm and the depth of installation – to 21.5 cm. Seasonal water supply was equal to 1063 mm (124 waterings with rates of 7–13 mm). Thus, according to the simulation results, for the filtration coefficient of soil equal to 15 cm/day, an increase of the pre-irrigation threshold leads to a significant increase in moisture losses.

The correlation between the simulated irrigation water supply within 10 days for pre-irrigation threshold equal to 80% FC and seasonal water supply is shown in Fig. 5 for the case of the pipelines installation depth varying from 10 cm to 40 cm and the distance between pipelines varying from 50 cm to 200 cm. The relative error of calculating seasonal water supply from water supply within 10 days did not exceed 11 % that proves the ability to use the simplified optimization problem for decision support.

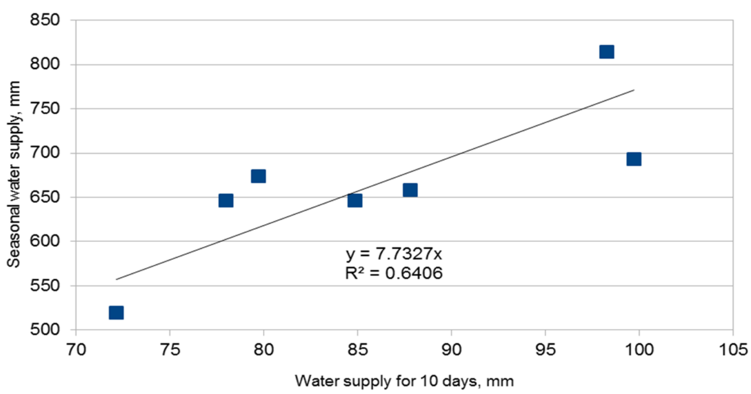

Fig. 5. Correlation between the simulated irrigation water supply within 10 days and the corresponding seasonal water supply

Assessing the efficiency of pulse irrigation regime. Mathematical modeling of high-frequency pulse regime was carried out according to the above-described model with the following values of parameters:

- pipelines installation depth – 20 cm, flow rate – 1.6 l/h, distance between emitters – sufficient to form strip moistening, distance between pipelines – 66 cm;
- Soil characteristics obtained on the base of survey data at the State Enterprise "Experimental Farm "Velyki Klyny" (*Romashchenko et al., 2021a, 2021b*) were used as basic ones: filtration coefficient – 15 cm/day, saturated moisture content – 33.6 %, field capacity – 25.8 % (pressure – 8.0 kPa). Similar simulations were carried out using the hydrophysical characteristics of 20 types of soils obtained on the basis of the data of their granulometric composition using the Rosetta software (we thank S.S. Kolomiyets, who conducted laboratory studies of soils at the State Enterprise "Experimental Farm "Velyki Klyny", and V.P. Kovalchuk, who processed literature data on the granulometric composition of soils). Soils were considered homogeneous; data on their upper layer (up to 20/30 cm) were used throughout the simulation domain depth. The values of the parameter β in Averyanov model was assumed to be equal to 3.5 for all 20 soils;
- The maintained moisture content range is 95–100 % FC. 95% FC corresponds for a basic soil to volumetric moisture content of 24.5% (pressure – 10.4 kPa). The initial moisture content was taken at the level of the pre-irrigation threshold;
- The average evapotranspiration over the modeled surface was taken at the level of 5.1 mm/day. Evapotranspiration in the zones shaded by the plants was assumed to be entirely due to transpiration, and in the inter-row area it was modeled as exclusively evaporation from soil surface. We assume that the width of plants' root systems is equal to the width of the zone where plants shade the soil.

The results of modeling according to the presented technique in the case of soil characteristics obtained according to the surveys at the State Enterprise "Experimental Farm "Velyki Klyny" with fixed evapotranspiration are shown in Table 1. The change in irrigation regimes with a change in evapotranspiration is shown in Table 2. In the case of the results given in Table 2 watering time was not less than 10 minutes and increased if necessary.

From the data given in Table 1 it can be seen that an increase in irrigation time leads to an increase in the volume of moistened zone and, accordingly, the total volume of irrigation. At the same time, the loss of moisture due to outflow into the horizons lower than the root zone also increases.

In all cases, the dynamics of total moisture volume in the simulation domain became close to periodic after 1–2 days of simulation. Stability was ensured due to the initial use of moisture reserves, the volume of which decreased with an increase in watering time.

According to the simulation results given in Table 1, the overall outflow moisture volume and the use of moisture reserves decreases when moving from 5-minute to 10-minute waterings, remaining constant with a further increase of duration. Because of this, in further computational experiments, the value of 10 minutes was chosen as the basic duration of watering.

The data given in Table 2 demonstrate that under such an irrigation regime, an increase in evapotranspiration by 1.5 times compared to the base level leads to the need to increase the duration of irrigation by 9% to ensure the maintenance of the required moisture content range. In this case, the flow below the *1* m layer decrease with an increase in the use of moisture reserves. In the case of 1.5 times evapotranspiration decrease an opposite trend is observed. Thus, the modeling results give us grounds for stating that with the implementation of pulse water supply regime in order to minimize infiltration water losses it is necessary to maintain a differentiated level of moisture supply – higher in periods of high evapotranspiration and lower in periods of low evapotranspiration.

The results of modeling for 20 types of soils of Ukraine, whose hydrophysical characteristics were determined on the base of the data on their granulometric composition, with duration of irrigation equal to 10 minutes are shown in Table 3.

Table 1

Results of simulation of pulse regime of subsurface drip irrigation with different fixed irrigation durations

Duration of watering	5 min	10 min	20 min	30 min
Irrigation rate, m^3/ha	1.5	3	6	9
Root zone/moistened zone — depth, cm	16–24	13–27	10–30	7–33
Root zone/moistened zone — width, cm	8	16	20	26
Threshold for determining the moistened zone, kPa	0.4	0.6	0.6	0.5
Pipeline installation depth	20 cm			
The number of waterings per 10 days	479	252	144	102
Total volume of irrigation, m^3/ha	664	761	842	902
Total evapotranspiration in 10 days, m^3/ha	518			
Outflow below 1 m layer, m^3/ha	328	364	405	436
Residual (accumulation or use of moisture reserves in 1 m layer with the influence of modeling errors), m^3/ha	–181	–120	–80	–52

Table 2

Change in irrigation regimes with changes in evapotranspiration (controlled zone determined for irrigation time of 10 min with evapotranspiration in 10 days at the level 518 m^3/ha)

Total evapotranspiration in 10 days, m^3/ha	345	690
Watering time, min	10	10.9
The number of waterings per 10 days	215	287
Total volume of irrigation, m^3/ha	627	893
Outflow below 1 m layer, m^3/ha	378	349
Residual (accumulation or use of moisture reserves in 1 m layer with the influence of modeling errors), m^3/ha	–96	–146

Table 3

Results of simulation of pulse regime of subsurface drip irrigation for different soils (duration of irrigation – 10 min)

Soil	SMC	FC	α	n	K_f, cm/day	T_i, m³/ha	N_i	I_r, m³/ha	L
Silty heavily solodized soils on gleyed loess	50.3%	37.9%	0,017	1,267	1.41	730	249	3.0	29.0%
Sod gleyed solonchak soils on gleyed loess	63.0%	47.8%	0,029	1,241	1.74	769	262	3.0	32.6%
Sod, gleyed on surface, solodized soils on gleyed loess	59.6%	45.6%	0,026	1,233	1.43	726	237	3.0	28.6%
Chestnut salinized soils on loess	56.5%	42.3%	0,021	1,277	1.42	686	233	3.0	24.4%
Meadow–chernozem, gleyed on surface, slightly solodized soils on gleyed loess	51.9%	38.6%	0,015	1,306	1.29	663	226	3.0	21.8%
Chestnut medium solonetz on loess	49.4%	36.5%	0,014	1,319	1.26	651	222	3.0	20.4%
Dark–chestnut soils on loess	56.5%	41.9%	0,019	1,301	1.42	666	227	3.0	22.2%
Dark–chestnut salinized soils on loess	55.7%	41.6%	0,020	1,282	1.40	678	231	3.0	23.5%
Common deep low–humus chernozems on loess	61.4%	46.2%	0,026	1,257	1.76	759	248	3.0	31.7%
Common deep medium–humus chernozem on loess	58.2%	43.6%	0,022	1,274	1.52	701	239	3.0	26.1%
Common medium–depth low–humus chernozem on loess	55.4%	41.3%	0,020	1,287	1.43	681	232	3.0	23.9%
Low–depth chernozems on the eluvium of clay shale	51.6%	37.9%	0,017	1,330	1.41	649	221	3.0	20.1%
Low–depth chernozems on the eluvium of sandy shale	39.0%	29.2%	0,027	1,271	1.07	625	213	3.0	17.1%
Chernozems on the eluvium of clay shale	48.3%	35.9%	0,018	1,306	1.19	639	209	3.0	18.8%
Chernozems on the eluvium of sandstones	53.7%	38.8%	0,019	1,365	1.73	657	224	3.0	21.1%
Chernozems on the eluvium of sandy shale	40.0%	29.7%	0,025	1,286	0.96	584	199	3.0	11.2%
Chernozems on red clays	50.5%	40.3%	0,020	1,160	1.23	859	45	19.1	39.7%
Southern micellar–carbonate chernozems on loess	55.3%	41.8%	0,021	1,257	1.24	672	229	3.0	22.9%
Southern chernozems on loess	61.7%	46.2%	0,025	1,266	1.74	744	246	3.0	30.3%
Highly salinized alkaline chernozems on saline Paleogene clays	49.8%	38.8%	0,020	1,197	1.26	795	154	5.2	34.8%

** SMC – Saturated moisture content, FC – field capacity, K_f – filtration coefficient, T_i – Total irrigation volume for 10 days, N_i – Number of irrigations, I_r – Irrigation rate, L – Irrigation water losses.*

Based on the simulation results, it can be concluded that outflows below the 1 m layer, which are the main cause of irrigation water losses in all simulated scenarios, are primarily correlated with the filtration coefficient ($R^2 = 0.6$) as well as with the volumetric moisture content value for field capacity ($R^2 = 0.7$).

At the same time, the modeled residual of water balance, which is defined as the accumulation or use of moisture reserves in 1 m soil layer, significantly correlates with water head value at the level of field capacity ($R^2 = 0.86$).

The total volume of irrigation shows the strongest correlation with the parameter *n* of van Genuchten model ($R^2 = 0.63$). However, this level of correlation is first of all provided by soils for which $n < 1.2$. Such values in the studied dataset correspond to absolute values of water heads at the level of field capacity more than 30 kPa and the situations when higher irrigation rates than the specified basic rate of 3 m³/ha are required to maintain moisture content in the range of 95–100% of field capacity. If we consider soils with $n \geq 1.2$, the total volume of irrigation has high correlation level with the same initial parameters as outflows below 1 m layer: the filtration coefficient ($R^2 = 0.65$) and the volumetric moisture content value for field capacity ($R^2 = 0.75$).

Considering the connection of the modeling results with hydrophysical properties of soils, particularly their filtration and water-holding capacity, we can state that on soils of heavy mechanical composition (heavy loams, clays) with low filtration and high water-holding capacity pulse regime of water supply to the moistened zones should maintain moisture level as close as possible to field capacity with relatively large irrigation rate per pulse and low frequency of pulses. On soils of light mechanical composition (sandy soils, sandy loams) with high filtration and low water-holding capacity in moistened zones it is necessary to maintain a lower level of moisture supply, but in the narrowest range (90-95 % of field capacity) that requires conducting irrigation at lower rates with higher frequency of pulses.

Conclusions. The determination of cost-effective design parameters of subsurface drip irrigation systems requires combined consideration in the optimization problem of such factors as soil moisture transport, crop development, and variability of weather conditions. The proposed approach of solving this problem uses a genetic algorithm to find such a depth of irrigation pipelines installation and a distance between them that would ensure maintaining a given range of root zone moisture content with minimal costs for system construction and operation within a given period. Consideration of a series of randomly generated weather scenarios allows assessing the impact of possible extremes in weather conditions on the ability of the system to maintain the required level of moisture content and allows taking climate change into account.

We also propose to use a simplified optimization problem that allows significant reduction of execution time modeling irrigation scheduling only within a limited period when maximum level of water consumption is observed.

The performed computational experiments demonstrated the compliance of simulation results with the observations of the dynamics of moistening zones and general practice of SDIS design in the south of Ukraine.

Further development of the proposed technique is possible in the direction of its application to generate practical recommendations for growing different crops in different climatic zones and substantiation of design water supply regimes that allow achieving the maximum level of economic efficiency of irrigation.

Regarding the second considered problem – the justification of pulse irrigation regime under subsurface drip irrigation – we used the technique of modeling moisture transport based on the hypothesis that in this case root systems of plants develop first of all in the zones of active moistening. For a given duration of watering, the technique allows evaluating irrigation water losses, the use of moisture reserves, and system's resistance to changes in water demand, providing information about the efficiency of irrigation water use to decision-makers.

Modeling according to hydrophysical characteristics of 20 types of soils of Ukraine showed that the indicator that has the greatest correlation with the volume of irrigation is the parameter *n* of van Genuchten model. Water losses due to outflow below 1 m layer correlate with the filtration coefficient of soil, while the use of moisture reserves is the smaller the lower is the value of water head that corresponds to the level of field capacity.

Thus, the determination of these three hydrophysical parameters (parameter *n*, filtration coefficient, and water head that corresponds to the level of field capacity) is, according to the results of mathematical modeling, critical for assessing the possibility of using pulse water supply regime for subsurface drip irrigation and its effectiveness.

In general, the obtained results strongly suggest that on soils with heavy mechanical composition subsurface drip irrigation with pulse regime should maintain a high level of moisture supply with a relatively large irrigation rate per pulse and low frequency of pulses. On soils with light mechanical composition, irrigation regime should have the opposite character – lower rates with higher frequency of pulses.

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ВИЗНАЧЕННЯ ПАРАМЕТРІВ СИСТЕМ ПІДҐРУНТОВОГО КРАПЛИННОГО ЗРОШЕННЯ НА ОСНОВІ МАТЕМАТИЧНОГО МОДЕЛЮВАННЯ ВОЛОГОПЕРЕНЕСЕННЯ

Розглянуто задачу визначення глибини закладання краплинних стрічок та відстані між ними під час проєктування систем підґрунтового краплинного зрошення (СПКЗ), а також задачу оцінки ефективності імпульсного режиму водоподачі. Відповідна оптимізаційна задача має як цільову функцію витрати на створення та експлуатацію системи і розв'язується генетичним алгоритмом. Для кожного з набору значень параметрів системи моделюється призначення поливів протягом сезону вегетації згідно із заданим передполивним порогом. Моделювання проводиться на основі двовимірного рівняння Річардса, дискретизованого скінченно-різницевою схемою. Для цього параметри розвитку рослин визначаються згідно з моделлю, що базується на зміні фаз розвитку при накопиченні заданої суми активних температур. Для врахування варіативності погодних умов, моделювання проводиться для серії випадково згенерованих метеосценаріїв. Результати тестування розробленої методики підтверджують її відповідність експериментальним спостереженням та практиці проєктування систем підґрунтового краплинного зрошення.

Ключові слова: підґрунтове краплинне зрошення, імпульсний режим водоподачі, вологоперенесення, моделювання, оптимізація.