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To cite this article: P Kalandarov *et al* 2023 *IOP Conf. Ser.: Earth Environ. Sci.* **1142** 012052

IOP Conf. Series: Earth and Environmental Science 1142 (2023) 012052 doi:10.1088/1755-1315/1142/1/012052

Automated control system of drip irrigation and mathematical modeling

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Abstract. In this article, the theoretical and methodological foundations for the use of an automated control system for drip irrigation of crops are considered. The analyzed system is automated through integration, which allows controlling the entire irrigation process through a control device with controllers, shows the main elements of the drip irrigation system that carry out complete controlling and the procedure for moistening the soil and fertilizing, presents a functional diagram of the automated system for regulating soil moisture, as well as pressure in the pipeline, mathematical modeling of water consumption of crops under drip and combined irrigation is considered, the influencing factors that require regulation, which will ensure the management of plant development are shown. The complexity of the simulated system "Plant-moisture-soil-atmosphere-solar radiation" and its subsystems are explained by a large number of interrelated factors of various nature and requires the construction of numerical schemes, computer simulation using various computer programs.

1. Introduction

For conducting research work in the farm "Nihol-the grandchildren of Alisher" in the territory of the Bagat district of Khorezm region, 1.5 hectares of land were allocated for the use of rain and drip irrigation. From the beginning, due to difficulties in accessing river water to the crop area, winter wheat and slaughterhouse plants were planted, requiring little water during the growing season.

According to the analytical results, laboratory analysis, the nutrients necessary for plant nutrition in the soil were analyzed, and according to the results of the analysis, norms were established when feeding rice with mineral fertilizer. On the experimental site, it is planned to carry out research work on obtaining high yields of rice using rain and drip irrigation technologies.

For studying the mechanical composition and salinity level of the studied soil of the experimental field, soil samples were taken. To analyze the level of sizot water and the degree of mineralization of groundwater, control wells were installed on the experimental site.

All known drip irrigation systems are used to supply water to fields that lack moisture, to increase water reserves in the root layers of the soil in order to increase soil fertility. Irrigation generally improves the supply of moisture and nutrients to plant roots, lowers the temperature of the aboveground air and increases its humidity. Humidity is one of the main indicators that affects the growth and other biological factors of the plant.

Analysis of literary sources in the field of moisture control [1-6] showed that soil moisture and plant root system can be measured by various methods, which makes it possible to use express devices for instant moisture determination.

For deciding the choice of sensor, firstly, it is necessary to study the classification of the choice of method, as well as the measuring device. Analysis of all known moisture control devices (moisture meters) of the studied materials (soil) [7] based on the electrical method, i.e. on the microwave method are classified according to various criteria [8, 9, 10]. For drip irrigation, in which water is directly supplied in small portions to the zones, where the roots of grown plants are located using dropper dispensers, the above humidity control devices can be used [11]. In the process of manual irrigation, it is difficult to achieve uniform irrigation in sloping areas and arid lands. To do this, depending on the advantages of automatic irrigation, it is possible to include the operation of a system that performs only the required time interval and a strictly regulated water supply in a fully automated way. At the same time, the issues of optimizing the parameters and modes of combined (drip + finely dispersed) irrigation of various crops remain insufficiently studied. Therefore, the development and optimization of the parameters of combined irrigation of root crops based on the modeling of moisture transfer processes is an urgent problem for the efficient use of water resources and obtaining stable highly productive crops [12].

2. Materials and Methods

One of the options for a drip irrigation control system is shown in Figure 1.

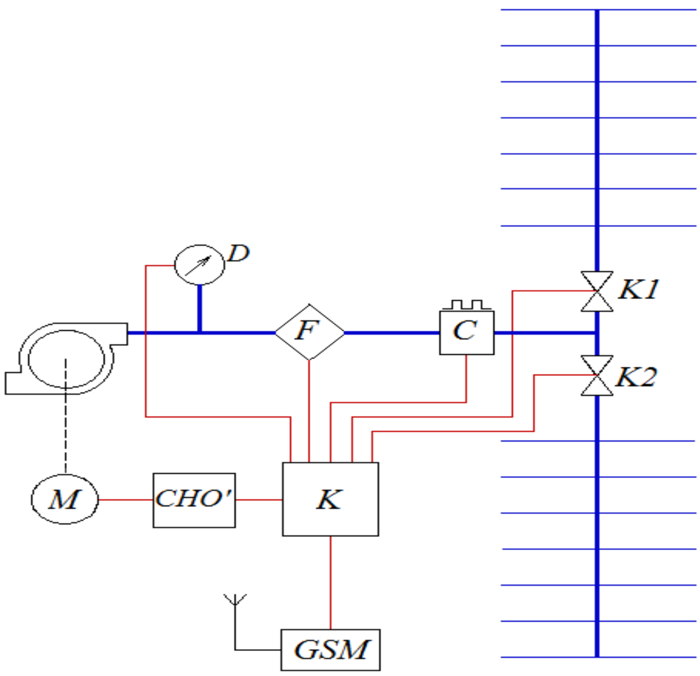

Figure 1. Structured scheme of control system: M - motor pumps; FC - frequency converter; K - controllers; D - pressure sensor; C – flow meter (pulse flow meter); K1, K2 - Valves; F - Filter; GSM - GSM modem

The principle of operation of the block diagram of the above control system (Figure 1) is that the system is automated through integration, which allows controlling the entire irrigation process through a control device with controllers.

The recommended automatic irrigation and control system has the following features:

- manual and automatic control;
- management from 2 to 17 irrigation lines;
- humidity sensor (external);
- connection of dry running sensor;

- connection of pressure sensor;
- connection of a pulse flow meter;
- function "Water budget" (allows changing the duration of watering for all lines without additional changes);
- ensuring full protection of pump motor;
- automated cleaning of filters;
- ability to work according to a given schedule;
- automated maintenance of pressure in the barrel;
- taking into account water consumption;
- pump operating time function;
- function of automatic restart of the pump in the event of a catastrophic event;
- management of the irrigation system in the GSM network using SMS messages;

Remote data collection is also very important in the automatic irrigation of orchards and vineyards. To do this, you can take various automatic irrigation devices, for example, Tevatronic [13]. This device collects data on the controller, stores it on the server and sends it to the user via SMS. It also sets the watering time and the amount of water needed, automatically organizes watering and provides constant information.

In agriculture, drip irrigation systems are more commonly used. Drip irrigation is an irrigation method in which, with the help of dropper dispensers, water is directly supplied in small portions to the zones where the roots of the grown plants are located.

Drip irrigation is a method of supplying agricultural plants with water and nutrients in the form of weakly concentrated solutions, in which water or nutrient solutions are supplied with a drip or close to it flow into the area where the bulk of the plant root system is located.

In modern concepts, "a drip irrigation system is a whole complex of various technological links interconnected by a pipeline network system, the last link of which is a dropper." The main elements of the drip irrigation system are: water intake facilities, pumping station, water treatment unit, fertilizer preparation unit, irrigation network, communication lines, automation system.

In this regard, the given research is focused on improving the information support for the tasks of automating the management of the soil water regime [14, 15]. This can be achieved through the use of optimization algorithms, the use of calculated values and reference databases, modern methods in the field of monitoring the water regime of the soil using automated instrumental and measuring technical means of remote sensing.

For developing the n automated drip irrigation system, an integrated approach to solving problems is necessary [16]. This is primarily due to the elements of automation, which should ensure the stable operation of the system. The drip irrigation system mainly consists of the following elements: drip tape i.e. a polyethylene tube with built-in droppers with a pitch of 10 cm to 50 cm, a fertilizer application unit, a pump, as well as valves and taps. A dropper is an element consisting in the form of a capillary labyrinth; water, passing through it, slows down and flows out drop by drop. The stern of these elements in the system must have various measuring instruments, such as weather stations, as well as soil moisture control sensors. The controllers used for automatic irrigation can usually be divided into household (for watering small areas) and professional, designed for irrigating a large number of areas.

The use of an automatic system for drip irrigation will significantly save time, and the used automation elements will conduct full control, and this, in turn, will facilitate the procedure for moistening the soil and fertilizing, while addressing the potential risks associated with the human factor [17].

The use of an automated system will organize a fully automated irrigation cycle, where all elements will automatically turn on and off, and it will also regulate not only the planned duration of irrigation for each plot, but also the frequency: during the day, week, month, according to all the necessary demanded numbers. Depending on the adjustment of the settings, watering will automatically be carried out according to the set mode. Sometimes many experts call the automatic irrigation system “smart rain”, for the ability to remotely control it, which will provide information from sensors, for this purpose it is necessary to know which parts of the plots need to be controlled [18].

3. Results and Discussion

One of the options for implementing a drip irrigation system is shown in Figure 2.

Description of the technological cycle: 1) the pump supplies water from the well, from which it is purified, to the water filtration unit; 2) a concentrated solution of fertilizers is added to the purified water; 3) water with the addition of fertilizers enters the main pipeline; 4) water from the main pipeline is supplied to plants through a distribution pipeline and drip pipes (tapes).

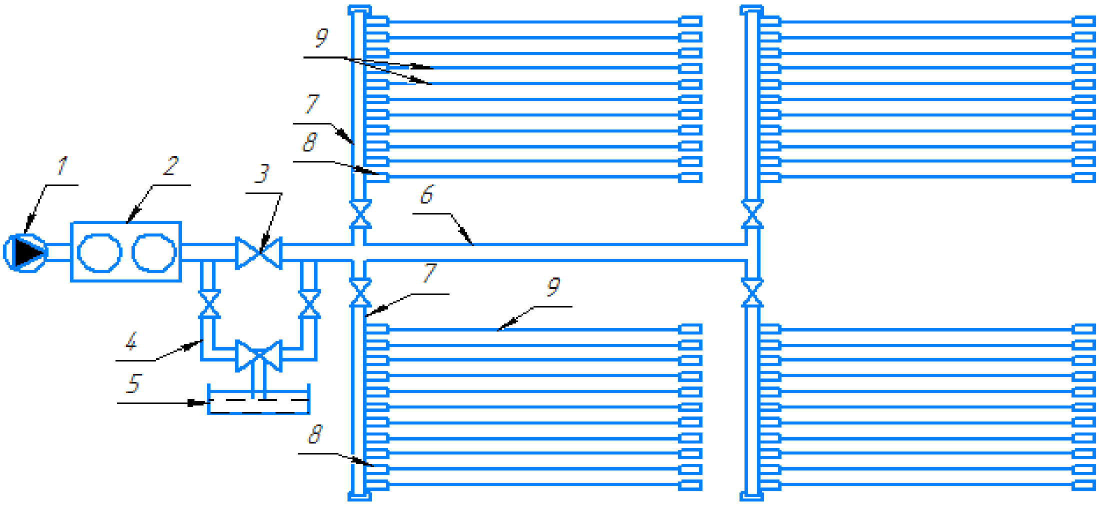

Figure 2. Scheme of the drip irrigation system: 1 – pump; 2-block of water filtration; 3-faucet; 4-block of fertilizer application; 5-capacity for liquid fertilizers; 6-main pipe; 7 - distribution pipe; 8 - connector for associating the dropper tube; 9-tube dropper (tape)

For ensuring high yields in an irrigated area, it is important to control soil moisture. Humidity is one of the main factors affecting soil fertility. Depending on crops and soil conditions, for controlling soil moisture, the field area is divided into several irrigation zones. Each zone has 1 soil moisture sensor, which sends a signal to the microcontroller that controls the solenoid valves installed on the distribution pipes. Figure 3 shows a functional diagram of an automated soil moisture control system.

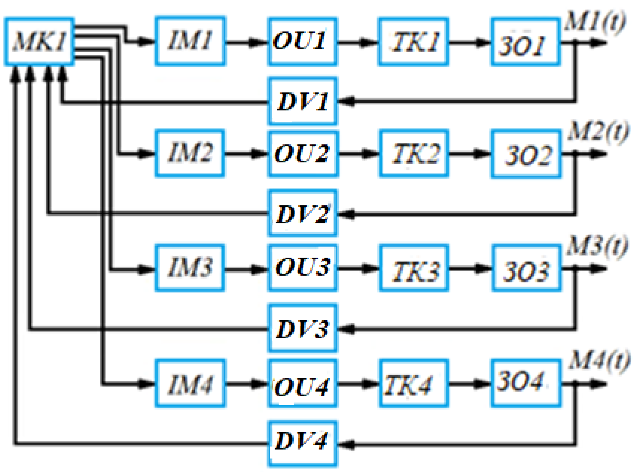

Figure 3. Functional diagram of ASR (system of automatic control of soil moisture)

Where: MK1- microcontroller; IM1 - 4-actuator mechanisms (solenoid valves); OU1 - 4-controls (membrane valves); TK1 - 4-distribution pipes; ZO1 - 4-irrigation zones; DV1 - 4-humidity sensors.

The controller sets the maximum allowable humidity level. When the level of humidity is exceeded, an electromagnetic valve closes the section of the distribution pipe leading to the corresponding irrigation zone. In the process of controlling the valves, a change in the flow of water in the system occurs. If the operation of the pump is not controlled, the pressure in the network increases, the concept of the network includes a complex of tanks, pipes, shut-off and control valves, filters through which fluid flows to the pump and from the pump to the consumer.
Figure 4 shows a functional diagram of an automated control system (ACS) of pipeline pressure.

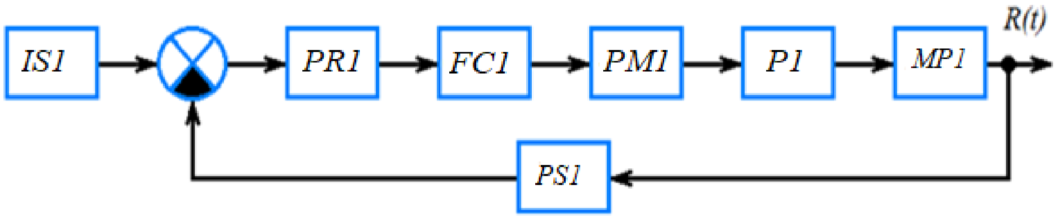

Figure 4. Functional diagram of the ACP of pressure in the pipeline: IS 1 - intensive setter that determines the required pressure; PR 1-pressure regulator, including RP-regulator pump; FC 1 – frequency converter; PM 1 - pump motor; P1 - pump; MP1-main pipeline; PS1- pressure sensor

If the pressure in the system does not match the required pressure, the frequency converter changes the speed of rotation of the pump impeller until the pressure reaches the required level.
Thus, when automating a drip irrigation system, it is necessary to control the operation of the pump to ensure its uninterrupted operation and increase reliability [19, 20]. To automate this process, a frequency converter is perfect [21].
For automatic controlling, it is necessary to use control panels, flow sensors, water pressure and soil moisture, electromagnetic valves, programmable timers, weather controllers and other high-precision equipment, additional premises, communication lines and power supply.
At the same time, the issues of optimizing the parameters and modes of combined irrigation of various crops remain poorly understood.
Mathematical modeling will require taking into account the characteristics of the root system of agricultural crops. Therefore, the development and optimization of the parameters of combined irrigation of root crops based on mathematical modeling of moisture transfer processes using digital information technologies is an urgent problem for the efficient use of water resources and obtaining stable, highly productive crops. At the same time, it is required to develop mathematical models of new technologies that describe the processes of spatial moisture transfer during combined irrigation.
Let's consider mathematical modeling of water consumption of agricultural crops under drip and combined irrigation. Theoretical prerequisites for modeling moisture transfer under various irrigation methods, using the example of root and tuber crops, we will construct differential equations for the movement of moisture in the soil. The Richards equation, which describes the movement of moisture in incompletely saturated soil is obtained by substituting the generalized Darcy law into the continuity equation.

$$\frac{dW}{dt} = -\frac{d\left[K(h)\left(\frac{dh}{dz}+1\right)\right]}{dz} - S(h) \tag{1}$$

For solving the direct problem of heat transfer, as well as the inverse one, it is necessary to study the process of heat transfer in the soil:

$$\frac{dT}{dt} = k\frac{d^2T}{dx^2} \qquad \left(k = \frac{\lambda}{c_v}\right), \tag{2}$$

Where T (x, t) is the soil temperature at points x at time t;
λ - coefficient of thermal conductivity;
$c_v = \rho c_m$ - volumetric heat capacity of the soil;
c_m - specific heat capacity;
For considering the effect of filtration on changes in the field of the soil aeration zone associated with changes in the temperature of the soil surface, the one-dimensional unsteady heat transfer equation was studied in more detail in [2]

$$(c_m\rho_m)\frac{dT}{dt} = \frac{d}{dx}\left(\lambda_m\frac{dT}{dx}\right) \pm \left((c_f\rho_f)\frac{d(q_xT)}{dx}\right), \tag{3}$$

Where λm is the coefficient of thermal conductivity of the soil;
c_m- is the specific heat capacity of the soil;
ρ_m - soil density;
$c_{v=\rho}c_m$ - volumetric heat capacity of the soil;
cf - c_f_fheat capacity per unit mass of water; ρ_f is the density of water; $q_v = \theta \cdot v_x$ - filtration rate;
v_x - average speed of water movement in soils;
θ - is the total porosity of the soil.
One of the main issues in the use of drip irrigation is the study of patterns of formation of soil moisture. To resolve this issue, we consider earlier studies of the description of the nature of the distribution of moisture and salts, described in the works of D. P. Gostishchev, N. S. Skuratov, E. P. Borov, E. A. Vetrenko, A. D. Akhmedov and others.
An analysis of these works shows that the calculation formulas for the dependence of the coefficient on humidity (D (W)) have been developed, which allow determining the size of the humidification contour, based on the formulas obtained by Gardner and L. E. Chernyshevskaya:

$$D(W) = D_o\exp\left[\beta(W - W_o)\right], \tag{4}$$

$$\beta = \frac{1}{W_n - W_o}\ln\left[\frac{3(W_n - W_o)^{3,5}}{W_n(W_o - W)^{3,5}\left(\frac{1}{W_o^2} + \frac{2W_0}{W_n^3}\right)}\right], \tag{5}$$

$$D_o = \frac{K_\phi\psi W}{1 - \left(\frac{W}{W_n}\right)^3}\left(\frac{W_o - W}{W_n - W}\right)^{3,5}\left(\frac{1}{W_0^2} + 2\frac{W_o}{W_n^3}\right), \tag{6}$$

where β is a parameter characterizing the soil; D0 is the diffusion coefficient at the initial moisture content Wo; Wn - is the total moisture capacity; Wo is the initial humidity; W is the maximum molecular moisture capacity; Kf - filtration coefficient; ψ - capillary pressure at a moisture content equal to the maximum molecular moisture capacity.

$$W = \frac{m(W_n - W_m)^{10/7} - W_n(m - W_m)^{10/7}}{(W_n - W_m)^{10/7} - (m - W_m)^{10/7}}, \tag{7}$$

$$\psi = -h_k \sqrt[3]{\frac{10}{7\nu} \ln \frac{W - M_m}{m - W_m}}, \text{ при } W \geq W^*. \quad (8)$$

Where - Wм - maximum hygroscopicity, %; hk is the maximum height of the capillary rise (for loamy soils 2-5 m); ν is an empirical coefficient determined for mineral soils and is taken equal to 2.7; m is porosity, % of soil volume. The direction of moisture transfer and the dimensions of the humidification circuit can be calculated from the known values of porosity and maximum hygroscopicity using equations. During the study, a number of factors were identified, the dependence of which depends on the composition of salts accumulating in the soil, and other unfavorable soil processes can also develop.

In many foreign studies, for example, in the USA, with drip irrigation, when irrigation is carried out frequently, daily or every other day, determine the value of the minimum additional amount of water (in fractions of the amount of water applied) LRt, which must pass through the root zone to prevent salinization using the formula:

$$LR_i = \frac{EC_w}{2(\max EC_e)}, \; LR_i = \frac{EC_w}{2(\max EC_e)},$$

where E Ce is the electrical conductivity of the extract from saturated soil, d S/m; ECW – electrical conductivity of irrigation water, d S/m.

The theoretical yield reduction (Y), in percent, for various crops, caused by salinity with drip irrigation, if $EC_w > \min EC_e$ can be calculated by the formula

$$Y = \frac{EC_w - \min EC_e}{\max EC_e - \min EC_e} \cdot 100.$$

Table 1 - Granulometric composition of the soil of the experimental plot

Pit	Horizonts, sm	Content of fruction, %								Actual clay
		>1.0	1.0-0,25	0.25-0,10	0.10-0,05	0.05-0,01	0.01-0,005	0.005-0,001	<0,001	
P-1	0 …20	2,2	4,0	8,1	10,0	48,2	6,6	9,1	11,6	27,3
	20 …40	2,4	3,8	6,3	10,6	49,7	9,1	6,3	11,8	27,2
	40 …60	2,1	3,9	5,8	8,3	51,6	9,3	10,1	8,9	28,3
	60 …80	3,0	2,7	5,3	8,2	52,1	9,5	10,8	8,4	28,3
	80 …100	2,5	1,8	2,5	12,4	51,8	8,5	9,6	10,9	29,0
	0 …100	2,4	2,7	5,9	11,4	49,3	8,6	10,3	9,4	28,3
P-2	0 …20	2,4	3,7	8,9	11,1	47,1	6,2	9,7	10,5	27,3
	20 …40	2,5	3,9	5,9	10,2	48,6	8,7	7,0	11,4	27,2
	40 …60	2,3	4,4	5,2	8,7	49,6	9,7	10,8	7,9	28,3
	60 …80	2,8	2,4	5,0	7,6	51,5	9,3	10,2	8,0	28,3
	80 …100	2,5	3,3	2,8	11,0	50,9	8,3	9,9	10,1	29,0
	0 …100	2,6	2,5	5,1	10,9	48,8	8,9	10,1	8,9	28,3
P-3	0 …20	2,3	4,6	8,5	10,6	48,0	6,9	9,3	11,6	27,3
	20 …40	2,2	4,8	7,3	11,6	48,7	9,1	6,3	11,8	27,2
	40 …60	2,1	3,9	5,8	8,3	51,6	9,5	10,4	7,9	28,3
	60 …80	3,1	2,9	5,6	8,0	52,5	9,8	10,5	8,6	28,3
	80 …100	2,4	1,7	2,3	12,7	51,4	8,0	9,2	10,3	27,0
	0 …100	2,6	2,5	4,6	10,8	48,7	8,9	11,2	9,6	27,3

For frequent irrigation $EC_w \leq \min EC_e$, Y will be 0. The use of drip irrigation has a certain impact on the soil, which mainly depends on the irrigation regimes used, the quality of the irrigation water used and soil conditions. An analysis of literary sources showed that information on the direct effect of water quality on the properties of chernozem soils when drip irrigation is used is extremely insufficient and research is required to study soil processes that occur when irrigation water of various qualities is used.

During the period of the study, three pits were laid at the objects of study. As a result, soil samples were taken every 20 cm. At the same time, the soils contain a small amount of humus, which was 0.02 ... 1.42%. When moistened and mechanically affected, they were easily destroyed. The soils are medium loamy in their granulometric composition, the content of physical clay is 24.7...37.7%. Where the filtration coefficient of the calculated layer averaged 0.3 m/day. During the research, attention was paid to determining the water-physical properties of the soil. The results of the granulometric composition of the soil, which was used to determine the water-physical characteristics, are shown in Table 1.

The soil of the experimental pilot object has a density of about 1.33 g/cm3, the lowest moisture content in the 0.8 m layer is 21-23% of the soil mass, water permeability in the first hour is 5.1 cm/h.

The level of calculated groundwater data at the site is about 6-9 meters. According to their characteristics, the considered soil conditions are suitable for the use of the drip irrigation method for intensive fields of wheat and rice. Figure 5 shows the main characteristics of the soil required to justify the irrigation regime.

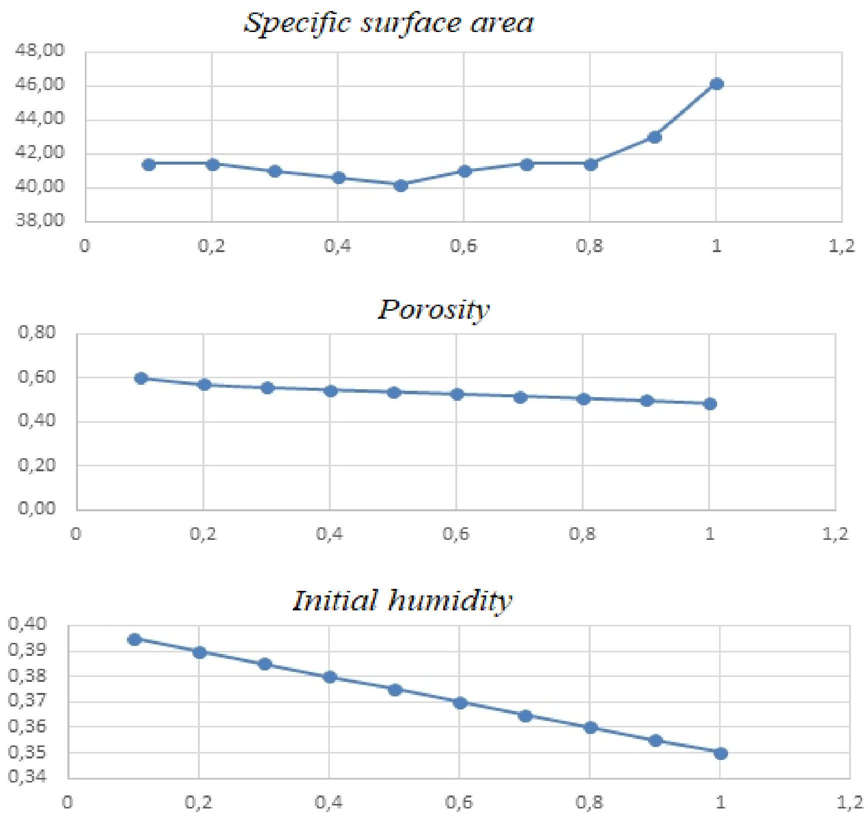

Figure 5. Graphs of the distribution by depth of the water-physical characteristics of the soils of the site

The considered models require further theoretical and experimental development and verification for various soil conditions, the integrity of the model, and the main problems of plant development is to consider all the interfering factors of their influence on the biological processes of green mass formation. First of all, it is necessary to clarify what factors affect the growth of green mass development, in most cases, such factors include radiation, air and soil humidity, air and soil temperature, soil density and chemical composition, precipitation, groundwater level and the energy component of all these processes and much more than others [22].

For solving the influencing factors, it is necessary to regulate all the factors that will ensure the management of plant development. However, it is very difficult to analytically describe a plant development model that would consider all-natural features at the same time. It is known that the main factors that determine the development of a plant can be divided according to the type of energy interaction: photosynthesis, evapotranspiration, moisture and salt transfer.

All these systems are interconnected and cannot be considered separately from each other. Each system has its own subsystems and factors, energy interconnection laws, as well as interdependent factors that can be expressed both analytically and empirically using the appropriate mathematical apparatus, including differential (ordinary and partial derivatives) and algebraic (regression, empirical) equations. A separate problem is the construction and computer implementation of a scheme for the joint numerical solution of a system of equations describing the above processes, considering the initial and boundary conditions. To construct such a scheme, one can use specialized computer mathematics packages, for example, Mathcad, Matlab and others [23, 24].

The considered mathematical model makes it possible to evaluate the leaching of the soil layer at different depths of groundwater and the lateral outflow from the wetted strip, which can serve as indicators of the environmental friendliness of the irrigation method. On its basis, it is necessary to perform predictive calculations of the garden drip irrigation regime in years of different weather conditions based on long-term observations [25, 26, 27].

Thus, the complexity of the simulated system "Plant-moisture-soil-atmosphere-solar radiation" and its subsystems is explained by a large number of interrelated factors of various nature and requires the construction of numerical schemes, computer simulation using a computer [28, 29].

4. Conclusions

While implementing an automated device, it allows automatic watering of vegetable crops in different areas and zones, by constantly monitoring humidity, and reporting problems in the irrigation system. Insufficient knowledge of the issues of optimization of parameters and modes of combined (drip + fine) irrigation of various crops requires the following developments:

1. Information technology for an automated system for managing the water regime of crops for various irrigation methods, soil types and natural conditions;

2. Techniques for computer simulation of the moisture field based on the numerical solution of differential equations of moisture transfer in combined irrigation, considering the location of droppers and humidifiers;

3. A mathematical model of water-physical processes in combined irrigation based on the theory of moisture transfer and optimization of the parameters of combined irrigation of root crops based on mathematical modeling of moisture transfer processes using digital information technologies.

4. Analysis of a system-dynamic model of plant development under irrigation to build a mathematical model of moisture transfer during drip irrigation using differential equations in partial derivatives, which allows building areas of moisture for various combinations of parameters.

6. Mathematical models family of moisture transfer by combined irrigation, in the form of differential equations in partial derivatives, considering the physical and mechanical properties of soils, and the method of their numerical computer integration to obtain the configuration of the moisture distribution field in the soil.

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