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THE NECESSITY, SCIENTIFIC AND PRACTICAL PRINCIPLES OF IMPROVING METHODS OF DRAINAGE SYSTEMS DESIGN AND CALCULATION

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Abstract. *The paper presents a new approach to improving the methods of design and calculation of drainage systems and their technical elements in the drainage mode and in the subsoil moistening mode. This was done on the basis of substantiating the connection of all technical elements of the system and taking into account the influence of their work efficiency on the effectiveness of regulating the water regime of drained lands. The existence and structure of the hierarchical and hydraulic relationship between the parameters of soil flow movement, the parameters of the closed collector-drainage network, and the parameters of canals and structures of drainage systems were determined based on the application of the system methodology. A physical model, a structural model, a mathematical model, and a hydraulic model of the drainage system were developed. By using these models, the principles of determining the parameters of the hydraulic characteristics of drainage or water supply (discharge, pressure, velocity etc.) for all elements (drained massif of reclaimed field, collector and drainage network, open canals of the network, main canal, water intake) in the entire range of variation with possible consideration of changes in slopes were obtained. The considered approach will make it possible to evaluate the efficiency of water flow movement simultaneously on every technical element and on the drainage system as their interconnection. In the future, this will make it possible to improve the methods of designing and calculating the technological and structural parameters of drainage systems, and thereby ensure the overall technical, technological, economic, and ecological efficiency of their functioning in accordance with modern conditions and requirements. This is a further improvement of the methods of design and calculation of drainage systems and their technical elements, taking into account the structural, hierarchical, and hydraulic relationship between them in accordance with modern conditions and requirements. This will make it possible to increase the validity and general technical, technological, ecological and economic efficiency of the creation and functioning of drainage systems during the implementation of adaptive measures regarding the changes in climatic conditions and the level of agricultural production in the area of drainage reclamation, for example, in Ukrainian Polissia. It will also provide an opportunity to ensure the necessary level of food security in the region and the country as a whole in the war and post-war periods.*

Key words: *design, construction and operation, drainage system, optimization, ecological and economic principles*

Relevance of research. Among the biggest challenges of our time is the issue of food, water, and environmental security exacerbated by climate change and the harmful consequences of Russian aggression, which already impacted the national and global economies [1–3].

At the same time, the technical condition of the drainage systems (DS) built 40–50 years ago has deteriorated due to wear and tear along with a failure to perform the necessary set of operational measures, which has led to the deformation and silting of the closed collector and drainage network (CCDN), as the main regulatory element of such systems that work in the regime of drainage and subsoil moistening. As a result, there was a deviation of their parameters from the design values, a violation of the regime and operation of the CCDN and all other technical elements of the DS, a decrease in their throughput. The overall efficiency of the functioning of such systems and the productivity of drained lands decreased by 25…50 % compared to the design [4–6], etc.

In agricultural production, land reclamations traditionally play a leading role in ensuring its sustainable development in adverse climatic conditions.

Based on the generalized research of domestic and foreign scientists, specialists of Ukrhydromet, the Institute of Water Problems and Land Reclamation of the National Academy of Agrarian Sciences, Odesa State Ecological University, as well as the results of authors' own research, an assessment of the current state of weather and climate conditions in the Polissia zone of Ukraine, their changes and impact on the yield of cultivated crops, soil fertility and moisture availability, operating conditions of water and reclamation facilities, and the natural and reclamation state of drained lands was carried out [7–9].

At the existing speed and levels of changes in weather and climate conditions, we should expect a deterioration of natural and reclamation conditions in general both in the Polissia zone and in Ukraine as a whole. This will inevitably affect the functioning of water and reclamation objects and complexes as a result of changes in the ecological and economic resources, which determines the need to develop adaptive regime-technological and technical measures for the management of these objects on the basis of relevant research, complex scientific sectoral, state, and interstate programs.

Based on the results of the analysis and generalization of the content of programmatic international and national documents (IPCC and Working Group II) regarding the necessity and general recommendations for the development of adaptive measures related to climate change, the results of research and the general assessment of domestic and foreign scientists and specialists, the general recommendations for the development of adaptive operational, construction and design measures that have their own clear goals and are closely interconnected have been considered [10–12].

Therefore, the question of changing approaches and developing a number of appropriate measures for the adaptation to climate change aimed at effective regulation of water regime, regulation and accumulation of moisture in soil profile and within the system, the transition from traditional periodic to the implementation and provision of regular moistening of drained lands, improvement of water regulation technologies, types and structures of DS and their technical elements, methods of their design and calculation becomes extremely urgent.

Thus, the improvement of the methods of design and calculation of DS in compliance with modern economic and environmental requirements, the wide use of information and computer technologies is a mandatory condition and an integral component of the successful implementation of adaptive measures and solving the problem of increasing the general technical, technological, economic, ecological efficiency of their creation and functioning [5; 13; 14].

Analysis of the latest studies and publications. Traditionally, issues of substantiation of the type and design of the DS and their constituent technical elements (drainage, collector, canals of the lateral and fencing network, main canal, hydrotechnical structures, etc.) were solved on the basis of the application of ***water balance, hydromechanical, and empirical*** methods. At the same time, each of them has its advantages and disadvantages.

At one time, many well-known domestic and foreign scientists fruitfully dealt with various aspects of the creation and functioning of the DS (V.A. Hurin, P.I. Kovalenko, L.F. Kozhushko, O.Ya. Oliynyk, M.G. Pivovar, V.L. Polyakov, M.I. Romashchenko, O.V. Skrypnyk, V.A. Stashuk, M.M. Tkachuk, M.M. Khlapuk, V.F. Shebeko, A.M. Yangol, A.V. Yatsyk, Engelsmann K., Ernst, Hooghoudt, Kirkham, Kunze G., Ramanauskas, Schilfgoarde, Ylover R. and many others) [15–19].

In order to increase the efficiency of the DS operation with two-way regulation of the water regime of drained lands, in the 70s and 80s of the last century, issues related to the automation of water regulation management and production processes of water distribution on drying and moistening systems were intensively developed by means of hydraulic automation (B.O. Bakhovets, V.D. Dupliak, P.I. Kovalenko, Y.G. Kovalchuk, S.K. Matus, O.M. Naumchuk, V.Y. Pastushenko, O.I. Tyshenko, Y.V. Tkachuk, B.I. Chalyy, M.V. Yatsyk, etc.) [6].

Such developments on the methodology for the creation and functioning of the DS acquired a high scientific level, received comprehensive recognition, were included in the relevant industry standards and were widely implemented in practice. But, as global and domestic practice, accumulated experience, as well as scientific research have shown, unfortunately, these methods do not sufficiently take into account the changing nature of weather and climate conditions, terrain relief, water-physical properties of soils, geological and hydrogeological conditions, etc., by profile and area of the drained massif, common conditions and modes of operation of all the main technical elements and the system as a whole in their interconnection, as well as modern economic and ecological requirements for such objects.

In turn, this requires a change in scientific and methodological approaches to the justification

in projects of construction, reconstruction, and modernization of drainage systems of their optimal constructive solutions (type, design, parameters of systems and their constituent technical elements) according to relevant technologies (methods, regimes, schemes) of water regulation depending on multiple variables of natural and climatic, relief, soil, hydrogeological, agrotechnical, and other conditions of the object's functioning in their interrelationship. This will make it possible to create a new generation of DS, which, in accordance with modern conditions and requirements, can regulate not only the water regime of the drained territory, but also accumulate moisture, both in the soil and within the system as a whole.

In this regard, **the purpose** of the research is to further search for new approaches to improving the design and calculation methods of DS and their technical elements that work in the mode of drainage and subsoil moistening, based on the substantiation of the relationship of all technical elements of the system and taking into account the influence of efficiency of their operation on the efficiency of regulating the water regime of drained lands.

Research methods and materials. Modern challenges related to the food, water, and environmental crises, as well as climate change, determine the need to change approaches to the creation and functioning of DS on the basis of the further development of the systematic methodology and the optimization method, as its integral component, the application of system optimization, the essence of which is a finding of intermediate local optima, when each subsequent optimal decision is made taking into account the previous one in the sequence, which corresponds to the hierarchical subordination of all their interconnected heterogeneous elements [13; 14].

According to such principles and scientific and methodical approaches

– general approaches, methods, and models for optimizing technical and technological solutions for water regulation of drained lands on ecological and economic grounds were developed by moving from the established practice of considering land reclamation objects not purely as technical, but as complex natural and technical systems;

– we prove the presence of a structural connection in such a system between disparate elements, which have a type **effect ⇔ mode ⇔ technology ⇔ design**;

– we developed the principles of construction and implementation of complex optimization models for regime-technological and constructive solutions for water regulation of drained lands;

– the criteria of economic and ecological optimization regarding different levels of management decision-making in time are substantiated (1-project, 2-planned operation, 3-operational management);

– we developed a set of predictive and simulation models for prognosis assessment on a long-term basis of variable natural, agricultural, and reclamation conditions of a real object;

– we substantiated a set of adaptive measures, which includes agromelioration (improvement of technologies and means of deep loosening of drained mineral soils) and hydrotechnical (improvement of technologies and regimes of water regulation on drained lands, corresponding types and structures of DS, technologies of their design and calculation methods) and ensures the implementation of reconstruction, modernization, and new construction of DS that meet modern conditions and requirements;

– on the basis of consideration of structural, hierarchical, mathematical models of the object and its management model, the principles of construction and implementation of relevant complex models of system optimization were developed grounding on a sequential justification based on the hierarchical subordination of regime, technological and constructive solutions in their interaction, when each subsequent optimal solution is accepted taking into account the previous one;

– complex models of system optimization were developed and the methods of their implementation were improved according to the relevant criteria and models, which make it possible to justify regime, technological and constructive solutions in projects of construction, operation, reconstruction, and modernization of substations in compliance with modern economic and ecological requirements in their interconnection;

– we improved the technology of designing DS on the basis of system optimization regarding the step-by-step assessment of technical, technological, economic, and environmental parameters of heterogeneous elements and the system as a whole using a multivariate approach and corresponding heterogeneous methods, in contrast to the existing, mostly monovariant, by combining them and sequentially implementing them according to an hierarchical subordination with decision-making according to the relevant basic project procedures. This makes it possible to comprehensively assess and improve the overall efficiency, as well as the technical, technological, economic, environmental, and investment soundness of their projects in accordance with modern conditions and requirements.

Research results and their discussion. Based on and in the development of the main provisions and principles regarding the application of the system methodology and the optimization method during the creation and functioning of water and land reclamation objects (Kovalchuk V.P., Kovalchuk P.I., Lazarchuk M.O., Turchenyuk V.O. etc.) and, based on their various definitions, we established interdependent relationships between disparate elements and such systems' characteristic technological, economic, and ecological features [20–26].

Therefore, according to [27] and other papers, when applying the most modern methodology of the system approach and system analysis to the creation and functioning of water and land reclamation objects, DS are presented as complex natural-technical and ecological-economic systems (CNTEES) in which there is a structural relationship is the form

effect ⇔ mode ⇔ technology ⇔ construction.

This determines the need for more detailed studies of the regularities of interconnected processes of water movement both in the main elements and in the system as a whole.

Therefore, by analogy and in the development of such an approach, it is advisable to single out and consider a technical subsystem of the type *soil flow movement parameters ⇔ CCDN ⇔ parameters of canals and structures of DS*, the elements of which have a structural, hierarchical, and hydraulic relationship (Fig. 1).

At the same time, a specific feature of the DS with two-way regulation of the water regime of drained lands is that the processes of water flow in the elements of the CCDN of the DS during its operation in the mode of drainage and subsoil moistening are similar, but mutually opposite and are implemented using the same CCDN.

Accordingly, the determined connection between the regime of the groundwater level and the CCDN is provided by the transformation of the filtration movement of a relatively uniform and continuous soil flow on the reclaimed field into a heterogeneous structure of a collection of separated water turbulent flows in hierarchically and hydraulically connected pressure drainage pipelines, as constituent elements of the CCDN, canals of the lateral network, main canal and water receivers with different conditions of formation of their gradients of pressures and velocities when operating in the drainage mode and vice versa – when operating in the subsoil moistening mode. This can be reflected by the corresponding subsystem

mode of movement of soil flow ⇔ mode of flow in CCDN ⇔ mode of flow in the canals of the lateral network ⇔ mode of flow in the main canal ⇔ flow mode in the water receiver.

In turn, according to the general theory of the movement of water flow in a pressure pipeline, the efficiency of the flow regime in the CCDN is determined by the parameters of the hydrodynamic structure of the velocity distribution in the cross section of the flow in a separate collector and drainage pipeline, as its main element, which determines the efficiency of each such element and the CCDN in general. At the same time, it is obvious that the efficiency of the CCDN in the pressure mode is determined by the efficiency of the canals of the lateral network, the main canal, and the water receiver, in which the movement of water occurs in an open canal.

According to the construction structure and connections between the elements of a self-flowing DS (see Fig. 1), we developed its physical model (Fig. 2), which works in the mode of drainage and subsoil moistening, for which a patent for a useful model was obtained (No. 147568) [28].

The advantage of the proposed scheme is that it reflects the principles of determining the parameters of the hydraulic characteristics of drainage or water supply (discharge, pressure, velocity, etc.) simultaneously for all elements

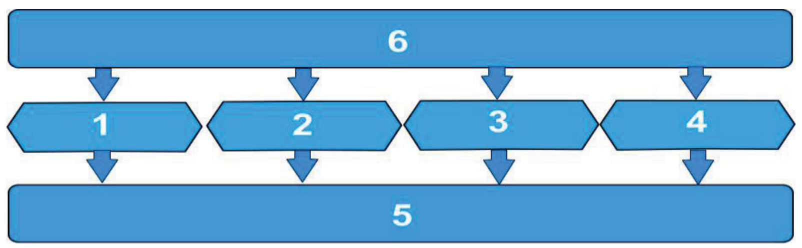

Fig. 1. Structure diagram of DS:
1 – collector and drainage network on the reclaimed field; 2 – lateral canal network; 3 – main canal; 4 – water receiver; 5 – facilities and means of drainage automation; 6 – facilities and means of water supply automation

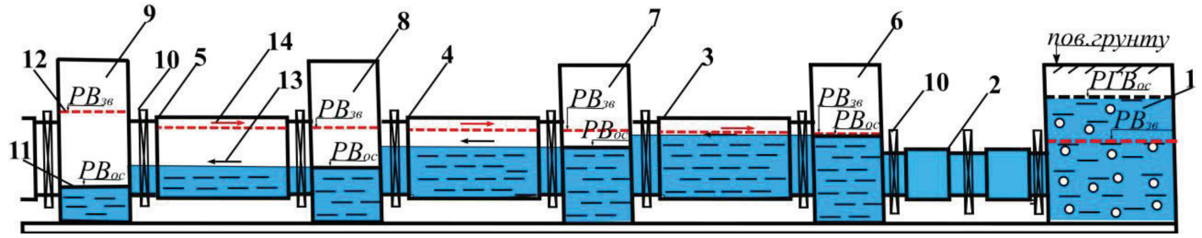

Fig. 2. Structural diagram of the interconnection of the main technical elements of the DS:
1 – an element of the reclaimed field; 2 – CCDN; 3 – an element of open canals of the lateral network; 4 – the main canal element; 5 – a water receiver element; 6 – the tank that displays the water level in the CCDN; 7 – lateral network; 8 – main canal; 9 – water receiver;
10 – capacity regulators; 11, 12 – water levels during system operation, respectively, in drying and moistening modes; 13, 14 – directions of water movement through system elements when working in the drying and moistening mode, respectively

of the DS (drained massif of the reclaimed field, collector and drainage network, open canals of the lateral network, main canal, water receiver) in almost the entire range of their variation with the possible consideration of changes in slopes.

Accordingly, by introducing the necessary notation, the functional relationship between its components can, in the general case, be represented as a complex function that does not have an explicit solution

$$y_i = f_1\left(f_2\left(f_3\left(x_i\right)\right)\right),\ i=\overline{1,n_i}, \qquad (1)$$

where f_1 is the function that depends on the parameters of the movement of soil flow R_i, $i=\overline{1,n_i}$; f_2 is the function that depends on the parameters of the CCDN FS_i, $i=\overline{1,n_i}$; f_3 is the function of arguments x_i, which depends on the parameters of canals and facilities K_i, $i=\overline{1,n_i}$; i is the set $\{i\}$, $i=\overline{1,n_i}$ of possible options for the implementation of appropriate technical and technological solutions for water regulation of drained lands in the appropriate natural, agricultural, and land reclamation conditions of a real object.

The listed functions f_1 ... f_3 are functions of complex interconnected arguments, i. e.

$f_3\left(x_i\right)$ – as a function that depends on the parameters of canals and facilities;

$f_2\left(f_3\left(x_i\right)\right)$ – as a function that depends on the parameters of the closed collector and drainage network;

$f_1\left(f_2\left(f_3\left(x_i\right)\right)\right)$ – as a function that depends on the parameters of the movement of soil flow.

Then, the search for the parameters of the components of the composite function (1) and, first of all, the parameters of water regulation technologies and the type and design of technical elements related to them, depending on the created mode of flow movement, can be formally carried out from the expression (1) through the corresponding inverse functions.

Namely:

– regarding the parameters of canals and facilities FK_i, $i=\overline{1,n_i}$

$$f_3\left(x_i\right) = f_2^{-1}\left(f_1^{-1}\left(y_i\right)\right),\ i=\overline{1,n_i}; \qquad (2)$$

– regarding the parameters of the closed collector and drainage network FS_i, $i=\overline{1,n_i}$

$$f_2\left(f_3\left(x_i\right)\right) = f_1^{-1}\left(y_i\right),\ i=\overline{1,n_i}; \qquad (3)$$

– regarding the parameters of soil flow movement FR_i, $i=\overline{1,n_i}$

$$x_i = f_3^{-1}\left(f_2^{-1}\left(f_1^{-1}\left(y_i\right)\right)\right),\ i=\overline{1,n_i}. \qquad (4)$$

The implementation of complex functions (1) – (4) should be based on the studies of the regularities of interconnected processes of water movement in all the constituent elements (subsystems) of the DS as CNTEES, which are different by their nature.

In this setting, models (1) – (4), which are presented in a general implicit form, cannot be sufficiently adequately expressed analytically and have no practical solution. But they make it possible to theoretically substantiate the possibility of setting a problem at least on an empirical or even on a much more objective empirical-functional level of determining the dependence between them.

Based on the structural model of the DS (see Fig. 1) and the established nature of the connections between its system elements in general according to mathematical models (1) – (4), the integral amount of water during the operation of the DS in the mode of water removal (drainage -) or subsoil moistening (water supply +) ($\pm W_S$) in time (T) and space (F), in the general case can be determined as

$$\pm W_S = \int_0^T\int_0^F w_i\cdot\left(T,F\right)\ dt\ df,\ i=\overline{1,n_i}, \qquad (5)$$

where w_i is the integral amount of water during water removal or water supply, which passes through each DS's technical element in the set $\{i\}$, $i=\overline{1,n_i}$; T is the period of system's operation; F is the area of the system as a whole.

Then, the volume of water for DS during drainage or water supply, taking into account the necessary and technically possible amount of it, can be generally defined as

$$\pm W_S = \Delta_s \left(\hat{q}_s \cdot T \cdot F_s \right), \quad (6)$$

where Δ_s is the coefficient of imperfection of the system as a whole in relation to the ratio of the required and possible amount of drainage or water supply by it; $\hat{q}_s$ is the time- and space-weighted average value of the drainage or water supply module within the system and the period of the object's operation.

The coefficient Δ_s of imperfection of the system as a whole regarding the ratio W_{sf} of possible (actual) and the ratio W_{st} of necessary (calculated) drainage or water supply by it can be represented a dependency

$$\Delta_s = \frac{W_{sf}}{W_{st}} = \frac{\sum_{i=1}^{n_i} W_{if}}{\hat{u}_S \cdot T \sum_{i=1}^{n_i} f_i \cdot F_s}, \quad (7)$$

where $\hat{u}_S$ is the average value of the velocity of water flows movement in the system, m/s; f_i is the share of the DS area that is served by a certain technical element: the collector and drainage network of the set $\{kd\}$, $kd=\overline{1,n_{kd}}$, lateral canals network of the set $\{b\}$, $b=\overline{1,n_b}$; main canal of the set $\{m_k\}$, $m_k=\overline{1,n_{m_k}}$; water receiver (υ).

Accordingly, for any technical element of DS (see Fig. 1)

$$\pm W_i = \sum_{m_{i=1}}^{n_{m_i}} \Delta_{n_{i-1}} \left(\overline{q}_i \cdot T_i \cdot f_i \cdot F_s \right), \quad (8)$$

where $\pm W_i$ is the volume of water that is diverted or supplied to the DS by any of its technical elements; m_i is the number of constituent elements of the i-th technical element of the DS; $\Delta_{n_{i-1}}$ is the coefficient of imperfection of the technical elements of the DS when the efficiency of each subsequent element is determined by the previous one; $\overline{q}_i$ is the calculated module of drainage flow or water supply in relation to the corresponding mode of operation of the i-th technical element of the DS, l/s·ha; T_i is the period of operation of the technical element on the system.

The efficiency of the system is determined by the corresponding efficiency of each of its elements, the nature of the complex relationships between which is similar to the models (1) – (4):

$$\Delta_s = f_n \left(f_{n-1} \left(\sum_{i=1}^{n_i} \Delta_{n_{i-1}} \right) \right). \quad (9)$$

That is, the efficiency of each subsequent element of the system is determined by the corresponding efficiency of the previous one and vice versa.

In turn, by the analogy with the formula (7), the coefficient of imperfection $\Delta_{n_{i-1}}$ of the system's element is the ratio of the possible (actual) volume of water W_{if} and the necessary (calculated) volume of water W_{if}, which is drained or supplied to the DS by any of its technical elements:

$$\Delta_{n_{i-1}} \left(W_i \right) = \frac{W_{if}}{W_{it}}. \quad (10)$$

Then, applying the equations of the statistical theory of determining the influence of each operating factor on the initial parameter, the following equation can be obtained:

$$\Delta_{n_{i-1}} \left(W_i \right) = \frac{W_{it} - \sqrt{\sum_{j=1}^{z} \left(\Delta x_j \frac{\partial y}{\partial x_j} \right)^2}}{W_{it}}, \quad (11)$$

where x_j is the main j-th operating factor (average speed in the element of the system; the area of any technical element of the system; time, etc.); z is the number of active factors in the equation of the initial parameter; Δx_j is the absolute change of values of j-th factor of the initial parameter.

Since the movement of water in the self-flowing DS during its operation in the drying and moistening mode is caused by the presence of the necessary pressure gradient due to the difference in levels (see Fig. 2), the hydraulic model of the system and any of its technical elements in general can be represented as: (12) – for the system; (13) – for its technical elements:

$$\pm W_s = \Delta_s \hat{u}_S T \sum_{i=1}^{n_i} \omega_i; \quad (12)$$

$$\pm W_i = \sum_{m_{i=1}}^{n_{mi}} \Delta_{n_{i-1}} u_i \omega_i \cdot T_i \quad i=\overline{1,n_i}, \quad (13)$$

where ω_i is the area of a technical element of the system, m; u_i is the average speed of water flow in the technical element, m/s; l_i is the parameter of the system's element (canal bed or pipeline), from which water is drained at a certain stage i during the estimated time period T, m.

Conclusions. Thus, the considered issues cause the need for further improvement of the design and calculation methods of DS and their technical elements, taking into account the structural, hierarchical, and hydraulic relationship between them in accordance with modern conditions and requirements, which, in particular, is reflected in the adopted "Irrigation and Drainage Strategy in Ukraine on the period until 2030" [29].

This will make it possible to increase the validity and general technical, technological, and ecological-economic efficiency of the creation and functioning of the DS during the implementation of adaptive measures to the climatic conditions change and the level of agricultural production in the zone of drainage land reclamation, primarily in the Ukrainian Polissia, to ensure the necessary level of food security in the region and the country in general, in the war and post-war periods.

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НЕОБХІДНІСТЬ ТА НАУКОВО-ПРАКТИЧНІ ЗАСАДИ УДОСКОНАЛЕННЯ МЕТОДІВ ПРОЕКТУВАННЯ І РОЗРАХУНКУ ДРЕНАЖНИХ СИСТЕМ

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Анотація. *Розглянуто новий підхід до удосконалення методів проектування і розрахунку дренажних систем та їх технічних елементів, які працюють в режимі осушення та підґрунтового зволоження, на основі обґрунтування взаємозв'язку всіх складових технічних елементів системи та врахування впливу ефективності їх роботи на ефективність регулювання водного режиму осушуваних земель. На основі застосування системної методології визначено наявність та структуру ієрархічного та гідравлічного взаємозв'язку між параметрами руху ґрунтового потоку, закритої колекторно-дренажної мережі й параметрами каналів та споруд дренажних систем. Розроблено фізичну, структурну, математичну та гідравлічну модель дренажної системи, за якими розроблено принципи визначення параметрів гідравлічних характеристик водовідведення або водоподачі (витрата, напір, швидкість тощо) одночасно по всіх її елементах (осушуваного масиву меліорованого поля, колекторно-дренажної мережі, відкритих каналів бокової мережі, магістрального каналу, водоприймача) практично у всьому діапазоні їхнього варіювання з можливим урахуванням зміни ухилів. Розглянутий підхід дасть змогу оцінити ефективність руху водного потоку одночасно по всіх технічних елементах й дренажної системи в цілому у їх взаємозв'язку та в подальшому удосконалити методи проектування й розрахунку її технологічних та конструктивних параметрів й, тим самим, забезпечити загальну технічну, технологічну, економічну і екологічну ефективність їх функціонування відповідно до сучасних умов та вимог. Подальше удосконалення методів проектування й розрахунку ДС та їх технічних елементів з урахуванням структурного, ієрархічного і гідравлічного взаємозв'язку між ними відповідно до сучасних умов та вимог, дасть змогу підвищити обґрунтованість і загальну технічну, технологічну та еколого-економічну ефективність створення й функціонування ДС при реалізації адаптивних заходів щодо зміни кліматичних умов та рівень аграрного виробництва у зоні осушувальних меліорацій, насамперед в Українському Поліссі, забезпечити необхідний рівень продовольчої безпеки в регіоні та країні в цілому у воєнний й повоєнний періоди.*

Ключові слова: *проектування, створення та функціонування, дренажна система, оптимізація, еколого-економічні засади*

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GENERAL ASPECTS OF RESTORATION (RECONSTRUCTION) OF DRAINAGE SYSTEMS ON AGRICULTURAL LANDS (REVIEW OF PUBLICATIONS)

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Abstract. *The article presents a review of publications on the actual problem of restoring the functional capacity of drainage systems, which in modern conditions of climate change and military aggression acquires special significance not only from the standpoint of the need to increase the productivity of drained lands, but also to ensure the water security of our country. The study of problems and setting of directions for restoration (reconstruction) of drainage systems in Ukraine and regions of the world was performed using bibliometric analysis. For analytical research, domestic and foreign literary sources of a 55-year period were studied, the main number of which falls on the period 2002–2022. The conducted analysis made it possible to determine the main directions that are considered when solving the problems of restoration (reconstruction) of drainage systems on agricultural lands worldwide and in Ukraine. Approaches to the operation, maintenance, and controlled decommissioning of drainage systems are based on the development of scenarios for the adaptation to climate change, therefore, the priority of the state policy in a number of countries is, first of all, the restoration of systems, which allows to ensure the adaptation of agricultural production to modern climate changes. Worldwide, the assessment of the reclamation fund is carried out constantly and the need for reconstruction and modernization of drainage systems is determined according to the design characteristics and technical condition also providing for the restoration of their water-regulating function. The basis for the reconstruction of drainage systems is the economic and technical justification of feasibility, the application of the progressive methods of drainage, the priority implementation of restoration measures in the areas of drainage systems, which are in working condition, and on the drained territories, where intensive and medium-intensity agricultural use of the drained lands is planned. The scientists' developments are aimed at creating economically viable technical options for the restoration (reconstruction) of drainage systems, which take into account the directions of their use and investment options for reconstruction. Studying the global experience of restoration (reconstruction) of drainage systems on agricultural lands and its use is important for the implementation of the provisions of the "Strategy of Irrigation and Drainage in Ukraine for the period until 2030".*

Key words: *drainage systems, restoration (reconstruction) of drainage systems, drained lands, economic efficiency, bibliometric analysis*

Actuality of research. Drainage land reclamations have been known since ancient times, and the global long-term practice of agricultural production on drained lands shows that carrying out drainage measures ensures: the stability of growing and increasing the yield of agricultural crops, strengthening the economy of farms, and positive socio-economic changes [10; 24; 41; 42].

Reclaimed lands in the world occupy about 425 million hectares, in particular 164 million hectares are drained lands. In the total area of cultivated territories, the specific weight of reclaimed lands does not exceed 30%, but these lands provide 3/4 of the world agricultural production [33].

In the USA, the area of drained lands is about 60 million hectares, among which the area of large massifs is about 40 million hectares, and the are of small farm plots is up to 20 million hectares [7; 36]. Areas of drained lands in Europe make up about 70% of all reclaimed territories [29]. In Great Britain, Germany, Belgium, and Denmark, up to 70–90% of all overmoistened lands are drained [36]. In a number of countries (Finland, Sweden, the Netherlands), all overmoistened agricultural lands are completely drained [31]. More than half of the territory of the Netherlands is below the sea level, so the drainage of waterlogged lands is the basis of the country's livelihood [11].

In Lithuania, Latvia, and Estonia during the Soviet times, more than 8% of all overmoistened agricultural lands were drained.

Among the almost 3.3 million hectares of drained lands in Ukraine, which is 20% of the total area of agricultural lands in the humid zone, about 2.9 million hectares are used in agricultural production, in addition, on the area of about 1.1 million hectares there is an opportunity to carry out bilateral regulation of soils' water regime.

Modern global climate changes, their impact on the social, economic, and ecological development of mankind is becoming more and more tangible and vulnerable and is turning into one of the key problems of the global economy and politics. The main consequences of this impact include changes in the quantity and quality of water resources, their provision in various sectors of the economy, first of all, those aimed at solving the food problem, namely agricultural production.

The drainage systems in Ukraine are also one of the important factors of sustainable agricultural production in the humid zone, and the economic, ecological, and social stability of the regions with drainage land reclamation largely depends on the efficiency of the use of drained lands [43]. The global development of agricultural production shows that the greatest success was achieved by those countries that implemented large-scale national programs for the development, restoration, or reconstruction of both irrigation and drainage systems [5].

Today, the construction of new drainage systems in most countries [4; 8; 14], as well as in Ukraine, has practically stopped, and works on restoration, comprehensive reconstruction, and technical modernization of existing systems have been reduced to a minimum [25]. At the same time, in the current conditions of climate change and military aggression, the importance of restoring the functional capacity of drainage systems is growing not only from the standpoint of the need to increase the productivity of drained lands, but also to ensure the strategic and water security of our state.

The analysis of the latest researches and publications shows that few scientific works are dedicated to the study, analysis, and generalization of the global experience of conducting drainage land reclamations. General trends in the development of reclamation of overmoistened lands in the countries of Western Europe, the USA, Japan, and others indicate that their development was determined primarily by the needs of agriculture [10; 15; 29; 31; 35; 47].

According to literary sources, land drainage in the leading countries is a recognized necessity, and the area of drainage is an indicator of the technical level and possibilities of agricultural production [35]. At the same time, the modern period of drainage land reclamation in Ukraine, which began with the independence of our country, is characterized by difficult conditions for finding new forms of management and uncertainty of ownership of drainage systems' individual components and the lack of appropriate experience and legislative framework. To this day, the state is the main investor in the maintenance of inter-farm networks, and the existing level of funding does not allow to ensure their full maintenance, restoration, comprehensive reconstruction, and modernization. Therefore, taking into account that the land reclamation rate of the humid zone of Ukraine is quite high (60.5%) and corresponds to the level of such countries as the USA, Germany, and the Netherlands, it is important to study the global experience of restoration (reconstruction) of drainage systems on agricultural lands for its use in the implementation of the provisions of the "Strategy of Irrigation and Drainage in Ukraine for the period until 2030" [52].

The aim of the research is to study the experience and directions of restoration (reconstruction) of drainage systems on agricultural lands based on the materials of domestic and foreign publications and their use for the development of drainage land reclamations in Ukraine.

Research materials and methods. The methods of research are based on the use of historical-logical (identification of the most important existing domestic and global developments on the issues of restoration (reconstruction) of drainage systems), logical-abstract (expansion of information from literary sources, establishing the correctness of the use of the term "restoration (reconstruction) of drainage systems" in modern literary sources), analytical and synthetic methods (processing of the obtained information using the bibliometric method, systematic analysis, generalization and synthesis of research results).

Research results. The definition of the concept of "restoration (reconstruction) of drainage systems" in modern literary sources implies a set of measures. They are aimed at increasing the technical level of existing reclamation systems by changing the structures and basic parameters of the engineering infrastructure, replacing outdated structures with new ones, introducing automated management of soil's water regime in order to increase the productivity of reclamation lands on the basis of new equipment and advanced technologies, scientific organization of work, improvement of conditions, and productivity growth [39]. The following is used in literary sources and is considered as the reconstruction (modernization) of working and restoration of non-working drainage systems [25]: reconstruction [1; 21], construction or reconstruction of the drainage network [6], reconstruction of the irrigation and drainage system with options for segmental reconstruction [56], restoration and reconstruction of drainage systems [22], restoration of drainage systems [2; 9; 22], reconstruction, rehabilitation and restoration [17], restoration and modernization [28].

To confirm the correctness of the use of the term "reconstruction", an analysis of its use in recent publications in the countries of the Organization for Economic Cooperation and Development (OECD) was conducted [3; 17; 23; 19]. In the cited sources, it is observed that the term "reconstruction" in the normative documents of the OECD does not include the construction of new systems and hydraulic structures. The autonomous use of the term "reconstruction", which is used in the texts together with the restoration, modernization, and rehabilitation of reclamation objects, indicates that when preparing proposals, plans, projects, recommendations it is permissible to limit the use of the term "reconstruction" with its clarifications, such as, e. g., "complete", "comprehensive", etc.

The reconstruction of reclamation systems is a set of measures aimed at increasing the technical level of existing systems with the goal of increasing the efficiency of natural resources use by changing structures, the main parameters of the system and its elements, and changing obsolete equipment [39].

In a number of domestic studies and publications, it is noted that the complex reconstruction of reclamation systems is a radical technical solution in the improvement and modernization of existing systems. Modern developments define a number of criteria that should be followed when justifying the necessity and expediency of reconstruction, and principles that include technical excellence, economic efficiency, and environmental reliability [42; 45; 53; 56].

The study of problems and establishment of directions for restoration (reconstruction) of drainage systems in the countries and regions of the world was carried out using bibliometric analysis.

Domestic and foreign literary sources of the 55-year period were used for analytical research (Fig. 1). These are, in addition to domestic publications, the publications of the OECD countries, which include the most economically developed countries in the world and which also actively cooperate with Ukraine within the framework of the specialized programs and international projects.

The majority of literary sources selected for analysis fall on the period 2002–2022.

Studies on the global experience of creating, operating, and restoring drainage systems show that in the most developed countries (Great Britain, Belgium, the Netherlands, Germany, France, Denmark, etc.) permanent reconstruction of drainage systems is carried out.

In Great Britain, where reclamation measures have been carried out on almost all overmoistened lands (only about 1% of anthropogenically undisturbed lands have been preserved), the share of drained lands is more than half of all agricultural lands. The land reclamation fund is constantly evaluated in the country, and the need for reconstruction and modernization of drainage systems is determined according to their design characteristics and technical condition. Along with this, it is mandatory to solve the environmental problems that arise in the ecosystems of drained peatlands [12]. Drained lands, which are economically impractical to use (if they have not been used in agricultural production for more than 10 years), are removed from the reclamation fund [8; 15; 35; 37; 38; 42].

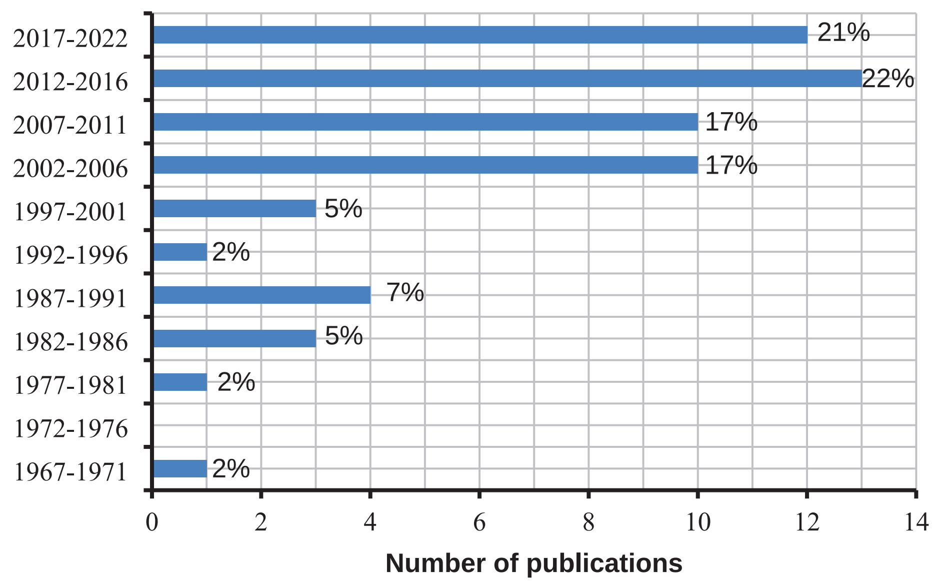

Fig. 1. Distribution of literary sources selected for analysis by 5-year intervals (1967–2022), %

Today, drainage systems in the Czech Republic are practically not constructed or reconstructed, but most of them are maintained in working condition. Their use is determined by the prospects and directions of the development of agricultural production and the expediency of reconstruction is determined by the need to ensure water regulation on drained lands [14].

In Latin America, there is a trend of reviving the old methods of reclamation of waterlogged lands, which are based on the principle of small contours or small sizes of drained massifs with the possibility of local collection of drainage water in special storage reservoirs. An an example we can mention the meliorative systems in the floodplain of the San Pedro River (Tabasco state, Mexico), the operation of which allows ensuring environmental safety within the limits of their influence [4].

Approaches to the operation, maintenance, and controlled decommissioning of drainage systems in the Netherlands are based on the development of climate change adaptation scenarios for artificial polders with marine clay soils along the coast, lowland areas with peat soils in the west and north, sandy and semisandy soils in the center, in the south and east of the country [20].

The experience of drainage systems reconstruction in the countries of the former members of the Council for Economic Mutual Assistance (Bulgaria, Germany, Poland, and the Czech Republic) shows that the basis of the reconstruction of the systems was economic and technical justification, the use of progressive methods of drainage, the priority of work on areas with high soil fertility, increasing the technical level of those sections of drainage systems that are in working condition [47].

One of the main problems agricultural production in Bulgaria is facing today is the technical condition of drainage systems. Literary sources indicate that on many systems within individual farms their condition is unsatisfactory, they are neglected and need reconstruction and modernization [28]. The priority of modern state policy is, first of all, restoration of systems, as this will allow adaptation of agricultural production to the consequences of climate change [18].

The change in soil's water regime and the development of degradation processes, the inadequate technical condition of the drainage systems is accompanied by a poor reclamation condition on almost 7% of drained agricultural lands in Lithuania. When substantiating the need for reconstruction of drainage systems, the needs of land users and their financial capabilities are taken into account. General approaches to the restoration of drainage systems are based on the expediency of such a measure in territories where intensive and medium-intensity agricultural use of drained lands is planned (according to the national strategy for the development of rural areas) [9]. The developments of Lithuanian scientists are aimed at creating economically viable technical options for the reconstruction of drainage systems, which take into account the directions of their use and investment options for reconstruction [26].

In Latvia, the rationale for the reconstruction of drainage systems is based on detailed mapping using geospatial research; on considering the need to protect the environment and improve the quality of water resources [22]. When choosing objects of reconstruction, the need to restore existing or build new drainage systems on overmoistened agricultural lands is determined [2].

A number of literary sources consider the feasibility of developing technological solutions that use drainage systems with selective drainage and the feasibility of the restoration and modernization of drainage systems based on the restoration of their water-regulating function thanks to the installation of irrigation systems [13; 16].

Modern results of scientific research indicate that it is important to use methods of statistical modeling and probability theory, on the basis of which mathematical models are developed, to justify projects of drainage systems reconstruction [13].

In China, during the reconstruction of drainage systems, the tasks of protecting rural areas from floods and agricultural lands from droughts are additionally solved by improving drainage and irrigation infrastructure, cleaning canals and increasing the efficiency of water resources use [30].

The reconstruction of drainage and irrigation systems in Indonesia was carried out simultaneously with the elimination of the consequences of the tsunami [1].

In general, global experience indicates that the restoration of drainage systems is a necessity, as they are one of the important means of minimizing the impact of modern climate changes on the social, economic, and ecological development of many countries [5].

The experience of reconstruction of drainage systems in Ukraine even in Soviet times shows that in the first post-war years (1945–1951) works were carried out to restore systems destroyed during the war. During the period of the fastest pace of construction (1965–1984), 38,000–72,000 hectares of reclaimed land with reconstructed systems were put into operation annually. In the period from 1965 to 1970, 190 thousand hectares were reconstructed in Ukraine, from 1971 to 1975–203 thousand hectares, from 1976 to 1980–214 thousand hectares, from 1981 to 1985–211 thousand hectares, from 1986 to 1990–240 thousand ha of drainage systems.

It was recommended to reconstruct the existing drainage systems on a technical basis that was new at the time: replacement of the open drainage network with horizontal and vertical drainage; replacement of existing collectors on a closed network with new ones that can ensure the passage of estimated water flows; laying of new (additional) drain-dryers to thicken the drainage; deepening, expansion, and strengthening of existing collection canals; replacement of separate open conducting canals with closed collectors of large diameters (0.3–1 m), which made it possible to increase the net drainage area by 10–12%; arrangement of an additional interception network to ensure drainage of surface runoff; combination of gravity drainage with mechanical drainage; the use of strong and durable materials in the construction of hydrotechnical structures; construction of reservoirs, storage ponds for guaranteed regulation of water, air, thermal, and nutrient regimes in the root layer of soil during the growing season of crops.

The reconstruction of previously constructed drainage systems was preceded by a detailed study of the reclamation condition at the sites.

Specific capital investments in Soviet times for the reconstruction, for example, of the Irpin drying-moistening system in Kyiv region, amounted to 1,100–1,300 rubles/ha with a payback period of 4–5 years and a land use ratio of 0.95–0.97; Berehiv cross-border polder system in Transcarpathian region – up to 1,200 rubles/ha, the payback period is 3–4 years with a land use coefficient of 0.97–0.98 [39].

At the current stage, the main goal of the complex reconstruction and modernization of drainage systems in the area of drainage reclamation is to increase the productivity and efficiency of the use of drained lands, the technical level of the systems, the preservation and restoration of soil fertility, the rational use of the natural potential of agricultural landscapes, and the provision of sustainable agricultural production in the years with different weather conditions [44].

It was determined that during the complex reconstruction and modernization of drainage systems of the humid zone, constructive solutions, water regulation technologies, and technical means for their implementation should be based on the following principles [44]:

– ensure maximum use of working elements that are in operational condition, have sufficient technical resources, and are suitable for further use;

– provide a system of engineering solutions and measures for the rational use of material, energy, water, and land resources, preservation and increase of fertility of reclamation lands, ensure their rational agro-landscape development, protection of adjacent territories, and water-receiving rivers from pollution;

– ensure a high level of efficiency in managing their work, simplicity and reliability in the operation of technical means, minimal operating costs;

– provide for autonomous management of individual plots and be flexible to implement different crop rotations in accordance with modern market needs and interests of land users of various forms of ownership.

General approaches to justifying the reconstruction of drainage systems in each specific case should be detailed taking into account the type of water supply, the existing design of the system and its technical condition, features of the terrain, soils, economic conditions, etc. [44].

One of the examples of modern (2019) positive experience is the reconstruction of the drainage system located within the Precarpathian Highlands, on which a drip irrigation system was built (on an area of 39.9 hectares, for blueberry and blackberry cultivation). Drainage is carried out with the help of pottery drainage built more than 35 years ago [13].

At the same time, the current stage of drainage reclamation development in Ukraine is characterized by a complex of unsolved problems, which are related to the peculiarities of the functioning of drainage systems in complex and changing conditions of the humid zone.

Today, there are a number of scientific developments aimed at substantiating drainage system reconstruction projects. However, the available scientific support for their restoration

(reconstruction and modernization) does not sufficiently cover all priority directions, which are determined by the current state and peculiarities of their functioning in the conditions of climate change [26; 42; 44–46; 48; 50; 51; 54; 56; 58].

Most of the drainage systems of the humid zone of Ukraine are in an unsatisfactory technical condition, which is manifested in the physical and moral aging of the main reclamation funds, low level of operation of the drainage network, failure, and in many cases the absence of hydromechanical equipment. Based on analytical and statistical sources, it was determined that the technical condition of drainage systems is characterized by general wear and tear of engineering infrastructure elements as a result of their long-term operation by an average of 60% (inter-farm network – 55% and intra-farm network – 65%) [56]. Consequently, the effectiveness of the use of drained lands and their role in the food and resource provision of the state has significantly decreased.

Restoration of drainage systems in the drainage area should be carried out according to two options, which are prescribed in the "Strategy of irrigation and drainage…": the modernization of working reclamation systems and the modernization of non-working reclamation systems [52].

The reconstruction of the working drainage systems is planned to be carried out taking into account the division of the existing systems into draining, drying-moistening, polder, and water circulation systems, which involves a complex of works to improve their parameters by adding the ability to regulate soil moisture. On drainage systems of one-way action, the basis of modernization measures is the improvement of water-regulating structures and the installation of irrigation systems; on drying-moistening ones – it is to ensure the possibility of implementing a guaranteed two-way regulation of water regime of soil under conditions of climate change. Modernization of polder and water circulation systems to the level of drainage and irrigation systems is carried out by building irrigation systems (drip irrigation or sprinkler systems) on them. The complex of modernization measures is determined on the basis of inventory data and should include different types of works on different types of drainage systems. The total area of such systems is 1311.2 thousand hectares.

Restoring the functionality of non-working drainage systems should be carried out taking into account the list of works on the modernization of working systems according to their various types and the restoration of such systems to the design level by performing repair and restoration works both on the inter-farm and on-farm networks. These works include cleaning canals and culverts; restoration of water control structures (gates, lifts, etc.); washing of collectors and drains, partial restoration of drainage; arrangement of wells-filters for removal the surface water; arrangement of existing dams, strengthening of mouths of drainage collectors, etc. The total area of such systems is 1962.9 thousand hectares.

Taking into account the current state and technical and technological features of the functioning of drainage systems of Ukraine, modern requirements for their structures should take into account changes related to the reform of the agrarian sector, agrotechnical and ecological requirements of land users on drained lands, modern climate changes. These requirements are determined based on the analysis of design materials of drainage systems located in different natural and climatic conditions of the humid zone and include the need to take into account the features of modern land management and changes in the specialization of agricultural production in the humid zone; ensuring operational management of technological processes of water regulation and maintaining the optimal water regime of the active soil layer; the expediency of using effective technological schemes along with resource-saving and environmentally sound technologies for regulating the water regime on drained lands; ensuring increased efficiency of agricultural production on drained lands by land users of various forms of ownership and management [25].

Analytical studies of the influence of modern climatic factors on the formation of soils' water regime established that modern agricultural production is under the direct influence of climatic changes, therefore, its effective management is possible provided that agricultural producers create suitable conditions for adaptation to them and minimize the impact [49]. At the same time, the impact of climate change on agricultural production by agro-enterprises today is particularly noticeable in the area of drainage reclamation, where the most changes in the production structure have recently taken place [27].

The current structure of cultivated areas is subject to both climatic changes and the market situation, which dictates the cultivation of economically attractive crops. Climate changes make corrections to technological maps and the structure of crop rotation of agricultural enterprises in the zone of drainage land reclamation. The fact that the period of a significant increase in the sum of active temperatures coincides with the period of rapid development of agricultural holdings in Ukraine (the beginning of the 21st century) contributes to the fact that such economically attractive crops as corn, sunflower, soybean are now gradually turning into the main ones. The main crops of traditional specialization (long flax, sugar beet, rye, oats, and others) of the humid zone have ceased to be a priority in modern agricultural production, however, due to the naturalness of domestic products and the uniquely favorable ecological and geographical position of their cultivation, they have the prospect of conquering the domestic and global markets, however today they are becoming mostly niche cultures [48].

Along with this, modern agricultural production on drained lands is characterized by inefficient use of the existing potential of drainage systems, therefore their water-regulating capacity is an unused resource for increasing productivity and sustainable agricultural production in the conditions of climate change. Given that the reform of the agrarian sector in Ukraine was carried out without taking into account the technological conditions of drainage systems operation, the established technologies of land use and management of drainage systems are currently violated. The formation of new conditions for the cultivation of agricultural crops and changes in the direction of the use of drained lands require the expansion of the functional tasks of drainage systems, which must be taken into account when carrying out the restoration (reconstruction) of drainage systems in the humid zone [52].

At the same time, literary sources testify to the importance of using agricultural drones (for example, Geoscan 201 A type), which allow solving the problems of operational decision-making regarding reclamation regimes on restored drainage systems based on the information obtained by remote determination of the drainage collectors location according to the state of vegetation [6].

The analysis of literary sources made it possible to determine the main directions that are considered when solving the problems of restoration (reconstruction) of drainage systems on agricultural lands worldwide and in Ukraine (Table 1).

Among the selected directions there is a number of developments aimed at creating economically profitable projects for the reconstruction of drainage systems, taking into account the directions of their use and possible investment options.

In general, literary sources indicate that the reconstruction of drainage systems is economically beneficial. Its average cost is 20–30% less than the cost of new construction and allows increasing land productivity by 25–40% [34].

The most economically expedient option is the reconstruction of systems in Ukraine with a source of financing from the equity capital of agro-industrial complex enterprises, for which the non-discounted (RR) and discounted (DPP) payback periods are 3.4 and 4.7 years, respectively [25].

1. The main directions of solving the problems of restoration (reconstruction) of drainage systems on agricultural lands worldwide and in Ukraine

Directions of restoration (reconstruction) of drainage systems	Source according to the bibliography
Expanding the functionality (water-regulating capacity) of drainage systems through their restoration (reconstruction)	[7; 19; 29; 38; 39; 40; 42; 45; 52]
Complex approaches when making decisions on restoration (reconstruction) of drainage systems	[21; 35; 36; 37]
Technical aspects of restoration (reconstruction) of drainage systems and reconstruction projects justification	[46; 48; 54; 55; 58]
Restoration of individual elements of the engineering infrastructure of drainage systems	[30; 57]
Taking into account the impact of climate change when making design decisions for the reconstruction of drainage systems	[18; 20; 22; 23; 34]
Modernization of drainage systems	[16; 17]
Features of the use of reconstructed drainage systems by agricultural enterprises	[1; 2; 5; 8; 9; 10; 11; 12; 13; 14; 15; 24; 27; 28; 30; 31; 33; 41; 42; 44; 48; 49]
Economic feasibility of drainage systems reconstruction	[9; 25; 26; 30; 32; 42; 43; 47; 50]
Ecological (nature-saving) aspects of drainage systems reconstruction	[3; 4; 5; 6; 12; 42; 44; 51; 53; 56]

It is noted that during the restoration (reconstruction) of drainage systems, it is important to take into account the possibilities of participation of international organizations, the role of beneficiaries (land users, territorial communities, associations of water users) [30]; the need to involve technologies of construction and reconstruction of systems that are certified according to international standards [28]; the expediency of application in scientific research and in the justification of projects of economic and statistical models and the importance, in addition, of compliance with normative indicators of economic and environmental efficiency.

At the same time, the need for complex reconstruction of drainage systems is substantiated by a resource-saving form of restoration of reclamation means with the maximum use of the engineering infrastructure of drainage systems and under the condition of maintaining soil fertility. The transition to a resource-saving form allows, due to the redistribution of capital investments, ensuring the growth of soil fertility, increasing the efficiency and reliability of drainage systems, land acculturation, the level of intensity of their use, and the extension of the term of their use by increasing the level of operation [32].

Conclusions. In modern conditions of climate change and military aggression (flooding of drained lands and direct destruction of individual elements of the systems), the problem of restoring drainage systems and their functional capacity acquires particular importance from the standpoint of the need to increase the productivity of drained lands and the role of Ukraine in solving the global food problem, as well as water security of Ukraine.

Based on the results of the literary sources analysis, the main directions that are considered when solving the problems of restoration (reconstruction) of drainage systems on agricultural lands worldwide and in Ukraine are determined. Approaches to the operation, maintenance, and controlled decommissioning of drainage systems are based on the development of scenarios for climate change adaptation, therefore the priority of the state policy of a number of countries is, first of all, the restoration of systems, which allows to ensure the adaptation of agricultural production to modern climate changes. Worldwide, the evaluation of the reclamation fund is mainly carried out on a permanent basis, and the need for the reconstruction and modernization of drainage systems is determined according to the design characteristics and technical condition involving the restoration of their water-regulating function.

The basis for the reconstruction of drainage systems is the economic and technical justification of feasibility, the use of progressive methods of drainage, priority for the implementation in areas of drainage systems that are in working condition, and in drained areas where intensive and medium-intensity agricultural use of drained lands is planned. The scientists' developments are aimed at creating economically viable technical options for the restoration (reconstruction) of drainage systems, which take into account the directions of their use and investment options for reconstruction.

Studying the global experience of restoration (reconstruction) of drainage systems on agricultural lands and its use is important in implementing the provisions of the "Strategy of Irrigation and Drainage in Ukraine for the period until 2030".

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ДОСВІД ВІДНОВЛЕННЯ (РЕКОНСТРУКЦІЇ) ДРЕНАЖНИХ СИСТЕМ НА ЗЕМЛЯХ СІЛЬСЬКОГОСПОДАРСЬКОГО ПРИЗНАЧЕННЯ (ОГЛЯД ПУБЛІКАЦІЙ)

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Анотація. *У статті представлено огляд публікацій з актуальної проблеми відновлення функціональної здатності дренажних систем, яка в сучасних умовах змін клімату та військової агресії набуває особливої значимості не тільки з позицій необхідності підвищення продуктивності осушуваних земель, але і забезпечення водної безпеки нашої держави. Вивчення проблем та встановлення напрямів відновлення (реконструкції) дренажних систем в Україні та регіонах світу відбулося з використанням бібліометричного аналізу. Для аналітичних досліджень вивчені вітчизняні та закордонні літературні джерела 55-річного періоду, основна кількість яких припадає на період 2002–2022 рр. Проведений аналіз дозволив визначити основні напрями, які розглядаються при вирішенні задач відновлення (реконструкції) дренажних систем на землях сільськогосподарського призначення у країнах світу та в Україні. Підходи щодо експлуатації, утримання та контрольованого вилучення з експлуатації дренажних систем базуються на розробленні сценаріїв адаптації до змін клімату, отже пріоритетом державної політики низки країн є, насамперед, відновлення систем, що дозволяє забезпечити адаптацію агровиробництва до сучасних кліматичних змін. У країнах світу оцінювання меліоративного фонду проводиться постійно, а необхідність реконструкції та модернізації дренажних систем визначається відповідно до проєктних характеристик, технічного стану і передбачає також відновлення їх водорегулюючої функції. Основою проведення реконструкції дренажних систем є економічне та технічне обґрунтування доцільності, застосування прогресивних способів осушення, першочергова реалізація відновлювальних заходів на ділянках дренажних систем, які перебувають у робочому стані, та на осушуваних територіях, де планується інтенсивне та середньої інтенсивності сільськогосподарське використання осушуваних земель. Розробки науковців спрямовані на створення економічно вигідних технічних варіантів відновлення (реконструкції) дренажних систем, які враховують напрямки їх використання та варіанти інвестицій в реконструкцію. Вивчення світового досвіду відновлення (реконструкції) дренажних систем на землях сільськогосподарського призначення та його використання є важливим при реалізації положень, які закладені у «Стратегії зрошення і дренажу в Україні на період до 2030 року».*

Ключові слова: *дренажні системи, відновлення (реконструкція) дренажних систем, осушувані землі, економічна ефективність, бібліометричний аналіз*

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MATHEMATICAL MODELLING OF WATER REGULATION PROCESSES ON DUAL-ACTION DRAINAGE SYSTEMS

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Abstract. *The solution of the problem of increasing water regulation areas in the Polissia zone of Ukraine requires investigation and development of new, more effective methods for determining structural parameters of drainage systems when developing projects for their reconstruction in accordance with the requirements aimed at ensuring water regulation during systems' operation. The paper considers the problem of improving the efficiency of water regulation on dual-action drainage systems by using mathematical modelling tools to determine the structural parameters of the systems and the parameters of their operational management. The proposed means are based on the use of Richards equation stated in terms of water head. As a tool for scenario modelling, an initial-boundary value problem of modelling moisture transfer on dual-action systems is formulated and a finite-difference scheme for obtaining its numerical solution is given. We consider the problem of determining the depth of drains installation and the distance between them at which the system provides not only the drainage of soil's surface layer, but also the maintenance of its moisture supply level in a given range with a minimum need for irrigation during the growing season. The algorithm for solving such a problem is presented. It is based on the construction of a set of admissible values of system's parameters using, in particular, the bisection method, followed by the minimization of an objective function on this set. Under the conditions when the implementation of underground water supply technology is economically impractical, the possibility of supplementing the drainage system with an irrigation system is considered. In this case, the cost of building a drainage system and an additional irrigation system is a criterion for the optimality of system's parameters. Additionally, we consider the problem of operational management of water regulation, i. e., the determination, given the initial distribution of moisture, of the optimal control influences necessary to ensure an acceptable level of moisture availability during a given period of time. This minimization problem is proposed to be solved by a genetic algorithm. The results of modelling the operation of a dual-action system and the optimization of its parameters under the conditions of drained peat soils of the Panfyly Research Station (Ukraine, Kyiv region) are presented.*

Keywords*: water regulation, dual-action systems, mathematical modelling*

Actuality of research. The problem of increasing the efficiency of water regulation is relevant for the territory of Ukrainian Polissia where 3.2 million hectares of drainage systems of various types are concentrated. These systems, built in 1970–1980s, were primarily intended to solve the problem of removing excess water in spring and creating a sufficient capacity in vadose zone for the accumulation of summer precipitation, the amount of which at that time was sufficient for water supply of most crops grown on drained lands. As a result of climate change, due to which the territory of Ukraine is characterized by one of the highest rates of growth in the average annual temperature in the world, conditions with an insufficient level of natural moisture supply are now forming in Ukrainian Polissia starting from July. Therefore, the approved "Irrigation and Drainage Strategy in Ukraine for the Period Until 2030" provides for the implementation of measures for the reconstruction and modernization of existing drainage systems by supplementing them with the function of water regulation during the entire growing season.

Implementation of this function is ensured through the possibility of using groundwater by regulating its level, or conducting irrigation, or a combination of these two options. The effectiveness of water regulation largely depends on the applied decision-making support tools.

Literature review. The main source of predictive data for physically-based decision-making support in water regulation is mathematical modelling of moisture transfer. On its base, forecasts of the dynamics of moisture availability to plants, necessary for operational water regulation, are obtained, and scenarios are simulated within the growing season to support medium-term planning of reclamation systems'

operation. Initial data for modelling are the data on the hydro-physical properties of soils, preferably obtained experimentally, and the data of field measurements of current state indicators of the "soil-plant-atmosphere" system.

The most commonly used class of models is based on the Richards equation [1]. The methods of solving direct problems stated for such models vary from analytical [2] to fully numerical [3]. In particular, when modelling changing groundwater level using the moving simulation domain's boundary, one of the effective numerical methods is the method of conformal mappings [4].

Decision-making support systems for water management mostly focus on one of its components (irrigation or drainage) and consist usually of only scenario modelling or operational management tools (see, e. g., [5]).

To solve the considered problems on dual-action systems, the following principles of using mathematical modelling tools in decision-making support systems in irrigation described in [6; 7] are applicable:

- the use of the Richards equation stated in terms of pressure/water heads to more accurately determine the availability of moisture to plants and manage it exclusively in the root-containing zones of the soil taking into account the structure of plants' root systems;
- adaptation of the model to actual conditions by laboratory determination of soil's hydro-physical characteristics and introduction of empirical parameters into the model [6]. The values of these parameters are further selected by solving inverse problems to obtain the best possible description of moisture dynamics within wetting-drying cycles;
- the use of swarm intelligence methods [8] to determine the parameters of design and operation of reclamation systems based on scenario modelling.

The aim of the research is the development of mathematical modelling tools that can be used for the determination of the design and operational parameters of dual-action systems that combine the functions of drainage and irrigation.

Materials and methods. We consider the problem of modelling the dynamics of water heads in a soil massif, on which water regulation is carried out by a double-acting system, under the following conditions [9]:

– drains are installed without a slope and connect two canals;

– drains are considered to be constantly completely filled with water;

– the same water level is maintained in both canals.

If there is a large distance between the canals, filtration from them can be neglected and, considering the uniform distribution of moisture along the drains, modelling can be carried out in a two-dimensional approximation by considering a section parallel to the canals, in the middle between them (Fig. 1). At the same time, the simulation domain can be limited to the zone of influence of one drain. The lower boundary of the domain is the confining bed.

The Richards equation stated in terms of water heads, which takes into account the transition of soil from unsaturated to saturated state, is used in the simulation in the form described in [10]:

$$\left[C(h,z)+\frac{\theta(h,z)}{\theta_s(z)}S_s(z)\right]\frac{\partial h}{\partial t}= =\frac{\partial}{\partial x}\left(k(h,z)\frac{\partial h}{\partial x}\right)+ +\frac{\partial}{\partial z}\left(k(h,z)_z\left(\frac{\partial h}{\partial}-1\right)\right)- -S(x,z,t), \quad 0\le x\le L,\ 0\le z\le L_z,\ t\ge 0 \qquad (1)$$

where $h(x, z, t)$ is the water head, m, $C(h,z)=\frac{\partial\theta}{\partial h}$ is the differential moisture capacity, $\theta(x, z, t)$ is the volumetric soil moisture,%, $\theta_s(z)$ is the saturated moisture content,%, $S_s(z)$ is the specific storage,

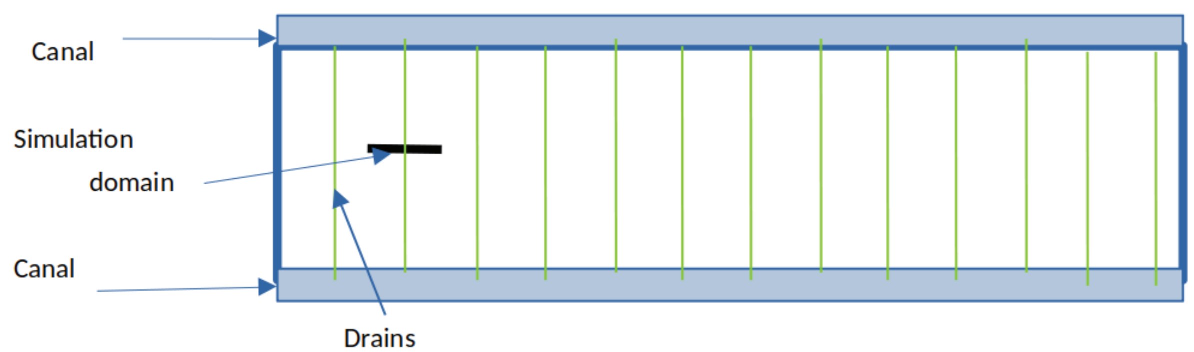

Fig. 1. Simulation domain

1/m, $k(h, z)$ is the hydraulic conductivity, *m/s*, *S(x, z, t)* is the function, *1/s*, that models moisture extraction by the roots of plants.

Soils are considered to have a layered structure. Their water retention curves are described according to the van Genuchten model [11] in the form $\theta(h)=\theta_0+\dfrac{\theta_1-\theta_0}{\left[1+\left(10\alpha|h|\right)^n\right]^{1-1/n}}$ with the values of the coefficients θ_r, θ_s, α, *n* that change from layer to layer. The dependency between hydraulic conductivity and water head is represented according to the Mualem model [12] in the form $k(h)=k_f\theta_r^{\beta}(h)\left[1-\left(1-\theta_r^{n/(n-1)}(h)\right)^{1-1/n}\right]^2$, $\theta_r(h)=\dfrac{\theta(h)-\theta_0}{\theta_1-\theta_0}$, where k_f is the saturated hydraulic conductivity, β is a fixed exponent.

The values of the coefficients of the models are determined by the least squares fitting of the data of laboratory studies.

The specific storage is also estimated from this data as $S_s=-\dfrac{\theta(h_1)-\theta(h_0)}{h_1-h_0}$ where $h_0 > h_1$ are the measured water heads that correspond to the close-to-saturated state of soil.

The width *L* of the simulation domain is equal to the distance between drains. One drain is modelled. It is considered to be located at a point with $x = L / 2$. At the location of the drain, water head equal to the water level in the canals above the drain is set [4; 13]. We assume that water head in the drain is fixed along its length.

The level *l, m,* of water in the canals changes taking into account the flows in the drains *Q, m/s*, and the evaporation from water surface *E, m/s*, as follows:

$$\frac{dl}{dt}=k_1Q-E,\ k_1=\frac{2\pi R\cdot l_d\cdot k_d}{w_cL},$$

where *R* is the radius of the drain, l_d is the length of the drain, w_c is the width of the canals (their shape is considered rectangular), k_d is the coefficient of linear dependency between pressure and flow in the drain. The evaporation from water surface is considered proportional to the evaporation from soil surface.

To Equation (1) we set the following boundary condition on soil surface $z = 0$ [14; 17]:

$$k(h,z)\frac{\partial h}{\partial z}=Q_e(t)-Q_p(t)-Q_i(x,t),$$

where $Q_e(t)$, $Q_p(t)$, $Q_i(x, t)$ are the fluxes, *m/s*, of evaporation, precipitation, and irrigation. The absence of flux condition is set on the side faces of the domain, and the condition $\dfrac{dh}{dx}=1$ is set on the bottom face.

The function *S* models the extraction of moisture by the root systems of plants the way it is described in [14]. Here the distribution of transpiration on the depth *z* is described according to [18] in the form $S_z(z,t)=\dfrac{T(t)L(z)}{\int_0^{z_r}L(z)dz}$, *m/s*, where z_r is the depth of the root-containing layer, $L(z)=1.44-0.14\dfrac{z}{z_r}-0.61\left(\dfrac{z}{z_r}\right)^2-0.69\left(\dfrac{z}{z_r}\right)$ is the function of the distribution of root length density and its specific form used in this paper, *T*(*t*) is the transpiration rate, *m/s*. We assume that n_p plants with the centres of root systems, the depth of which is equal to r_{pi}, located in the points x_{pi}, $i = 0\ ...,\ n_p - 1$in the simulation domain. The density of root systems is assumed to decrease linearly subject to the horizontal coordinate *x* that is described by the function

$$S_{xi}(x)=\begin{cases}\dfrac{r_{pi}-(x-x_{pi})}{r_{pi}^2}, r_{pi}-(x-x_{pi})\geq 0\\ 0, r_{pi}-(x-x_{pi})<0\end{cases},\quad 1/m.$$

Then the total moisture extraction function has the form $S(x,z,t)=\dfrac{1}{n_p}S_z(z,t)\sum_{i=0}^{n_p-1}S_{xi}(x)$, *1/s*.

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 [19] on a uniform grid with respect to the space variables with the use of the algorithm for adaptive time step selection [15].

Similarly to [15], we consider the uniform finite-difference grid

$$\omega=\left\{(x_i=ih_x, z_k=kh_z, t_j=j\tau):\ : i=\overline{0,m}, k=\overline{0,n}, j=0,1,2,...\right\},$$

where h_x, h_z are the steps with respect to the spatial variables, τ is the time step. Here and further the grid analogue of the water head function *h* and, similarly, other functions, is designated as $h_{ik}^j=h(x_i,z_k,t_j)$. As the results of discretization we obtain [15] the following linear system that is further solved by the TFQMR algorithm [20]:

$$h_{i-1,k}^j\times A_{1,i,k}^{j-1}+h_{i,k-1}^j\times A_{2,i,k}^{j-1}+h_{i+1,k}^j\times$$
$$\times B_{1,i,k}^{j-1}+h_{i,k+1}^j\times B_{2,i,k}^{j-1}-h_{i,k}^j\times R_{i,k}^{j-1}=\Phi_{i,k}^{j-1},$$

$$A_{1,i,k}^{j-1}=\frac{1}{4h_x^2}\left(k\left(h_{i-1,k}^{j-1}\right)+k\left(h_{i,k}^{j-1}\right)\right),$$

$$A_{2,i,k}^{j-1}=\frac{1}{4h_z^2}\left(k\left(h_{i,k-1}^{j-1}\right)+k\left(h_{i,k}^{j-1}\right)\right),$$

$$B_{1,i,k}^{j-1}=\frac{1}{4h_x^2}\left(k\left(h_{i+1,k}^{j-1}\right)+k\left(h_{i,k}^{j-1}\right)\right),$$

$$B_{2,i,k}^{j-1}=\frac{1}{4h_z^2}\left(k\left(h_{i,k+1}^{j-1}\right)+k\left(h_{i,k}^{j-1}\right)\right),$$

$$R_{i,k}^{j-1}=A_{1,i,k}^{j-1}+A_{2,i,k}^{j-1}+B_{1,i,k}^{j-1}+B_{2,i,k}^{j-1}+$$
$$+\frac{1}{\tau}\left(C\left(h_{i,k}^{j-i}\right)+\frac{\theta\left(h_{i,k}^{j-1},z_k\right)}{\theta_s\left(z_k\right)}S_s\left(z_k\right)\right),$$

$$\Phi_{i,k}^{j-1}=-h_{i-1,k}^{j-1}\times A_{1,i,k}^{j-1}-h_{i,k-1}^{j-1}\times A_{2,i,k}^{j-1}-$$
$$-h_{i+1,k}^{j-1}\times B_{1,i,k}^{j-1}-h_{i,k+1}^{j-1}\times B_{2,i,k}^{j-1}+$$
$$+\left(\begin{array}{l}A_{1,i,k}^{j-1}+A_{2,i,k}^{j-1}+B_{1,i,k}^{j-1}+B_{2,i,k}^{j-1}-\\-\dfrac{1}{\tau}\left(C\left(h_{i,k}^{j-1}\right)+\dfrac{\theta\left(h_{i,k}^{j-1},z_k\right)}{\theta_s\left(z_k\right)}S_s\left(z_k\right)\right)\end{array}\right)\times$$
$$\times h_{i,k}^{j-1}-S_{i,k}^j+\frac{1}{2h_z}\left(k\left(h_{i,k+1}^{j-1}\right)-k\left(h_{i,k-1}^{j-1}\right)\right)$$

$$h_{0k}=h_{1k},h_{mk}=h_{m-1k},k=\overline{0,n},$$
$$H_{in}=H_{in-1}+h_z,i=\overline{0,m},$$
$$H_{i0}=H_{i1}-\frac{h_z\left(Q_e+Q_p+Q_i\right)}{\frac{1}{2}\left(k_{i0}+k_{i1}\right)}.$$

To adapt the model to the actual conditions of the processes, the coefficients of the van Genuchten and Mualem models can be varied to achieve a better correspondence of the simulation results to the measured water head dynamics. In particular, the procedure of applying the particle swarm optimization approach for solving such a problem is given in [6].

In the process of modelling, we calculate the minimum and maximum water head levels in the root zone, averaged in each column of grid nodes with the values of root system's distribution function as weights.

Modelling of water regulation in order to increase water content in the root zone of the soil is modelled as follows. At first the increase in water level in the canals is simulated for no more than a given period of time. After that, the simulation is carried out without control actions until the maximum water head level stops increasing and the minimal one starts increasing (thus determining the maximum influence of the increase in water level in the canals on moisture content in the root layer).

If the maximum water head level is lower than the upper limit of the maintained range or the minimum water head level is lower than the pre-irrigation threshold, then the surface supply of irrigation water is simulated, similarly, for no more than a given period of time.

When the maximum water head level in the root zone increases above the threshold value for which drainage is necessary, a decrease in water level in the canals is simulated.

The controlled change in water level in the canals is simulated with a given fixed speed.

Results. The main problem that should be solved by decision support systems when designing dual-action drainage systems consists of determining their main constructive parameters, in particular, the depth of installation and the distance between drains.

Given the known characteristics of drainage pipelines, we assume that a double-action system fulfils its functions if, by setting a fixed water level in the canals, it allows

- for a given period of time, transfer the upper layer of the soil of a given thickness from saturated to non-saturated state in order to ensure at the beginning of the season the passability of machinery that must carry out soil cultivation;
- at a fixed low level of evapotranspiration at the initial stages of plant development, ensure a given range of moisture availability in the root layer without additional irrigation;
- at a fixed high level of evapotranspiration and the maximum level of root system's development, similarly to the initial stages, ensure the availability of moisture.

In the case when the system is not able to provide water consumption for plants, the possibility of additional construction of a surface irrigation system should be considered.

The objective function to be minimized is the cost of constructing a dual-action system, which consists of the cost of drainage pipelines, the cost of their installation, and, if necessary, the cost of constructing a surface irrigation system.

The proposed decision-support algorithm consists in finding a set of values of system's constructive parameters, under which it properly performs at least the drainage function, followed by finding, by the greedy algorithm, of such values from this set that minimize the objective function.

Building of a set of allowable values of constructive parameters under known hydro-physical properties of the soil is performed according to the following algorithm:

• the depth of drains installation decreases with a given step starting from the depth of the bottom of the canals and ending with the depth of the layer that needs drainage. For each depth value three tests are performed:

◦ test 1: the maximum distance between drains at which the system performs the drainage function at the beginning of the season is determined (initial water head distribution $h=-z$ corresponds to fully saturated soil, the water head in the drain is set to be constant at the level of $h=0$). We assumed that the dependency between the inter-drain distance and the depth of the drained layer is monotonic and solve the corresponding problem by the bisection method. If drainage cannot be carried out at the minimum inter-drain distance, we proceed to the next depth of drains installation;

◦ test 2: for the distance between drains determined on the previous step, the minimum value of the fixed maintained water level in the canals is found by the bisection method, for which, in a close-to-steady state, the minimum weighted average water head in the vertical section of the root zone is greater than the level of pre-irrigation threshold in a situation of low water consumption. The test is considered passed if the above-described condition regarding the maximum weighted average water head in the root zone is met;

◦ test 3: similar modelling is carried out for the situation of high water consumption;

◦ in the case when tests 2 or 3 are not passed, the cost of constructing a surface irrigation system is added to the value of the objective function.

For an active dual-action system, which contains both a network of drainage pipelines and a surface irrigation system, the problem of operational management is also considered. It consists in finding, for a given initial distribution of water heads, the control actions (changes in water level in the canals and, if necessary, surface irrigation) necessary to maintain moisture availability in a given range during a given period of time. Given the known cost of water level regulation and the cost of surface irrigation application we determine a regime (using the genetic algorithms approach [16]), in which the total cost of water regulation is minimal.

Since water regulation by changing water level in the canals has a delayed effect on the moisture content of the root layer of the soil, on the first step of the algorithm we determine the time when, in the absence of water regulation, the minimum weighted average water head level in the vertical section will become less than the pre-irrigation threshold. Water regulation is further modelled in a way to finish at this specific moment of time. If, after water regulation is performed, water heads do not belong to the maintained range, a given large penalty value is added to the value of the objective function.

The operation of a dual-action system was simulated for the conditions of drained peat soil of the Panfyly experimental station (Ukraine, Kyiv region, 50°13'16.9"N31°45'46.4"E).

The coefficients of the van Genuchten and Mualem models for soil layers, obtained on the base of experimental study, are presented in Table 1.

The model parameters had the following values:

• The radius of the drain is 0.2 m, the length of the drain (distance between canals) is 150 m. The depth of simulation domain is equal to 3 m.

• The depth of the canal is 2 m. The width of the canal is 3 m.

• The maintained range of average water heads in the root zone is –40 – –15 kPa. Drainage by lowering water level in the canals is carried out when the average water head level in the root zone is greater than –5 kPa.

• Evapotranspiration for the high water consumption case is equal to 5 mm/day and for the low level case – to 2 mm/day. The distance between plants is 66 cm, the depth of the root system is 50 cm at the high water consumption case, and 20 cm at the low water consumption case.

• The rate of change in water level in the canals is 2 m/day. The flow of irrigation water is 7 mm/hour.

• The cell size of the finite-difference grid is 10×10 cm, the maximum length of the time step is 100 s.

The results obtained by applying the procedure for determining the permissible values of system's constructive parameters, provided that at the beginning of the season the minimum depth of the saturated zone should become more than 40 cm due to the drainage during no more than 5 days, are shown in Fig. 2 and 3.

1. Coefficients of the van Genuchten and Mualem models

Layer	θ_r	θ_s	α	n	k_f, m/s	β	S_s, 1/m
0.05–0.2 m	0.37	0.81	0.1	1.5	2.3×10^{-4}	-0.75	0.0823
0.2–0.4 m	-0.5	0.87	0.01	1.1	6.0×10^{-6}	-15	0.0186
0.4–0.6 m	-1.5	0.962	0.01	1.1	6.0×10^{-6}	-20	0.0063
0.6–0.8 m	-2	0.957	0.01	1.1	1.0×10^{-5}	-15	0.0156

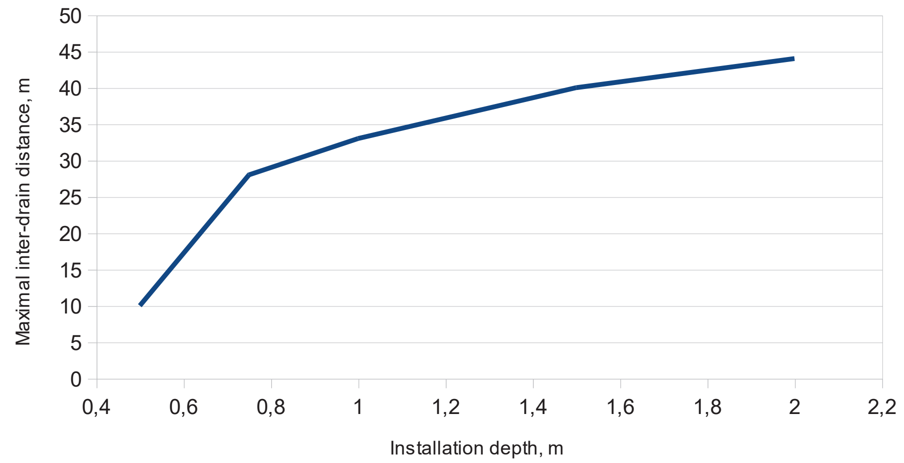

Fig. 2. The maximum inter-drain distance subject to the depth of installation

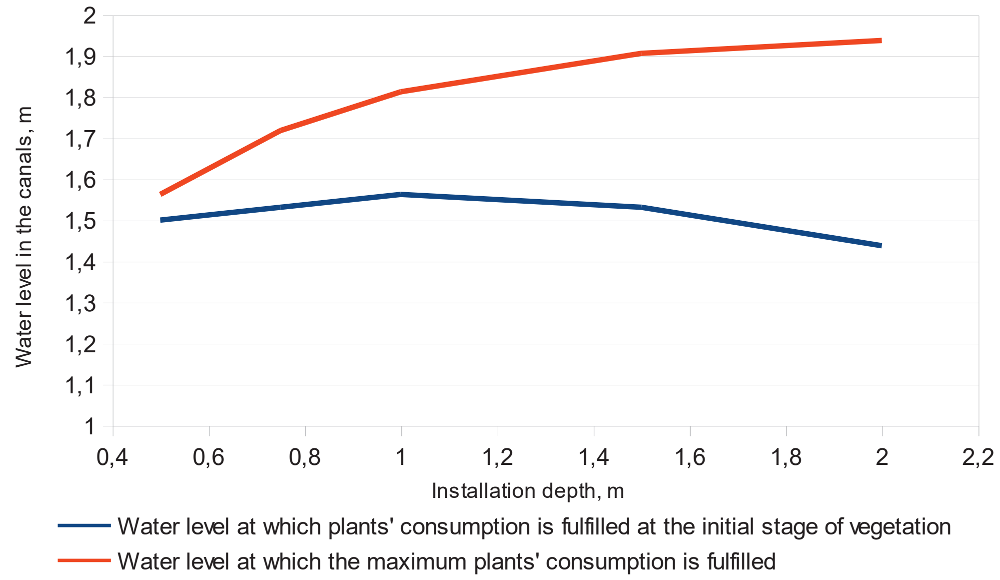

Fig. 3. Water levels in the canals at which plant's water consumption is fulfilled at the specified maximum distance between drains

For the installation depth of more than 75 cm, with high water consumption level, ensuring the required level of moisture availability in zone between drains was accompanied by the saturation of soil by water in the vertical section at the location of the drain. Thus, the depth of 75 cm with the inter-drain distance of 28 m was determined as the greatest depth of drains installation, at which the dual-action system effectively performs both the functions of drainage and irrigation.

This set of admissible values of system's constructive parameters was used to simulate operational assignment of control actions to maintain the moisture availability in the root layer in a given range. With constant evapotranspiration at the level of 3 mm/day, which is greater than the level at which the system performs the function of irrigation without the use of surface irrigation, and the depth of the root system equal to 20 cm, the water level in the canals was modelled as being maintained at the level of at least 1.53 m. Initial distribution of water heads was taken as $h=-0.4-z$.

In the absence of control actions, the need for water regulation according to the simulation results arises in 3.3 days after the starting moment of time. The determined optimal regime of maintaining the given water head range consisted in increasing the water level in the canals at the time of 1.74 days for 1.43 days. In such case, water regulation is possible without additional use of surface irrigation.

The dynamics of weighted averaged water heads in vertical section is shown in Fig. 4. In the considered situation, water heads in the vertical

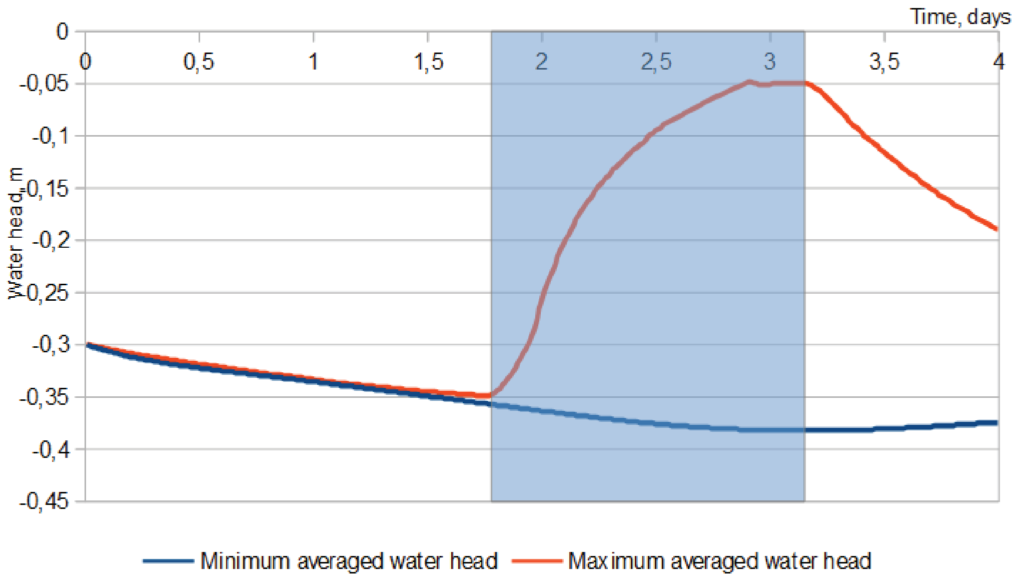

Fig. 4. Dynamics of averaged water heads in vertical section
(water regulation period is marked with colour)

section at the point of drain installation rise in the process of water regulation to the level at which the drainage procedure is activated in the model (–5 kPa) while moisture content in the zone between drains still continues to decrease. As a result, the two applied control actions do the opposite – a decrease and an increase of water level in the canals – that lead to the fixation of this level together with the maximum average water head in vertical section in the period of time preceding the completion of water regulation.

Conclusions. We propose to determine the technologically effective and economically feasible values of such constructive parameters of double-action drainage systems as the installation depth and the distance between drains using mathematical modelling methods on the base of the Richards equation stated in terms of water head.

The calculated values of parameters are considered admissible if the system is able to drain water within a specified period to the depth sufficient for the operation of agricultural machinery in spring, and allows maintaining, through vertical flow of moisture, the moisture supply of the root layer of the soil during the period of maximum water consumption by plants not below the lower limit of the range of optimal moisture supply without the use of irrigation.

Under the conditions when the implementation of such a technology is economically impractical, the possibility of supplementing the drainage system with an irrigation system is considered. In this case, the criterion for the optimality of system's parameters is the cost of building a drainage system and an additional irrigation system. In order to determine the operational necessity of applying irrigation, a suitable decision support algorithm is proposed.

Approbation of the methodology on the data of the existing drainage system demonstrates the adequacy of the obtained modelling results.

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УДК 631.62

МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ ПРОЦЕСІВ ВОДОРЕГУЛЮВАННЯ НА ДРЕНАЖНИХ СИСТЕМАХ ПОДВІЙНОЇ ДІЇ

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Анотація. *Вирішення завдання нарощування площ водорегулювання в зоні українського Полісся потребує пошуку та розроблення нових, більш ефективних методів визначення конструктивних параметрів дренажних систем при розробленні проєктів їх реконструкції згідно з вимогами забезпечення водорегулювання в процесі експлуатації. Розглядається задача підвищення ефективності водорегулювання на дренажних системах подвійної дії шляхом застосування засобів математичного моделювання для визначення конструктивних параметрів систем та оперативного управління ними. Пропоновані засоби базуються на використанні рівняння Річардса, записаного у термінах напорів. Як засіб сценарного моделювання, сформульовано початково-крайову задачу моделювання вологоперенесення на системах подвійної дії та наведено скінченно-різницеву схему отримання її чисельного розв'язку. Розглядається задача визначення таких глибини закладання дрен та відстані між ними за яких система забезпечує не тільки дренування поверхневого шару ґрунту, але й підтримання рівня його вологозабезпечення в заданому діапазоні за мінімальної необхідності застосування зрошення протягом сезону вегетації. Наведено алгоритм розв'язання такої задачі, який базується на побудові множини допустимих значень параметрів системи використовуючи, зокрема метод бісекції, з подальшою мінімізацією цільової функції на цій множині. За умов, коли реалізація технології підґрунтового живлення є економічно недоцільною, розглядається можливість доповнення системи дренажу системою зрошення. Критерієм оптимальності параметрів системи в цьому випадку є затрати на будівництво системи дренажу і додаткової системи зрошення. Також розглядається задача оперативного управління водорегулюванням – визначення за заданого початкового розподілу вологи оптимальних керуючих впливів, необхідних для забезпечення допустимого рівня доступності вологи протягом заданого періоду часу. Цю задачу мінімізації пропонується розв'язувати генетичним алгоритмом. Наведено результати моделювання роботи системи подвійної дії та оптимізації її параметрів за умов осушуваних торфових ґрунтів Панфильської дослідної станції (Україна, Київська область).*

Ключові слова: *водорегулювання, системи подвійної дії, математичне моделювання*

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DETERMINATION OF WATER DEMAND FOR IRRIGATION BASED ON THE CLIMATIC WATER BALANCE IN THE EASTERN FOREST STEPPE OF UKRAINE IN VIEW OF THE NATURAL WATER SUPPLY

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Abstract. *The results of the research show that even today crop cultivation in the entire territory of the steppe and in a large part of the forest-steppe zone is carried out in conditions of a significant deficit of the climatic water balance, which necessitates a significant expansion of irrigation application as a mandatory element of the of highly efficient and sustainable cultivation technologies of the most of crops. Therefore, without active measures to adapt agricultural production to climate change, which is accompanied by a significant increase in the frequency and duration of drought events and, accordingly, a shortage of moisture supply, the restoration and development of irrigation remains the main factor in increasing the productivity of field crops. The research was conducted in the Eastern Forest Steppe zone. For the assessment and analysis of climate change, raw meteorological data for 1961–2020 were used. The data source is the Global Climate Monitoring (GCM) system developed by the Climate Research Group of the University of Seville. According to the results of the assessment of the dynamics of the average annual air temperature for 1961–2020, it was established that over the past 30 years the temperature has risen on average by 1.2°C, and since 1987 the rate of its growth is 0.79°C over the decade, while the annual amount of precipitation remains practically unchanged. It was established that the potential evapotranspiration increased by 70 mm and is almost 850 mm per year. With such a difference between precipitation and potential evapotranspiration, the deficit of the annual climatic water balance reaches on average almost 300 mm over the last 30 years, against 247 mm in 1961–1990, and the tendency to its increase persists. Simulation modeling of the economic efficiency of irrigation based on preliminary results indicates the efficiency of its implementation, and especially restoration on areas with existing reclamation infrastructure.*

Key words**:** *water demand of plants, irrigation, climate change, water balance, productivity, efficiency*

Relevance of research. Currently, the fact of modern climatic change is recognized by the world scientific community and does not cause doubts [1–7]. The main factor that reflects these changes is a steady increase in the temperature regime. At the same time, it should be noted that in Ukraine it is recorded the highest rates of growth of the average annual air temperature. If in most European countries the growth rate of this indicator does not exceed 0.6°C over the decade, while in Ukraine on average it is 0.71°C over the decade and varies geographically from 0.62–0.68°C in the western regions to 0.75–0.78°C in the southern and eastern regions of Ukraine.

Unfortunately, such a rapid increase in the average annual temperature in Ukraine is not accompanied by a significant increase in the amount of precipitation. Both in Ukraine as a whole and in its individual regions, it remains practically unchanged. The results of the research [5–6] indicate that even today crop cultivation in the entire territory of the steppe and in most of the forest-steppe zone is carried out in conditions of a significant (from 150 to 450–500 mm and more) deficit of the climatic water balance, which necessitates significant expansion of irrigation application as a mandatory element of technologies for highly efficient and sustainable cultivation of most crops. In view of the significant potential of reclaimed land in Ukraine, namely 2178.3 thousand hectares of irrigated land, of which about 540 thousand hectares are actually irrigated, the issue of their effective use remains open and is the main measure of active adaptation of agriculture to climate change [8–12].

Analysis of recent research and publications. The Ukrainian climate is becoming more vulnerable and unpredictable, warming is happening faster than in general on a global scale. According to the Hydrometeorological Center of Ukraine, in our country, the years 2019–2020 were the warmest in global measurement. The average annual air temperature exceeded the standard by three degrees. Over the last 20–25 years, the highest temperatures ever observed during the entire period of meteorological observations were observed in most of the territory [13]. In recent decades, water supply has significantly decreased. Currently, 90 % of the steppe zone in Ukraine needs irrigation. Such territories are increasing throughout the country as well.

The most important ecological, scientific and production problem of the agro-industrial complex of Ukraine is its timely adaptation to climate change [14].

The main stressful meteorological factors for the cultivation of field crops are the lack of moisture and a sharp change in temperature regimes. To obtain stable and high-quality crops, it is necessary to compensate for moisture with irrigation, control evaporation, and prevent stresses related to high and low temperatures.

Climate change and extreme weather conditions cause financial losses. The International Finance Corporation (IFC) has estimated that over the past 20 years, natural disasters have led to the loss of more than 2 billion dollars in the agricultural sector. Almost every farmer suffered losses [15].

A study by the World Bank [16] shows that, if emissions continue to rise, the temperature may increase by more than 4 °C by the end of the 21st century, while the winter will be wetter and the summer drier, with significant fluctuations in different regions of Ukraine. An increase in temperature in summer period may lead to heat and increased aridity in the south and east of Ukraine. According to forecasts, by the middle of the century due to various factors, including climate change, there will be a decrease in the yield of the main crops in Ukraine, including barley, corn and sunflower. However, the yield of winter wheat in the north and northwest of our country may increase by 20–40 percent by 2050 compared to 2010.

Therefore, without active measures to adapt agricultural production to climate change, which is accompanied by a significant increase in the frequency and duration of drought events [17] and, accordingly, a shortage of moisture supply, the restoration and development of irrigation remains the main factor in increasing the productivity of field crops.

Purpose of research is to determine the water demand for irrigation of field crops, taking into account the natural water supply in the conditions of modern climate change.

Research materials and methods. The research was conducted in the Eastern Forest Steppe zone (Krasnograd weather station, Kharkiv region). To assess and analyze climate change, raw meteorological data of average monthly (T_a), minimum (T_{min}), maximum (T_{max}) air temperature and monthly precipitation (R) for 1961–2020 were used. The data source is the global climate monitoring system (GCM) developed by the Climate Research Group of the University of Seville [18].

The calculation of potential evapotranspiration (PET) was carried out using the Hargreaves method (Hargreaves [19]) based on the empirical equation:

$$PET = 0.0023 \times R_a \cdot (T_{mean} + 17.8) \times TR^{0.50}, \quad (1)$$

where, R_a is the global solar radiation; T_{mean} – average daily air temperature, °C; TR – daytime temperature range ($T_{max} - T_{min}$).

Although the FAO Penman-Monteith method is recommended for PET estimation, due to the high data requirements, temperature-based methods are also considered suitable for calculations.

To assess the moisture supply, the climatic water balance indicator (CWB) was used, which is defined as the difference between precipitation and potential evapotranspiration [20; 21]:

$$CWB = R - PET, \ mm. \quad (2)$$

This indicator of moisture supply, namely the climatic water balance, is better suitable for the hydroclimatic characteristics of places, regions or periods, since the hydroclimatic conditions are described directly using the effective elements of the water balance, which are "precipitation" and "potential evapotranspiration" in the absolute dimension of "mm".

Depending on the amount of precipitation or potential evapotranspiration prevailing in the considered period, the climatic water balance takes positive or negative values and, thus, indicates climate-induced surpluses or deficits of the water balance and its regional distribution [22].

Research results. According to the results of the assessment of the average annual air temperature dynamics for 1961–2020 it was established that over the past 30 years (1991–2020), the temperature has risen on average by 1.2°C, and since 1987, its growth rate is 0.79°C over the decade. (Fig. 1). At the same time, the annual amount of precipitation remains practically unchanged and amounts to about 550 mm (Fig. 2).

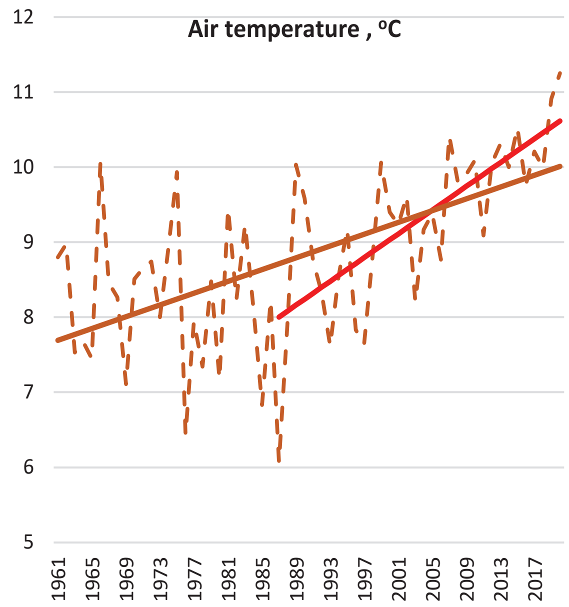

Fig. 1. Dynamics of the average annual air temperature for 1961–2020,°C

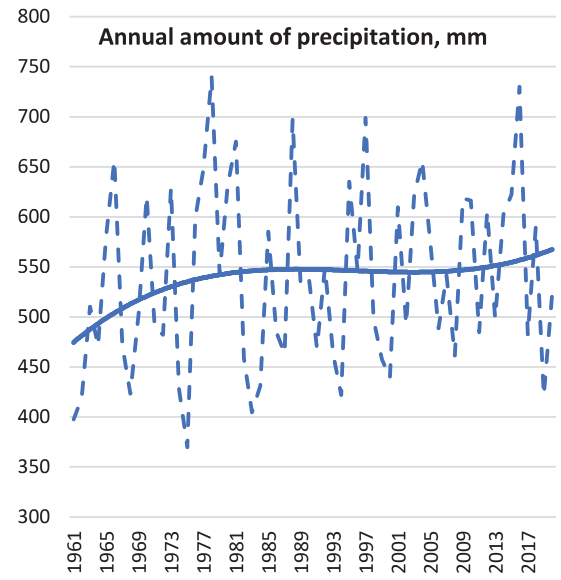

Fig. 2. Dynamics of annual precipitation for 1961–2020, mm

As a result of the steady increase in the temperature regime, potential evapotranspiration has increased by 70 mm and is almost 850 mm per year. With such a difference between the precipitation and potential evapotranspiration, the deficit of the annual climatic water balance reaches on average of almost 300 mm over the last 30 years, against 247 mm in 1961–1990, and the tendency to its increase persists (Fig. 3).

The assessment of the climatic water balance by the months of the hydrological year shows that

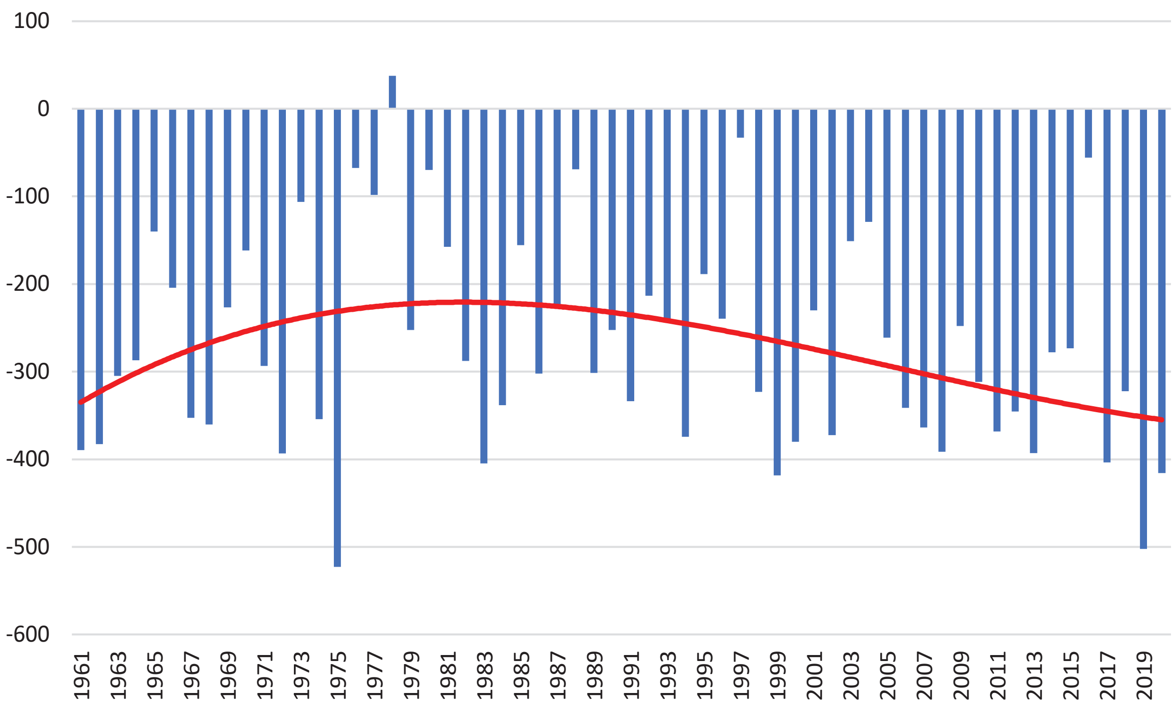

Fig. 3. Dynamics of the annual climatic water balance for 1961–2020, mm

the positive balance in the region is preserved on average until the end of May (Table 1). However, already in June, there is its deficit of 58 mm, and by the end of the growing season of late crops, it exceeds 250 mm.

Recalculating the deficit of the climatic water balance to the irrigation rate, the water demand for early crops is about 600 m^3/ha, and for late crops it is 2500 m^3/ha.

Irrigation efficiency. Simulation modeling of the economic efficiency of irrigation by the average production data of winter wheat, corn for grain and sunflower in the Kharkiv region, based on preliminary results, indicates the efficiency of its implementation, and especially its restoration on the areas with existing reclamation infrastructure.

The input data for calculating the economic efficiency of irrigation are the average yield, cultivation costs, and purchase prices for products (without VAT), which, according to the statistical reporting, were average in 2020. At the same time, the 2019–2020 hydrological year in terms of irrigation was generally estimated as dry with a water balance deficit of 433 mm, against 297 mm on average for 1991–2020 (Fig. 4).

The results of the economic analysis of the cultivation of individual crops as a whole in the Kharkiv region for 2018–2020 are given in Table 2, and in the case of irrigation in Table 3.

The analysis of the given data indicates an increase in production costs when using artificial irrigation by 1.7–2.1 times with a significant increase in the cost of gross profit – up to 8000 UAH when growing winter wheat, up to 18 000 UAH when growing corn for grain, and up to 10 000 UAH when growing sunflowers.

1. Climatic water balance by the months of the hydrological year, as a cumulative total, mm

Years	Months											
	XI	XII	I	II	III	IV	V	VI	VII	VIII	IX	X
1961–1990	31	74	110	138	140	98	28	-45	-126	-206	-246	-247
1991–2020	26	65	102	128	133	87	20	**-58**	-159	**-257**	-298	-297
Diference	-5	-8	-9	-10	-6	-11	-7	-13	-33	-50	-52	-49

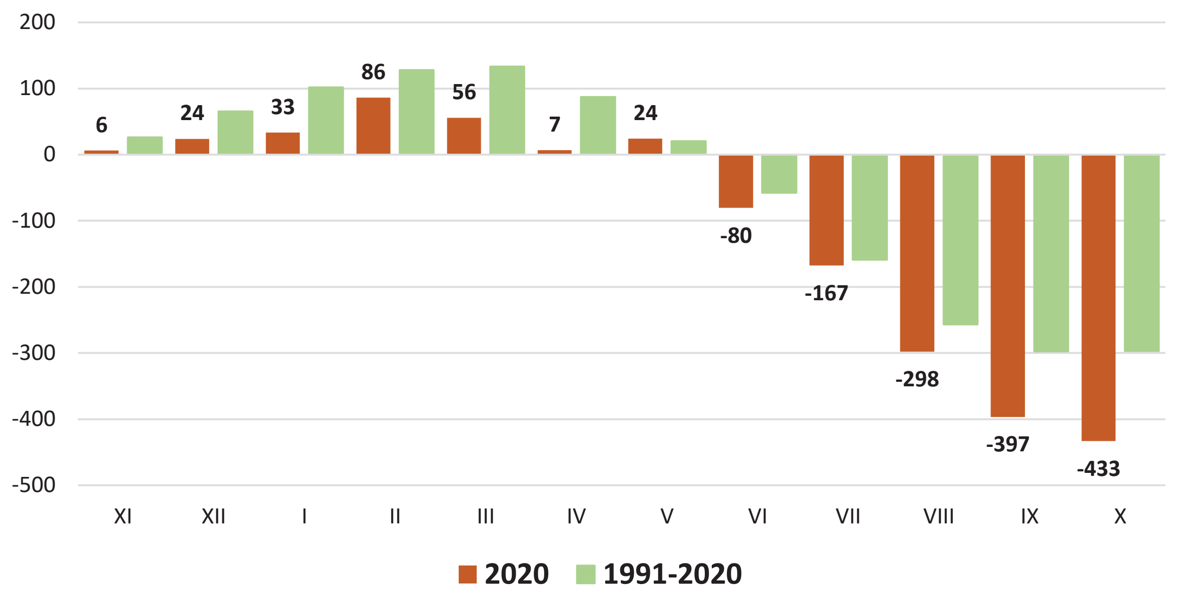

Fig. 4. Dynamics of the climatic water balance as a cumulative total for the 2019–2020 hydrological year (Krasnograd, Kharkiv region)

2. Economic efficiency of crop cultivation in 2018–2020 without irrigation (in the prices of 2020)

Crops	Yield, ton/ha	Cultivation costs, UAH/ha	Sale price (without VAT), UAH/ton	Cost of gross production, UAH/ha	**Gross profit, UAH/ha**	Profitability, %
Winter wheat	5.0	10740	5017	25085	**14345**	134
Corn for grain	5.5	11470	4669	25680	**14210**	124
Sunflower	2.3	10370	10860	24978	**14608**	141

3. Economic efficiency of crop cultivation in 2018–2020 with irrigation (in the prices of 2020)

Crops	Design yield, ton/ha	Irrigation rate, m^3/ha	*Costs for water transportation (2 UAH/m^3), UAH/ha	**Total irrigation costs, UAH/ha	Total cultivation costs, UAH/ha	Cost of gross production, UAH/ha	Gross profit, UAH/ha	Profitability, %
Winter wheat	8	600	1200	1440	17550	40136	22586	129
Corn for grain	12	2600	5200	6240	23445	56028	32583	139
Sun-flower	4	1300	2600	3120	18675	43440	24765	133

Note: *the cost was determined based on the average actual value of the final cost for the consumer in the Kharkiv region for 2020, excluding the fee for special water use; **without taking into account the amortization of capital investments for irrigation and the use of credit resources

Therefore, the main negative manifestation of modern climate change is a significant decrease in the moisture availability of the territory and, accordingly, an increase in the need for additional water resources for irrigation. Such changes, in view of the entire area of available irrigated land in the Kharkiv region, require additional 28 million m^3 of water. Even having the actual irrigated area of about 9000 hectares, the water demand to ensure high crop productivity increases by almost 4 million m^3. Thus, applying irrigation, despite the almost the same production profitability, the estimated gross profit of 9–18 000 UAH exceeds the option without irrigation. In addition, it should be borne in mind that irrigation practically eliminates the risks associated with droughts.

Conclusions. The dynamics of the average annual air temperature for 1961–2020 shows that over the past 30 years, the air temperature in the Kharkiv region has risen on average by 1.2°C, and since 1987, its growth rate is 0.79°C over the decade, while the annual amount of precipitation remains practically unchanged – 550 mm.

The assessment of the climatic water balance by the months of the hydrological year as a cumulative total for the studied period shows that the positive balance in the region is kept on average until the end of May. Recalculating the deficit of the climatic water balance to the irrigation rate, the water demand for early crops is about 600 m^3/ha, and for late crops it is 2500 m^3/ha. The results of simulation modeling of the economic efficiency of irrigation when cultivating the main crops in the Kharkiv region indicate the efficiency of its application, and especially of its restoration on the areas with existing reclamation infrastructure.

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УДК: 631.67;631.445:631.95 (477.72)

ВИЗНАЧЕННЯ ВОДОПОТРЕБИ ДЛЯ ЗРОШЕННЯ НА ОСНОВІ КЛІМАТИЧНОГО ВОДНОГО БАЛАНСУ В СХІДНОМУ ЛІСОСТЕПУ УКРАЇНИ З УРАХУВАННЯМ ПРИРОДНОГО РІВНЯ ВОЛОГОЗАБЕЗПЕЧЕННЯ

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Анотація. *Результати досліджень свідчать про те, що уже сьогодні вирощування сільськогосподарських культур на всій території степової і на більшій частині лісостепової зони ведеться в умовах значного дефіциту кліматичного водного балансу, що зумовлює необхідність суттєвого розширення обсягів застосування зрошення як обов'язкового елемента технологій високоефективного та сталого вирощування більшості сільськогосподарських культур. Отже, без активних заходів адаптації аграрного виробництва до змін клімату які супроводжуються значним зростанням частоти та тривалості посушливих явищ і відповідно дефіцитом вологозабезпечення, відновлення та розвиток зрошення залишається головним чинником підвищення продуктивності польових культур. Дослідження проводились в зоні Східного Лісостепу. Для оцінки та аналізу кліматичних змін використано вихідні метеорологічні дані за 1961–2020 рр. Джерело даних – система глобального моніторингу клімату (GCM) розроблена Групою дослідження клімату Університету Севільї. За результатами оцінки динаміки середньорічної температури повітря за 1961–2020 рр. встановлено, що за останні 30 р. температура підвищилась в середньому на 1,2 °С, а з 1987 р. швидкість її зростання становить 0,79 °С/10 р., при цьому, річна кількість опадів залишається практично незмінною. Встановлено, що потенційна евапотранспірація збільшилась на 70 мм і становить майже 850 мм в рік. За такої різниці між опадами та потенційною евапотраспірацією дефіцит річного кліматичного водного балансу сягає в середньому за останні 30 років майже 300 мм, проти 247 мм в 1961–1990 рр. і тенденція до його збільшення зберігається. Імітаційне моделювання економічної ефективності зрошення за попередніми результатами свідчить про доцільність його впровадження, а особливо відновлення на площах з наявною меліоративною інфраструктурою.*

Ключові слова: *водопотреба рослин, зрошення, зміна клімату, водний баланс, урожайність, ефективність*

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ANALYSIS OF METHODICAL APPROACHES TO THE FORMATION OF WATER TARIFFS FOR IRRIGATION AND COMPENSATION OF COSTS FOR RECLAMATION INFRASTRUCTURE: THE EXPERIENCE OF EU COUNTRIES

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Abstract. *The practice of EU countries on the establishment of water tariffs for irrigation of agricultural crops and the procedures for recouping funds spent on water supply for irrigation is considered. As the main sources of information for the manuscript were noted publications and regulatory documents of Ukraine, reports of EU bodies, and the World Bank, in which a critical analysis of pricing practices in irrigated agriculture in EU countries for 2005–2023 was carried out. The grouping of information on the area of irrigated land, the level of return of funds spent on water supply, and attention is paid to a methodical approach to the development of tariffs for water transportation. The interpretation of the reasons for the natural character, which were guided by state management bodies when applying economic tools for irrigation management in their territories, are presented. For certain countries with big areas of irrigated land (Italy, France, Greece, Spain, Portugal, and Romania), significant achievements of tariff formation and reimbursement of funds have been determined. Aspects of water tariff formation, water accounting, development of water user associations, and taxation of water fees are disclosed. countries were classified according to water pricing, taking into account the state of water resources and melioration systems, types of tariffs, pricing mechanisms, the state of return of funds spent on water supply due to tariffs, measurement of water volumes, as well as solving additional problems of applying economic tools in irrigated agriculture – institutional (administrative, legal) measures, the impact of water charges on the country's agricultural economy, etc. Since the requirements of the Water Framework Directive (WFD) are the dominant approach in the implementation of tariff formation in irrigation in EU countries, the level of achievement of indicators of the quality of WFD implementation by countries was considered. It has been established that the vast majority of global practices for forming tariffs for water supply services for irrigation, capital investments in reclamation infrastructure, and its maintenance, show that they are based both on national interests and on the interest of water users and organizations that provide logistical support.*

Key words: *water supply, irrigation, tariffs, cost compensation, management, system approach, European Union (EU)*

Relevance of research. Establishing tariffs for irrigation water supply is considered an important economic tool for implementing the state's water policy. The goal of the Strategy of Irrigation and Drainage in Ukraine for the period until 2030 [17] is to increase the potential of irrigation and drainage of Ukraine by stimulating the expansion of the areas of irrigated and drained land, the use of reclaimed land, and encouraging the efficient use of water by improving institutional efficiency and service to water users. The modern development of land reclamation using a systemic approach assumes that the solution to methodological issues of tariff formation for water supply and drainage services for irrigation and drainage in Ukraine should be based on best global experience in irrigation infrastructure management. In the USA, China and India the development of meliorative agriculture makes an important contribution to the policy goal of ensuring food security, in the most Eu countries produce most of their grains and oilseeds without irrigation, so it is hardly the basis of their food security. Restoring the key role of land reclamation in ensuring the sustainability of Ukraine's agriculture under climate change is one of the priority tasks of Ukraine's agrarian policy [6].

Analysis of recent research and publications. Researchers substantiated the feasibility of transferring irrigation in Ukraine to full self-funding, bringing the actual irrigated area to a higher design level, and to continue the useful practice of reimbursing the cost of water supply services until the implementation of the tariff system [3; 14]. For this, it was proposed to ensure the transparency of the tariff formation system, the necessity to involve water users in the formation of tariffs [11; 16], the participation of interested parties in decision-making in the relevant sphere of state policy, improving the quality of irrigation and drainage services and stimulating the public-private partnership mechanism [12]. Tariffs for irrigation water supply should cover all costs of those services, that is, their level should be sufficient to transfer irrigation to self-financing [16]. According to the results of calculations in 2019 prices, the transfer of irrigation to full self-funding will be possible with the average amount of water charges in the south of 3.0–3.5 UAH per m^3 and bringing the actual irrigated area on each irrigation system to 65–70 % of the design level [14; 6]. Calculations of the economic payback of investments in irrigated agriculture do not contradict the indicators of economic return with incomplete coverage of the control area in Ukraine now. Scientists previously noted that tariffs for services should be formed with the participation of all interested parties, which is realistic only under the condition of a transparent system of tariff formation [11; 14], at the same time, a transition from the practice of reimbursing the cost of water supply services to introduction of the tariff formation system [14].

The 2022 "Law on the organization of water users and stimulation of hydrotechnical land reclamation" provides the legal basis for Water Usera' Organizationa (WUOs) [13] and states that "the determining the tariff for WUO services or the methodologies (formulas) for calculating such a tariff, the order and terms of payment for WUO services to the exclusive competence of the general meeting of the WUO" [13, Article 12]; "the components of the tariff for WUO services are the costs of maintenance of the WUO, remedial network, water intake, delivery to the water user and its removal, and WUO maintenance costs" [13, Article 20]; "the costs for maintenance of WUOs and maintenance of the reclamation network of WUOs are paid by water users in proportion to the area of their land plots included in the territory of WUO service" [13, Article 20]. At the beginning of the 21st century, there was a significant development of the literature on the assessment of ecological assets related to ecosystems [1], and the issue of improving water resources management in the EU countries was considered [1–5; 7; 8]. In Ukraine, there are no publications summarizing the experience of EU countries regarding water charges and refunds.

The purpose of the study is to generalize and systematize scientific approaches to the methods of forming irrigation tariffs and recouping funds spent on irrigation water supply, in the context of developing a tariff formation mechanism for Ukraine.

Research methods. Research employed the historical-logical method (establishing significant results regarding the processing of water tariffs and the return of funds spent on water supply), the logical-abstract method (expanding information from official reports, literary sources, and best practices), the analytical-synthetic method (processing the received information and synthesizing the results in the form of consolidated data on water tariffs and compensation of funds spent on water supply by EU countries), and systematic analysis for summarizing the results of research and implementation of best practices of EU countries regarding water tariffs and reimbursement of funds for water supply.

Research results. Improving the management of water resources has found support in the European Union. Water reform in Europe is based on the Water Framework Directive (WFD) [10], which entered into force in 2000. Currently, EU member states have transposed the WFD into national legislation as a general framework governing the water policy of each member state, with key dates for the national implementation of the WFD, including development of river basin plans (2009); introduction of price policy (2010); achieving environmental goals (2015); and complete implementation of the entire WFD (2027) [7]. Each country must find its own balance between the three main sources of financing (tariff, tax, and transfer, or "3T") [7]. At the same time, typically countries of OECD (the Organization for Economic Co-operation and Development), where most of the agricultural sector (and domestic/industrial sectors) are connected to the water infrastructure network, rely heavily on water tariffs to cover the costs of operating and maintaining agricultural water supplies. EU regulations specify the role of water fees (water tariffs) as users' actual financial payment for water access. Tariffs are supposed to cover full costs (operation and maintenance, capital costs, environmental and other costs), although in less economically favorable regions or for reasons of social security and stimulation of reclamation development, some deviations from this principle are possible to guarantee all consumers access to water.

Table 1 shows data on irrigation water tariffs for all 27 EU countries. The countries in the table are placed in the order of their inclusion in the community during the period of formation and expansion of the EU, starting from 1957, until 2013, when Croatia became such a member.

The experience of tariff formation and cost compensation in countries with large areas of irrigated land are of greatest interest.

1. Summarized information on the availability of irrigated land, water tariffs for irrigation in EU countries

Name of the country, area of irrigated land, thousands of hectares, equipped/ actually irrigated [11]	Development of tariffs for supplied water [5]
Belgium, 23.8/5.5	Users who draw water from underground and surface sources pay a fee based on the declared amount of water.
Italy, 3977.2/2732.7	The tariff system is based on covering the current costs of servicing the territory. Only a small part of the irrigated area is measured and evaluated by volume. Water users pay directly for water (for a water abstraction license), as well as transportation tariffs.
Luxembourg, 0.036/0.027	Tariffs vary by the municipality but are calculated based on an agreed methodology.
The Netherlands, 476.3/119.2	Groundwater users pay a provincial fee to cover the costs of monitoring and controlling groundwater quality.
Germany, 515.7/234.6	The price of water is based on the costs of production, treatment, and transportation. Limits for calculating fees for water supply and drainage services are defined.
France, 2723/1939	Farmers pay a two-rate tariff (i) a fixed fee per hectare (ii) a volumetric fee for the water used.
Great Britain (as of January 31, 2020, the country left the EU), 228.9/147.3	Each region is allowed to set a fee to recover the costs of managing the water supply. Farmers pay a fee when they apply for a water abstraction license, as well as an annual fee that depends on location, type of water use, water quality and season.
Denmark, 299/–	A fixed rate of payment for water is established.
Ireland, No data available	Fees are charged based on the volumetric method.
Greece, 1521.6/1294.4	The amount of the water fee depends entirely on operating costs, including fuel or electricity consumption.
Spain, 3828.1/3437.4	The per-hectare fee is applied to 82 % of the irrigated area, the volumetric fee is applied to 13 %, and according to the two-rate (binomial) method to 5 % of the area.
Portugal, 647.4/248.0	Water users are obliged to pay an annual set fee (fixed) per hectare and depending on the profit from growing crops.
Finland, 103.8/15.0	Mixed tariff system (two-rate) fixed and volume.
Austria, 116.1/43.5	Mixed tariff system: fixed and volume fee; tariff systems differ between regions.
Sweden, 188.5/52.2	There is no data.
Poland, 82.3/70.5	Different schemes: mixed, fixed, volumetric.
Hungary, 208.4/148.7	The fee for water supply consists of a fee for water intake and transportation. It is established by the government to finance the costs of water resources management.
Czech Republic, –/17.3	Tariffs for water from public water supply systems are regulated by the Law: mixed tariff system, fixed and volume fee (additional for exceeding the limit).
Slovakia, –/57.0	Contractual prices for water supply and water for irrigation are not paid.

Ending of Table 1

Name of the country, area of irrigated land, thousands of hectares, equipped/ actually irrigated [11]	Development of tariffs for supplied water [5]
Slovenia, 15.6/7.1	There is no data.
Cyprus, 55.5/45.4	Government/State Irrigation Schemes: Single Volume Tariff with Variable Price Levels (Usage).
Malta, 3.6/–	Direct volumetric tariff for non-potable water supplied from public wells.
Estonia, 1.4/0.6	There is no data.
Lithuania, 4.1/1	Single volume tariff: volume fee for water intake depending on the source of water.
Latvia, 1.0/–	Single volume tariff: volume fee for water intake depending on the water source, extra-limit intake is taken into account.
Bulgaria, 545.2/–	Fee for water intake and water supply. Prices for irrigation depend on the methods of supply, it can be self-flow or with pumps.
Romania, 2149.9/221.1	Water prices are set by the government for each type of water use, and all farmers in the country pay a set fee. The government covers all electricity costs.
Croatia, 9.3/–	Mayors of municipalities must approve water prices; water suppliers publish price calculations.

Source: generated by the authors based on [5–7; 10; 11]

In Italy, all water bodies have been turned into public property (Law of 1933). The water supply system relies on “Reclamation and Irrigation Consortia” (RIC) (Consorzi di Bonifica e Irrigazione), which are managed by landowner associations that control land reclamation and water distribution in a given region. RICs distribute about 50% of the water used for irrigation. There are two payment instruments (i) tariff and (ii) fee for unregulated water and self-service (equally for surface water and groundwater) for self-abstraction. At the same time, the fee for drainage services is calculated in proportion to the benefit received (ranking plan) and based on the service area [2; 3].

France has a wide range of irrigation facilities. The share of the area with low-pressure sprinklers dominates (90%) in the area of irrigated land. By 2005, more than 70% of farms and 85% of irrigated areas were equipped with volumetric devices, and since 2006, the installation of volumetric meters has become mandatory for farmers. Pricing systems range from “average costs” to “marginal costs” used in conjunction with quota systems. The water charge has two components: a basin charge (based on the average water intake) and a consumption component (charged from the difference between water intake and return flows). The criteria, used to set the fee vary significantly from basin to basin, are mostly dependent on characteristics such as drought probability, user type, capital expenditure, ownership, and other basin characteristics.

The main consumer of water in Greece is the agricultural sector. Irrigated area has increased by about 65% over the past 20 years as a result of a strong political commitment to increase both agricultural production and farmers’ incomes. There was only one country that transpose the Directive [10] into national legislation. The appointment of regional water directors and councils for each water region/ river basin district has been established.

Irrigation provides 50% of Spain’s final agricultural output. Water management has traditionally been based on the existence of district basin administrations as the main bodies with the authority to regulate surface water, although they can enter into agreements to manage unregulated waters (e. g., tributaries of rivers without infrastructure) and groundwater. There is no charge for the use of groundwater. User communities (irrigators) function as associations of water users, which are controlled by farmers (irrigation associations), but mainly by the state.

Flood irrigation and gravity systems predominate in Portugal. The role of the state in promoting irrigation projects has traditionally been quite limited. Water tariffs for agriculture are charged by water user associations according to complex mechanisms and formulas. A fixed fee per hectare, taking into account the profit received, is dominant.

In Romania, ground (10%) and surface (90%) water for irrigation are used. In the southern regions, irrigation was created on three levels (terraces), mostly using the water resources of the Danube River. Restoration of the existing irrigation potential is the main measure for the economic development of the agricultural sector. The implementation of integrated management of water resources at the level of river basins and the modernization and reconstruction of existing irrigation systems using energy-saving self-propelled irrigation are considered the main goals of agrarian policy [9].

Since the reform of the water management system of Ukraine involves a significant increase in the area of irrigated land, not only the experience of EU countries with large size irrigated areas but also with small and medium areas of such lands are of great importance for Ukraine. Table 2 presents generalized information on tariffs for water supply for irrigation and on the return of funds spent on water supply through the tariff mechanism by grouping information by EU countries.

Conclusions of the European Commission report on the role of water prices [1]. Further and stronger efforts are needed in the EU countries to provide adequate incentives for the efficient use of water in the agricultural sector. Most often, the right to take or use water is first issued by a state authority through the granting of licenses or permits. Authorization and clearance procedures (e. g., permit requirements) may vary

2. Information on tariffs for water supply for irrigation and compensation of funds spent on reclamation infrastructure in EU countries

Measures / directions	Countries are the subjects of paid water use
Tariffs for supplying water for irrigation	
Water pricing	For use in agriculture (Greece, Malta, Spain, Cyprus, Hungary, and the Netherlands) or for irrigation (Estonia, Slovakia, and Finland).
Fee/tariff for direct water intake	The fee is paid above the specified threshold in Belgium, France, the Netherlands, Great Britain, the Czech Republic, Germany, Finland, and Ireland.
There is no minimum intake volume at which tariffs or the requirement for approvals start to apply	Denmark, Italy, Lithuania, Portugal, Bulgaria and Slovenia.
Fee for direct water intake	In Italy, small fees are paid for licenses or permits. In the Netherlands, farmers pay an area-based fee to cover the water board's maintenance costs.
The tariff depends on the level of service, where the pressurized water supply has a higher price compared to gravity-fed distribution systems	Volume (flat) tariffs are usually applied in Cyprus and Luxembourg. In Cyprus, a fee of m³ is charged from irrigator organizations when irrigating on systems built at the expense of the budget. Some collective systems in Greece, Spain, and Italy apply volume tariffs.
Mixed tariffs. These fees combine a flat rate based on area or yield with a volumetric element	Austria, the Czech Republic, Hungary, Finland (livestock and dairy farming), Germany, Ireland, Poland, and Spain use mixed tariffs for water supply for agriculture. In Spain, the volume component depends on the volume or time of irrigation. In France, mixed or binomial tariffs are most often used for non-gravity supply systems.
Rate based on area irrigated	Spain, Greece, Italy, France, Poland, Malta and, to a lesser extent, Cyprus.
Penalties for exceeding limits or for excessive use in conditions of water scarcity	Some water supply systems in a number of member states as Cyprus, Spain, France.
Compensation of funds spent on reclamation infrastructure	
Countries do not feel the burden on the water when the funds are returned	Austria, Denmark, Finland, the Netherlands, Luxembourg, and Great Britain used money 100% refunds for financial needs.
Operation and maintenance costs for providing water are only partially covered	Spain, Portugal, Poland, Italy, Greece, Bulgaria and Cyprus.

Ending of Table 2

Measures / directions	Countries are the subjects of paid water use
An unspecified portion of environmental and resource conservation costs is reimbursed	Great Britain, the Netherlands, France, Belgium (Flanders), Germany.
Reimbursement of costs for maintenance of reclamation systems due to tariffs	Less than 100% of capital expenditure for Italy, the Netherlands, Ireland, Greece, Spain, Portugal, Poland, Hungary, Bulgaria, and France; close to 100% for Belgium, Luxembourg, Great Britain, Denmark, Finland, Austria, Sweden, Cyprus, Romania, and 100% of financial costs for Latvia.
Problems with water metering for water billing	On a small part of the irrigated area, water is measured and assessed by volume, tariff, and fee for unregulated water and independent water abstraction, the priority level for Italy; based on metered water metering in Ireland, volume tariff with variable price levels for Cyprus, single volume tariff with differentiation for Lithuania, base and over-limit volume meter readings for France, capped volume rates for Latvia.
Achieving the quality indicators of meeting the requirements of the WFD [1]	Belgium, the Netherlands, and Germany reached 80%; not reached Spain, Slovakia, and Estonia; movement towards the introduction of volume payments in Italy.
Countries are in the process of improving the evaluation and internalization of the ERC	Cyprus, Spain.
Side/additional problems of applying economic instruments	
Institutional mechanisms of water use	The role of regional governments in Belgium, Great Britain, and Germany; participation of government institutions and water boards of the Netherlands, Luxembourg, Greece, Hungary, Italy, Romania, and Croatia; ecological and economic accounting in Spain, price subsidies by governments in Bulgaria, Romania, the government covers electricity costs in Romania, state policy to increase agricultural production and farmers' incomes in Greece, restrictions for calculating fees for services, price calculation is based on extraction, cleaning and transportation costs in Germany, publication of price calculations in Croatia.
Creation of an association of water users	Austria, Bulgaria, Great Britain, Greece, Denmark, Ireland, Spain, Italy, Cyprus, Portugal, Romania, Hungary, Sweden.
The impact of water charges on the agricultural economy	Share of water charges in total irrigation volume (2-8%) in France, irrigation costs are 20% of total costs of growing major crops in France, water costs are less than 7% of total farmer costs in the UK, water charges are 20% of costs farmers for water and 0.5-2% of the gross value of cultivated crops in Hungary.
Water for watering (for irrigation) is not paid for by farmers	The Netherlands, Germany, Slovakia.

Source: formed by the authors based on [1; 4; 7; 9]

depending on the amount of water withdrawn or the capacity of the pumps. For groundwater, threshold values are sometimes more stringent than for surface water. The justification of the initial distribution may take into account the availability of water resources, the purpose of abstraction (use), ecological needs, and other types of uses and sources. The time periods or duration of authorizations for the withdrawal of agricultural/irrigation water vary considerably between Member States.

There is great heterogeneity both in terms of structure and level of water prices. For water intake (with independent water intake), tariffs are usually volumetric, at low rates, and above the minimum limit. Some countries differentiate the tariff depending on the state of the resource. In more than a third of the Member States, farmers do not pay for water withdrawals. These exceptions tend to exist in several southern European Member States that experience water scarcity. This means that a significant share of the volume of water for agriculture in the EU is not estimated.

There are several pricing mechanisms for water supply to farmers. For gravity supply systems, disincentive area charges are still common, while mixed systems and volume charges are becoming more important. The volume price may be limited to certain regions of the country and usually depends on the provided pressurized water service. Some Member States have introduced fines for excessive consumption.

The level of cost compensation in EU countries, as well as water tariffs, is very different. For at least one third of the member countries, operation and maintenance costs for water provision are only partially reimbursed. More often, capital investments are subsidized (at least in part) by the country/regions. Environmental and resource costs have not become a central element of pricing policy. The practice of state capital subsidies to irrigators in water-scarce regions helps farmers in their country to be more competitive.

Although the use of economic instruments, such as tariffs, taxes, benefits, fines, funding of reclamation programs from the budget, etc., can contribute to solving problems of water quantity and quality, economic instruments for water management cannot replace conventional management and supply policies; rather, they should be designed to complement said policy. Achieving payback indicators, developing water pricing and trading mechanisms, clarifying and changing water rights, and institutional mechanisms should be supported by more reliable information [7].

Using the experience of EU countries in Ukraine. For Ukraine, given the significant achievements in irrigation at the end of the twentieth century and its transformation into a guarantor of world food security [6], its necessary urgently implement the recovery of irrigated agriculture in large areas due to its strategic and export-oriented nature, the presence of different climatic zones, the achievements of both the irrigation "grands" of the Mediterranean region of Europe and new EU members with a positive experience of renewing the agricultural and water sectors of the economy. The search for appropriate approaches, factors, and procedures for tariff formation in Ukraine is underway. Information on water tariffs and compensation for individual countries (Table 2) will be used critically as analogs of decision-making in Ukraine.

The influence of the experience of the EU countries on the methodical component of tariff formation in Ukraine will be the establishment of a clear procedure for fixing tariffs, the use of different pricing formulas by regions of the country, the use of progressive, seasonal and increased tariffs for water; introduction of regulations regarding tariff calculation, stimulation of efficient use of water resources; irrigation water accounting rules, ensuring compliance with the principle of justice (ensuring equal access to services and equal opportunities, strengthening trust in the system), effective coordination of actions between water user associations and reclamation system operators when owning the distribution/supply infrastructure. Tariffs are expected to be established while ensuring economic efficiency, financial stability, and fiscal clarity.

A combination of innovative water technologies, management measures, and economic tools (including a tariff-setting mechanism) will be needed to prevent water scarcity problems [2]. Effective use of reclamation (irrigation and drainage) infrastructure, on the one hand, and financing expected service requirements mainly through tariff levels (fees), on the other hand, will allow extending the life of irrigation infrastructure and improving the level of water use. This can lead to financial savings (providing better services and facilitating cost recovery), as well as assistance to avoid infrastructure deterioration and delay investment needs.

Conclusions. The positive experience of countries with a developed sector of irrigated agriculture will be valuable when transitioning from the system of water tariffs payment for water supply services to the introduction of tariffs. In terms of economic content, water tariffs tariffs for water supply services for the irrigation of agricultural crops are classified as an important economic tool of irrigation management. The study of the practice and experience of the EU countries shows that an effective tariff-setting mechanism for water supply services in Ukraine should be based both on the solution of administrative and legal problems in the plan of continuing water system management reforms [6], and on the approval of known schemes [13] and proposals regarding the combination of the interests of the state and water users regarding the effective use of irrigated lands.

Directions for further research: In order to obtain reliable data on the appropriateness of tariff options, should be ensured clear accounting of data concerning water volumes (payment and supply schedules), land areas, electricity, costs related to various areas of activity, making the calculation, and separate accounting of works on irrigated areas are required and drained objects of engineering infrastructure, drawing up plans for technical

maintenance, current, major repairs, investment plan; preparation of reports on the activity of WUOs and water users on the use of tariffs based on the results of pilot projects and individual systems.

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АНАЛІЗ МЕТОДИЧНИХ ПІДХОДІВ ДО ФОРМУВАННЯ ТАРИФІВ НА ВОДУ ДЛЯ ЗРОШЕННЯ ТА КОМПЕНСАЦІЮ ВИТРАТ НА МЕЛІОРАТИВНУ ІНФРАСТРУКТУРУ: ДОСВІД КРАЇН-ЧЛЕНІВ ЄС

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Анотація. *Розглянуто практику країн ЄС із запровадження тарифів на воду для зрошення сільськогосподарських культур та процедур повернення коштів, витрачених на водопостачання для зрошення. Основними джерелами інформації статті стали публікації та нормативні документи України, звіти органів ЄС та World Bank, у яких проведений критичний аналіз практики ціноутворення у зрошуваному землеробстві країн ЄС за 2005–2023 рр. Проведено групування інформації про площу зрошуваних земель, рівень повернення коштів, витрачених на водопостачання, увагу приділено методичному підходу до розробки тарифів на транспортування води. Викладено тлумачення причин природного характеру, якими керувалися органи управління державами при застосуванні економічних інструментів управління зрошенням на своїх територіях. За окремими країнами із значними площами зрошуваних земель (Італія, Франція, Греція, Іспанія, Португалія та Румунія) визначено вагомі досягнення (складові) тарифоутворення та відшкодування коштів. Розкрито аспекти тарифоутворення на воду, облік води, розвиток об'єднань водокористувачів, оподаткування плати за воду. Ознаками класифікації країн було: напрями ціноутворення на воду, врахування стану водних ресурсів та меліоративних систем, різновиди тарифів, механізми ціноутворення, стан повернення коштів, витрачених на водопостачання за рахунок тарифів, вимірювання обсягів води, а також розв'язання додаткових проблем застосування економічних інструментів у зрошуваному землеробстві – інституціональні (адміністративні, правові) заходи, вплив плати за воду на економіку агросфери країни тощо. Оскільки домінуючим підходом у реалізації тарифоутворення у зрошенні країн ЄС є вимоги водної рамкової директиви, розглядався рівень досягнення показників якості виконання ВРД країнами. Встановлено, що переважна більшість світових практик формування тарифів на послуги з подачі води для зрошення, капітальних інвестицій в меліоративну інфраструктуру та її обслуговування, свідчить, що вони базуються, як на загальнодержавних інтересах, так і на зацікавленості водокористувачів і організацій, що забезпечують логістичну підтримку.*

Ключові слова: *водоподача, зрошення, тарифи, компенсація витрат, управління, системний підхід, Європейський Союз (ЄС)*

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USING THE WATER STRESS INDEX FOR TOMATO IRRIGATION CONTROL

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Abstract. *The temperature of the leaf surface of plants can be used as an indicator of the water stress of agricultural crops. Since plant temperature is affected by weather factors, it is usually expressed through the crop water stress index (CWSI). To calculate the CWSI, two input parameters must be known that relate plant temperature under and without maximum water stress to the water vapor pressure deficit. These basic equations are specific to each culture and locale. Many studies on the definition of CWSI and basic dependencies for tomatoes have been conducted abroad, such a study has not yet been conducted in Ukraine. The purpose of the research is to establish CWSI values and basic equations that are needed for the purpose of watering tomatoes in the south of Ukraine under subsurface drip irrigation. The paper presents the results of determining the theoretical and empirical water stress index of tomatoes under subsurface drip irrigation. The research results confirm that the water stress index can be used to plan the irrigation of tomatoes both independently and in combination with other methods to increase the accuracy of decision-making. An analysis of the daily dynamics of the CWSI was carried out, according to the results of which it was established that in the morning hours the water stress index on average during the observation period was almost 0, then, as the intensity of solar radiation increased, the CWSI also increased and reached its maximum value (1.08) at 20:00. The correlation coefficient between the water stress index and the intensity of solar radiation was 0.63. The relationship between irrigation rate, soil moisture, change in plant stem diameter, and CWSI was established, the correlation coefficients are –0.60, –0.55, and –0.51, respectively. Theoretical and imperial methods estimate CWSI equally, there is a high correlation between both methods (r = 0.92). It is necessary to prescribe irrigation or increase the irrigation rate according to the theoretical and empirical methods of determining CWSI, respectively, for its values of 0.3 and –2.2. The empirical method of calculating CWSIE using the resulting equations is easier to use. The CWSI values obtained for tomatoes in this study are closely correlated with the other irrigation methods.*

Key words: *water stress index, tomato, subsurface drip irrigation, plant temperature, phytomonitoring*

Relevance of research. Tomato (*Solanum lycopersicom* L.) is a valuable vegetable crop that is grown for its fruits. About 75 % of tomatoes are consumed fresh, and the rest is processed. The sown area in Ukraine is about 80 thous. hectares, which is 20 % of the entire area under vegetable crops [1]. In the south of Ukraine, this is the most common vegetable crop. Tomatoes belong to agricultural crops with a high level of total water consumption: 5.2–5.5 thousand m^3/ha and are sensitive to water stress [2; 3]. Accordingly, the determination of the criterion for the appointment of watering tomatoes is an important element for the operational management of the irrigation regime. Today, there are many methods of irrigation [4; 5; 6], one of the criteria for their use is the availability of the necessary tools and qualified personnel. Studies on the determination of CWSI for tomatoes [3; 7–9] and other [10–15] crops conducted abroad indicate that this index is used to assess plant water stress and manage irrigation. Such studies have not yet been conducted in Ukraine. Therefore, the need to conduct research is due to the development of a method of assigning irrigation that does not require expensive tools in order to increase the efficiency and effectiveness of managing the water regime of the soil.

Analysis of recent research and publications. One of the simple and accurate methods of watering, which does not require complex and expensive equipment, can be the water stress index (crop water stress index – CWSI), which is based on measuring plant and air temperature. Infrared thermometers [3; 10] or leaf temperature sensors [7] can be used to measure plant temperature.

The experimental [16] and theoretical [17; 18] crop water stress index (CWSI), which can be used to predict irrigation time, was developed in 1981 and has not lost its relevance today [10; 19]. When plants experience water stress, the stomata immediately close, transpiration decreases sharply, and the temperature of the leaves rises. Studies have shown a close correlation between the temperature of the plant cover and the moisture supply of plants. [9; 11; 18; 20]. To calculate the CWSI, two input parameters must be known that relate the plant temperature under and without maximum water stress to the water vapor pressure deficit. These basic equations are specific for each culture and locality [8; 9; 16; 19].

Foreign scientists have conducted many studies on determining CWSI for tomatoes [3; 7; 8; 9], cowpea [10], corn [11; 14; 15; 19], sorghum [12], winter wheat [13], pumpkins, soybean, alfalfa [16], eggplant [21; 22], watermelon [23], cotton [24], sweet pepper [25] and concluded that this index accurately assesses the water stress of agricultural crops and can be used as a criterion for irrigation.

The purpose of the study is to determine the value of the water stress index (CWSI) and the basic equations that are necessary for the purpose of watering tomatoes under subsurface drip irrigation in the conditions of the Dry Steppe of Ukraine.

Research materials and methods. The study of the water stress index of tomato plants (CWSI) was conducted in 2019 in production conditions on the lands of PE "Organic Systems". The enterprise is part of the "Agrofusion" group of companies, which specializes in growing tomatoes on drip irrigation on an area of more than 7.5 thousand hectares with further processing at its own facilities [26]. The research and production site is located on the territory of the Chaplyns′koho district of the Kherson region, Ukraine (subzone of the Dry Steppe, Google Maps location 46040' N. 33035' E.). The climate of the research area is moderately hot and very dry. The sums of temperatures above +10°C are from 3300 to 3400°C, the amount of precipitation during this period is 200–220 mm, and the hydrothermal coefficient according to G.T. Selyaninov is equal to 0.6 [27]. The soil of the research and production site is dark chestnut, low in humus (1.7–1.9%), the soil moisture content for the 0–50 cm soil layer is 25.8% of the completely dry soil (174 mm), the bulk density is 1.35 g /cm³. Water intake for irrigation was carried out from the Chaplyns′kyi Canal (Chaplynska irrigation system, feeding from the North Crimean Canal, water from the Dnipro River). In the experiment, the Melman F1 Organic early-ripening tomato hybrid for machine harvesting was used. Planting scheme 1.50×0.25 m. Irrigation pipelines of the drip irrigation system are laid at a depth of 0.25 m.

To monitor meteorological parameters, an automatic Internet weather station iMetos IMT 300 [28] from the company "Pessl Instruments" [29] was used, which was located directly at the experimental site. The weather station is equipped with sensors for air temperature, air humidity, solar radiation, wind speed, and a rain gauge. The temperature of tomato plants was measured with an LT-1z sensor, and the change in stem diameter was measured with an SD-5z sensor, which was connected to a PM-11z phytomonitor from the company "Bio-Instrument S.R.L." [30]. Sensors for monitoring the physiological state of plants were installed according to methodical instructions [31].

The theoretical and imperial water stress index (CWSI) was calculated using the formula [16–18]:

$$CWSI = \frac{(T_c - T_a) - (T_c - T_a)_{LBL}}{(T_c - T_a)_{UBL} - (T_c - T_a)_{LBL}}, \quad (1)$$

where $(T_c - T_a)$ – the temperature difference of the plant (T_c) and air (T_a); $(Tc\text{-}Ta)_{LBL}$ is the lower baseline, the temperature difference that is achieved under conditions when plants are well-moistened and have potential transpiration. Under these conditions, the temperature of the plant was minimal under existing environmental conditions. $(T_c - T_a)_{UBL}$ is the upper baseline, the fictitious temperature difference under the conditions if the plant were instantly dried without any changes. Under these conditions, the temperature of the plant was the maximum under existing environmental conditions.

The lower baseline was calculated using the theoretical method [3; 18], taking the resistance of the stomata equal to zero (r_c=0).

$$(T_c - T_a)_{LBL} = \frac{(R_n - G)\times r_a}{\rho_{ar} C_p \left(1 + \frac{\Delta}{\gamma}\right)} - \frac{VPD}{\gamma\left(1 + \frac{\Delta}{\gamma}\right)}, \quad (2)$$

where: r_a – aerodynamic resistance, s/m; γ – psychometric constant, kPa/°C; R_n – total radiation balance, W/m²; G – heat flow into the soil, G = 0; ρ_{ar} – air density at constant pressure, kg/m³; C_p – specific heat capacity of air at constant pressure, J/kg·°C, C_p =1013; Δ – is the slope of the pressure curve of saturated water vapor at temperature, kPa/°C; VPD – water vapor pressure deficit, kPa.

The upper baseline was calculated using the theoretical method [3; 18], assuming the resistance of the stomata to be close to infinity ($r_c \to \infty$).

$$(T_c - T_a)_{UBL} = \frac{(R_n - G)\times r_a}{\rho_{ar} C_p}. \quad (3)$$

The aerodynamic drag (r_a) needed to calculate the CWSI according to the Jackson method [18] was calculated using the formula [32]:

$$r_a = \frac{4.72 \times \left(\ln\left(\frac{z-d}{z_0}\right)\right)^2}{1 + 0.54u}, \quad (4)$$

where z – wind measurement height, m; d – the height of the offset of the zero plane, m; $d \approx 0{,}63h$; z_0 – roughness length, m; $z_0 \approx 0{,}13h$; u – wind measurement height, m; h – the height of the plant, m.

Other parameters of equations 2 and 3 were calculated according to the FAO method 56 [33]. To calculate the slope of the pressure curve of saturated water vapor (Δ), we used the average temperature of the plant and air $\left(T = \frac{T_c + T_a}{2}\right)$ according to the Jackson method [18].

The Empirical Water Stress Index ($CWSI_E$) was calculated using Equation 1, replacing the lower and upper baselines with Equations 5 and 6 [3; 7; 10; 15; 16; 19].

The lower baseline ($(T_c - T_a)_{LBL}$) was calculated using the empirical method using the formula:

$$(T_c - T_a)_{LBL} = a + b \times VPD, \quad (5)$$

where T_c – plant temperature, °C; T_a – air temperature, °C; VPD – water vapor pressure deficit, kPa; a and b – different constant coefficients for agricultural crops.

The upper base line ($(T_c - T_a)_{UBL}$) using the empirical method is calculated by the formula:

$$(T_c - T_a)_{UBL} = a + b \times VPG = a + b\left[e_s(T_a) - e_s(T_a + a)\right], \quad (6)$$

where VPG – water vapor pressure gradient, kPa; coefficients a and b obtained from the lower baseline (5); $e_s(T_a)$ – saturated vapor pressure at air temperature Ta, kPa; $e_s(T_a + a)$ – is the saturated vapor pressure at the temperature of T_a+a, kPa.

$$e_s(T_a) = 0.6108 \times e^{\frac{17.27 \times T_a}{237.7 + T_a}},$$

$$e_s(T_a + a) = 0.6108 \times e^{\frac{17.27 \times (T_a + a)}{237.7 + (T_a + a)}}, \quad (7)$$

Research results and discussion. The water stress index was calculated for the daylight hours (2 hours after sunrise and 2 hours before sunset) [12]. Research results confirm that CWSI approaches "0" after irrigation and gradually approaches 1 as soil moisture decreases [12]. During the observation period, almost all CWSI values were in the range from 0 to 1. Deviations from this range were observed in the morning and evening, when the CWSI values were less than "0" and more than "1", respectively (Fig. 1). This result confirms research [13] on winter wheat culture conducted in northern China [13]. The results of the calculations confirm the relationship between CWSI and plant and air temperature. Thus, the correlation coefficients between CWSI and plant and air temperature were 0.71 and 0.64, respectively.

According to the analysis of the daily dynamics of the CWSI, the tendency of this indicator to increase from 05:00 to 20:00 is followed [12; 17; 19]. Thus, after sunrise at 06:00, CWSI was close to "0" on average during the observation period, then, as the intensity of solar radiation increased, CWSI also increased and reached its maximum value (1.08) at 20:00.

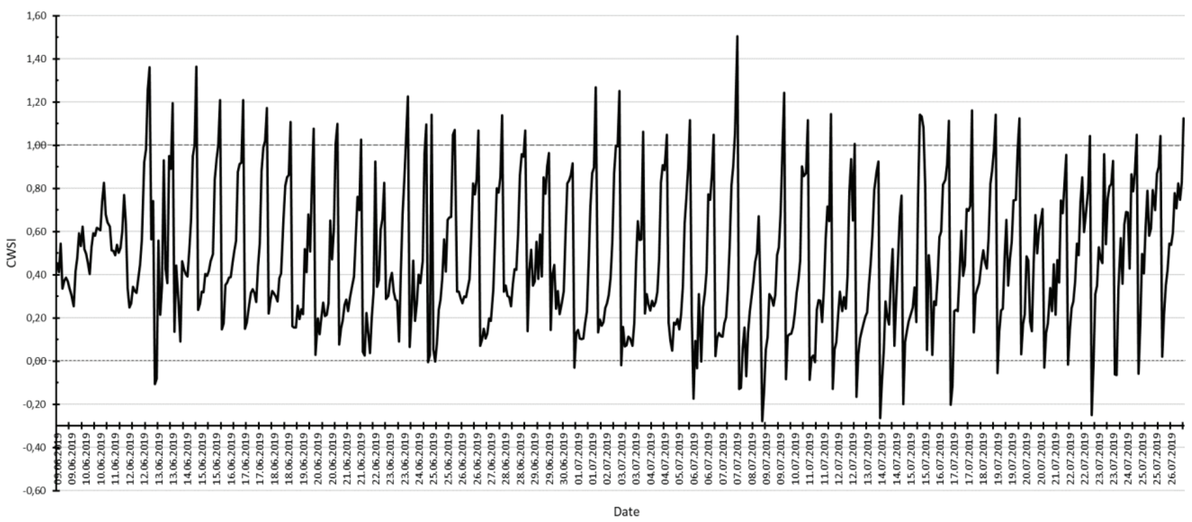

Fig. 1. Daily dynamics of the water stress index of tomato plants

The correlation coefficient between the water stress index and the intensity of solar radiation was 0,63 (Fig. 2).

For CWSI analysis, the average value of this indicator was taken at 12:00 and 13:00 [13; 16; 18]. Based on the results of calculations, it was established that the average CWSI value of tomato below 0,2 did not decrease against the background of sufficient soil moisture, which was also established by Brazilian scientists [3]. At the beginning of observations (June 10), the value of CWSI was 0.47–0.50. Then, due to precipitation, and, as a result, a decrease in the water vapor pressure deficit, the CWSI decreased to 0.28. After three waterings of 100 m^3/ha on June 14–16, the CWSI increased to 0,42, which indicates an insufficient irrigation rate. After increasing the irrigation rate from June 17 to 120 m^3/ha, the CWSI index decreased to 0,30, and later to 0,21. From June 17 to July 15, CWSI was in the range of 0.20–0.30, indicating no water stress during this period. The exception was the period from June 26 to 29, when for technical reasons the irrigation rate was reduced to 80–100 m^3/ha, and as a result, CWSI increased to 0.32–0.35.

Starting on July 15, the CWSI began to gradually rise from 0.30 to 0.50. This is due to the onset of fruit ripening, an increase in air temperature, and a deficit of water vapor pressure [9], as well as a decrease in the intensity of irrigation. Based on the results of the analysis, a relationship between the irrigation rate and CWSI was established, the correlation coefficient is –0.60. Increasing the irrigation rate reduces CWSI. It is necessary to prescribe irrigation and increase the irrigation rate for a CWSI value of 0.30 (Fig. 3).

The dependence of CWSI on soil moisture is similar to that on the irrigation rate. An increase in the rate of irrigation led to an increase in soil moisture, and as a result, CWSI decreased. Thus, at the highest soil moisture of 80–81 % MMHC (June 24 and July 1), CWSI values were the lowest and amounted to 0.18–0.20. On June 29, soil moisture decreased to 79 % MMHC and CWSI increased to 0.35. The decrease in soil moisture from July 15 to 78 % MMHC led to an increase in CWSI to 0,4. Based on the results of the study, a relationship between soil moisture and CWSI was established, the correlation coefficient is –0.55. A decrease in soil moisture by 2–3 % MMHC increased the CWSI to the threshold values (0.30) for determining the irrigation period (Fig. 4).

The phytomonitoring method is used for operational management of tomato irrigation [4], therefore the established relationship between CWSI and the change in stem diameter confirms that the water stress index can be used to plan tomato irrigation both independently and in combination with other methods. Thus, with an increase in the diameter of the tomato stem, the CWSI decreased and vice versa. The correlation coefficient between CWSI and the change in stem diameter was –0.51 (Fig. 5).

Calculation of CWSI using the empirical method [3; 7; 10; 15; 16; 19] simplifies the use of the technique compared to the theoretical method, which requires more complex calculations. The Empirical Water Stress Index (CWSIE) was calculated using Equation 1 by changing the lower and upper baselines to Dependencies 5 and 6.

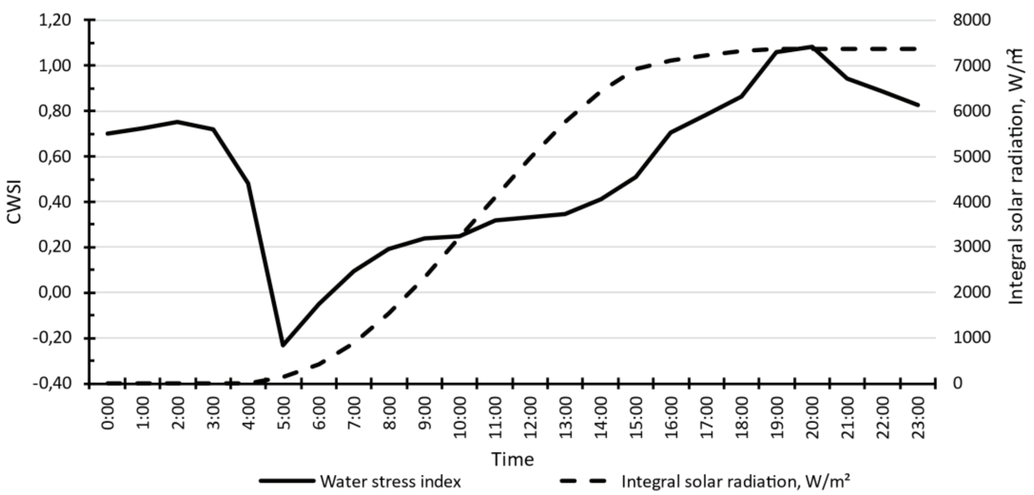

Fig. 2. Daily dynamics of tomato water stress index and solar radiation

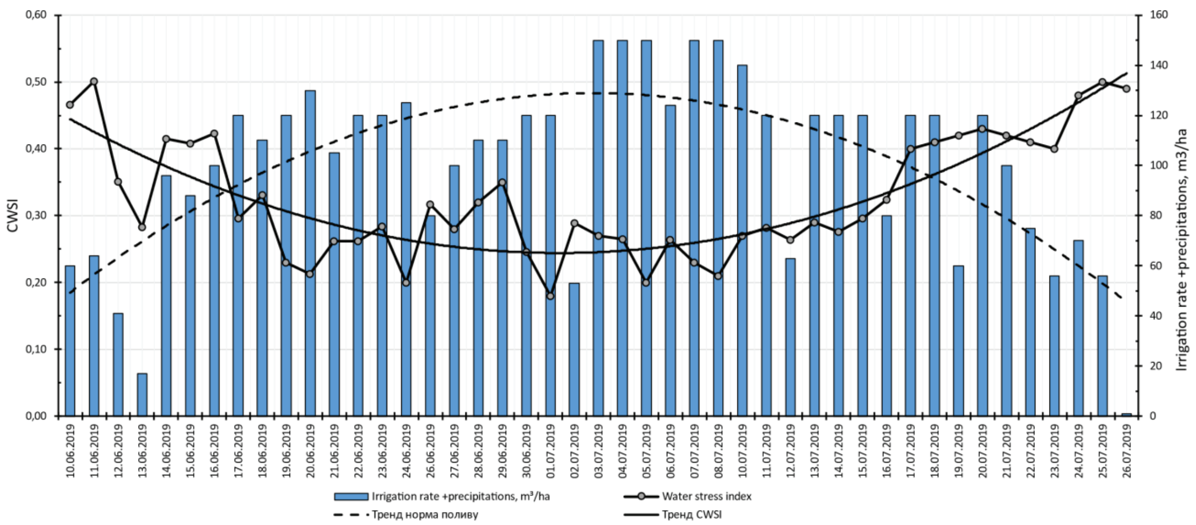

Fig. 3. Dependence between tomato irrigation rate and CWSI

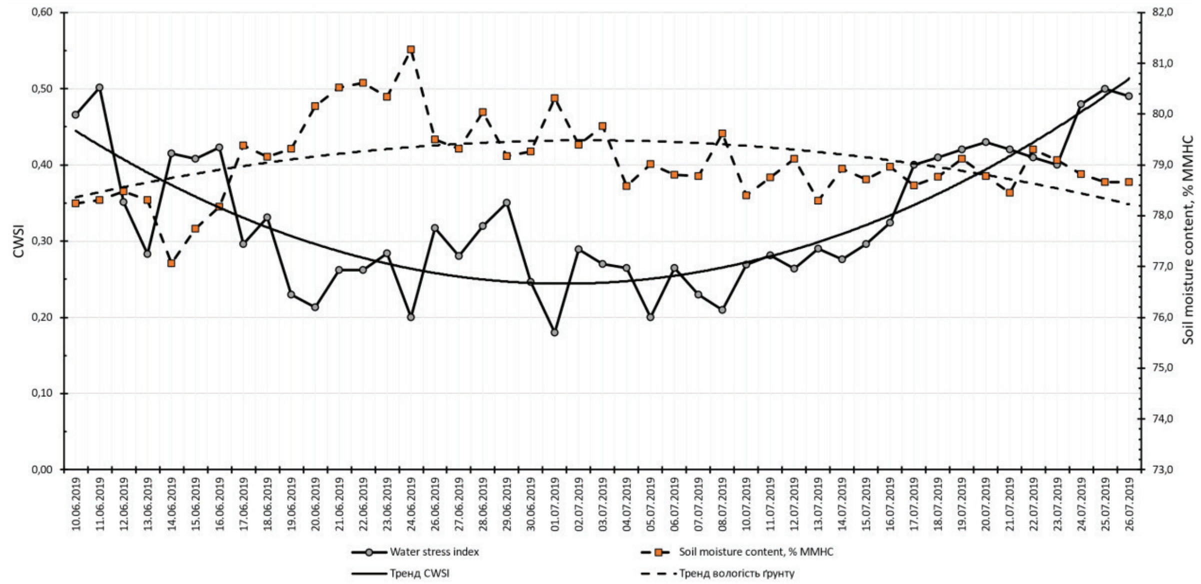

Fig. 4. The relationship between soil moisture and CWSI of tomatoes

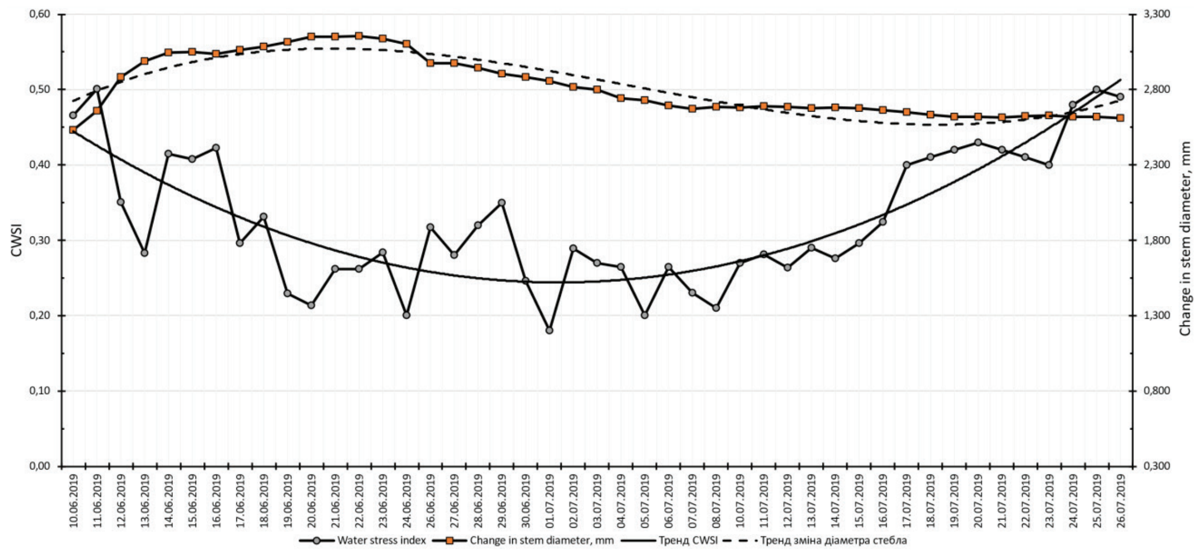

Fig. 5. The relationship between the change in stem diameter and CWSI of tomatoes

To obtain the equation of the lower baseline $(T_r - T_a)_{LBL}$, we used the data obtained according to dependence 2. Based on the results of the calculations, we obtained the basic equations for determining the CWSI of tomatoes:

$$(T_c - T_a)_{LBL} = -0.842 - 2.591 \times VPD, \quad (8)$$

$$(T_c - T_a)_{UBL} = -0.842 - 2.591 \times VPG. \quad (9)$$

According to the obtained equation 8, it was established that with a water vapor pressure deficit of 0,1 to 4,2 kPa, the temperature difference between the plant and the air was from 1.2 to –6.30°C (Fig. 6).

It is possible to use the obtained equation of the lower baseline $(T_p - T_a)_{LBL}$ [10; 14; 34] to determine the irrigation of tomatoes. To do this, it is necessary to measure the temperature, the relative humidity of the air, and the temperature of the plant. Then, by substituting the water vapor pressure deficit (VPD) in equation 8, calculate the permissible temperature difference $(T_c - T_a)_{LBL}$. In order to determine the time of watering, it is necessary to compare the temperature difference between the plant and the air $(T_c - T)$, measured in the field, with the permissible value $(T_c - T_a)_{LBL}$, in this case, three conditions are met:

1. If the value of $(T_c - Ta)$ is less than $(T_c - T_a)_{LBL}$ – watering is not required.
2. If the value of $(T_c - T_a)$ is greater than $(T_c - T_a)_{LBL}$ – irrigation is missed, it is necessary to urgently prescribe irrigation.
3. If the value of $(T_c - T_a)$ is approximately equal to $(T_c - T_a)_{LBL}$ – it is time for watering.

The values obtained by CWSI calculations using the theoretical method are greater than the empirical ones [3; 9; 21]. But regardless of this, there is a close correlation between both methods (r = 0.92), which indicates the possibility of using these methods for the operational planning of watering tomatoes. The empirical method of calculating the $CWSI_E$ using the resulting equations 8 and 9 is preferred because of its simplicity. It is necessary to prescribe irrigation or increase the irrigation rate using the empirical method of determining $CWSI_E$ when the value is –2.2 (Fig. 7).

Conclusions. The research results confirmed that the water stress index (CWSI) can be used for the operational management of tomato irrigation. The correlation coefficients between CWSI and plant and air temperature were 0.71 and 0.64, respectively.

In the morning hours, CWSI was close to “0”, then, as the intensity of solar radiation increased, CWSI also increased and reached its maximum value (1.08) at 20:00. The correlation coefficient between the water stress index and the intensity of solar radiation was 0.63.

The relationship between irrigation rate, soil moisture, and CWSI of tomatoes was established – the correlation coefficient was –0.60 and –0.55, respectively. Increasing the irrigation rate reduced CWSI. It is necessary to prescribe irrigation or increase the irrigation rate for a theoretical CWSI value of 0.30.

The relationship between CWSI and the change in stem diameter was established: as tomato stem diameter increased, CWSI decreased, and vice versa. The correlation coefficient between CWSI and stem diameter change was –0.51.

Theoretical and empirical methods estimate the CWSI equally, and there is a high correlation between these methods (r = 0.92). The empirical method of calculating CWSIE using the resulting equations 8 and 9 is recommended due to its ease of application. It is necessary to prescribe irrigation or increase the irrigation rate using the empirical method of determining CWSIE when a value of –2.2 is reached.

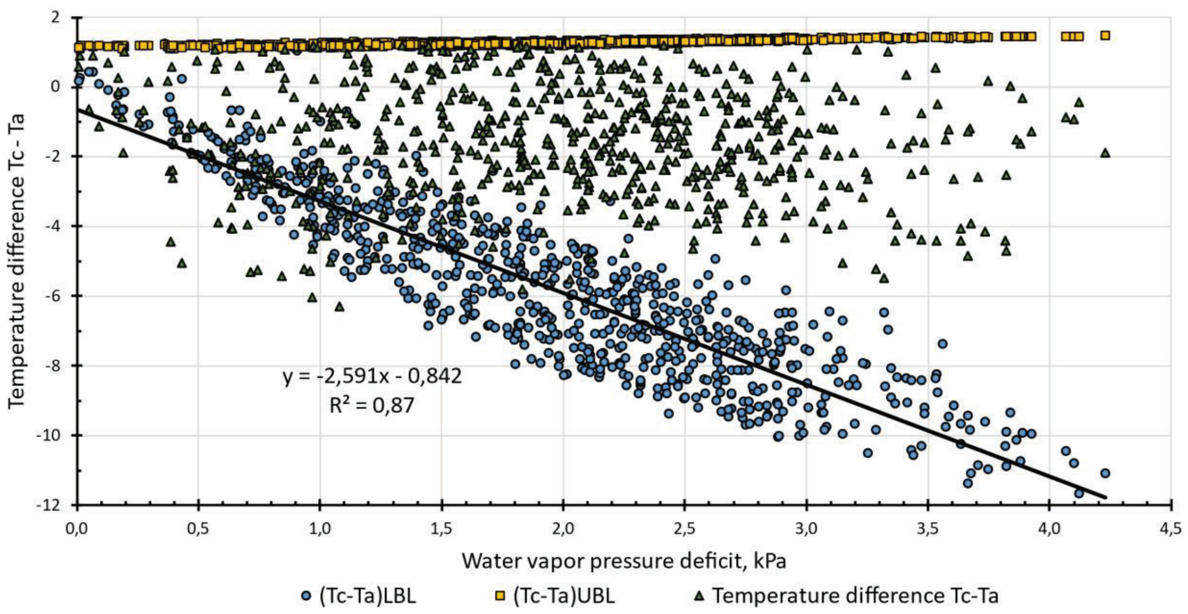

Fig. 6. Temperature difference between tomato plants and air depending on the deficit of water vapor pressure

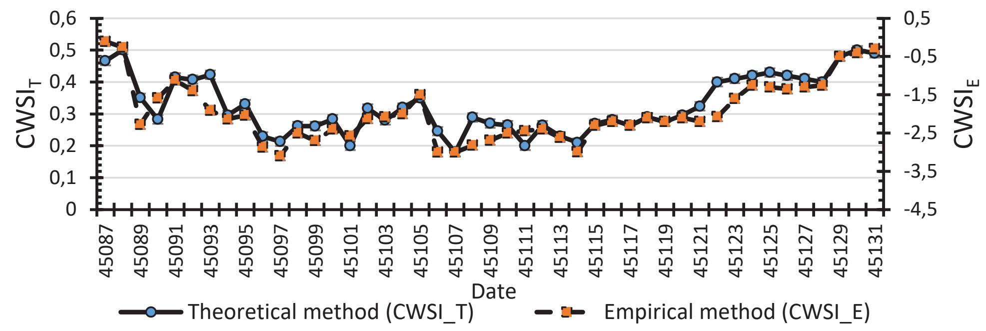

Fig. 7. Dynamics of the theoretical ($CWSI_T$) and empirical ($CWSI_E$) tomato water stress index

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ВИКОРИСТАННЯ ІНДЕКСУ ВОДНОГО СТРЕСУ ДЛЯ КОНТРОЛЮ ЗРОШЕННЯ ТОМАТІВ

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Анотація. *Температура листової поверхні рослин може бути використана в якості показника водного стресу сільськогосподарських культур. Оскільки на температуру рослин впливають погодні чинники, її, зазвичай, виражають через індекс водного стресу (crop water stress index – CWSI). Для розрахунку CWSI необхідно знати два вхідних параметра, які пов'язують температуру рослин в умовах максимального водного стресу та без нього з дефіцитом тиску водяної пари. Ці базові рівняння специфічні для кожної культури та місцевості. Багато досліджень із визначення CWSI та базових залежностей для томатів проведено за кордоном, в Україні таке дослідження ще не проводили. Мета дослідження – встановити значення CWSI та базові рівняння, які потрібні для призначення поливів томатів на півдні України за підґрунтового краплинного зрошення. У роботі наведено результати визначення теоретичного та емпіричного індексу водного стресу томатів за підґрунтового краплинного зрошення. Результати досліджень підтверджують, що індекс водного стресу можливо використовувати для планування поливів томатів як самостійно, так і в комплексі з іншими методами для підвищення точності прийняття рішення. Проведено аналіз добової динаміки CWSI, за результатом якого встановлено, що у вранішні години індекс водного стресу в середньому за період спостережень дорівнював майже 0, потім, за мірою підвищення інтенсивності сонячної радіації, CWSI також зростав і максимального свого значення (1,08) досягав о 20:00. Коефіцієнт кореляції між індексом водного стресу та інтенсивністю сонячної радіації становив 0,63. Встановлено зв'язок між нормою поливу, вологістю ґрунту, зміною діаметра стебла рослин та CWSI, коефіцієнти кореляції дорівнюють –0,60, –0,55 та –0,51 відповідно. Теоретичний та імперичний методи однаково оцінюють CWSI, між обома методами існує висока кореляційна залежність (r = 0,92). Призначати полив або збільшувати норму поливу за теоретичного та емпіричного методів визначення CWSI відповідно необхідно за його значення 0,3 та –2,2. Емпіричний метод розрахунку CWSIE із використанням отриманих рівнянь є більш простим у використанні. Значення CWSI, отримані для томатів, в цьому досліджені тісно корелюють з іншими методами призначення поливів.*

Ключові слова: *індекс водного стресу, томат, підґрунтове краплинне зрошення, температура рослини, фітомоніторинг*

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DRIP IRRIGATION REGIMES AND EFFICIENCY OF WATER USE BY SUNFLOWER HYBRIDS

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Abstract. *The article presents the results of experimental research on the effect of drip irrigation system designs on the formation of irrigation regimes, productivity, and efficiency of water use by sunflower hybrids. In addition, the main components of evapotranspiration were taken into account, and coefficients of water consumption (WCC), irrigation efficiency (IE), and irrigation water use efficiency (WUE) were chosen as criteria for the efficiency of drip irrigation. Short-term field research was carried out during 2020–2022 on the lands of the Brylivske experimental field of the Institute of Water Problems and Reclamation of the National Academy of Agricultural Sciences (Kherson region, subzone of the Dry Steppe). Analytical and mathematical as well as statistical methods were used to process experimental data. The scheme of the three-factor field experiment provided various options for laying irrigation pipelines of drip irrigation systems (in the horizontal and vertical planes), as well as the implementation of a pulsed water supply mode (standard). The version with a natural moisture supply (without irrigation) was the control. The results of experimental research proved that the method of laying drip irrigation pipelines had a direct effect on the parameters of the formation of drip irrigation regimes and the productivity of sunflower hybrids in the conditions of the Dry Steppe. The mechanism of evapotranspiration formation of sunflower crops in irrigated and non-irrigated conditions has been determined. It was statistically proven that the application of subsoil drip irrigation with the laying of irrigation pipelines at a depth of 0.3 m and a distance between them of 1.0 m is the most appropriate for growing sunflower hybrids. This is explained by biological features, namely drought resistance of this crop. Thus, in field experiments, the variant with in-soil laying of drip irrigation pipelines provided almost identical yield (4.01–4.09 t/ha) when having lower crop water consumption coefficients (1088.7–1125.7 m^3/t) and higher efficiency of irrigation water use – 2.27–2.41 kg of grain per 1 m^3 of irrigation water.*

Key words**:** *drip irrigation, subsoil drip irrigation, water consumption coefficient, irrigation efficiency coefficient, evapotranspiration, irrigation regime, sunflower*

Relevance of research. Over the past decades, the agricultural sector of the southern region of Ukraine has reoriented itself to the cultivation of drought-resistant, highly liquid, and marginal crops. In this regard, sunflower has a leading place, as this crop occupies the largest cultivated areas. Thus, as of 2021, sunflowers occupied about 20% or 6.43 million ha of the total crop structure [1]. Such dynamics can be considered negative, as it does not meet the requirements of scientifically based crop rotations and reduces soil fertility [2; 3; 4]. At the same time, the climate change trend towards aridity [5; 6; 7] is a significant factor in the further increase in the cultivated area of this crop. It is obvious that this path of development is extensive. An alternative and, at the same time, intensive direction is the application of irrigation. Over the past 5–10 years, the irrigated areas under sunflowers have grown dynamically and by 2022 they amounted to more than 70.000 hectares, of which more than 90% was under sprinkling [8].

The "Strategy of Irrigation and Drainage in Ukraine" [9] defines that the development of irrigation should be based exclusively on a new, water- and energy-saving concept. Micro-irrigation methods are ideal for this: drip irrigation with above-ground and underground placement of irrigation pipelines, as well as pulsed drip irrigation. Because of this, the conducted research on the substantiation of irrigation regimes and determination of the efficiency of water use by sunflower hybrids under drip irrigation is relevant.

Analysis of recent research and publications. Both domestic and foreign scientists have conducted a fairly significant set of studies aimed at studying the water regime and effectiveness of irrigation for sunflowers. In Ukraine, these experiments were carried out mainly when using sprinkler irrigation [10; 11; 12], while foreign scientists paid considerable attention to the cultivation of sunflowers by applying drip irrigation. They, in particular, specified the optimal parameters of the water regime [13], evapotranspiration and water use efficiency [14], growth processes and productivity on saline soils [15], and when using mineralized water for irrigation [16]. In the Steppe zone of Ukraine, very little attention has been paid to the efficiency of water use by sunflower crops under drip irrigation, and some local experiments were conducted by the Institute of Irrigated Agriculture of the National Academy of Agricultural Sciences [17; 18].

Therefore, **the research aimed** to specify the actual regimes of drip irrigation, and crop productivity and determine the efficiency of water use by sunflower hybrids depending on different designs of drip irrigation systems.

Research materials and methods. Field research was carried out within the land of the EE "EF "Brylivske" of the Institute of Water Problems and Land Reclamation of the National Academy of Agricultural Sciences (Privitne village, Vynogradivska rural community of Kherson District, Kherson Region, Dry Steppe subzone, 46°40' n. 33°12' e.) during 2020–2022. The parameters of the soil water regime were studied depending on the following designs of irrigation systems: drip irrigation (DI) with surface laying of irrigation pipelines (IP), and subsoil drip irrigation (SDI) with laying of IP to a depth of 30 cm. In addition, the design parameter was the distance between IP, which was 0.7 and 1.4 m. The variant of subsoil drip irrigation with pulsed water supply mode (PSDI) was reference, and the conditional control was the variant with natural moisture supply – without irrigation. The research was carried out according to generally accepted methods: placement of plots – systematic, repetition – four times, area of record plots – 32 m^2 [19; 20], sunflower hybrids for confectionery use – Ukrainian F1 and Rimisol F1.

The soil of the experimental site is a dark chestnut light loam, the density of the 0–50 cm layer is 1.47 g/cm^3, humus content is 1.44%, alkaline hydrolyzed nitrogen content (determination method by Kornfield) (DSTU7863:2015, 2016) is 7.0 mg/100g of soil, mobile compounds of phosphorus and potassium content (determination method by Chirykov) (DSTU4115:2002, 2003) is 32.3 mg/100g and 9.3 mg/100g of soil, respectively.

The amount of productive precipitation during the growing season of sunflowers was different during the years of research. Thus, in 2020, it was only 68 mm, which is 35.5% of the climatic norm, in 2021 it was 393.8 mm or 205.5%, which is also an abnormal phenomenon for the conditions of the Dry Steppe, and in 2022 r. it was 167.6 mm or 87.5% of the climatic norm. The rate of antecedent soil water in experiments was 80% of the minimum moisture-holding capacity of the 0–50 cm soil layer. The following tools were used to determine the timing of watering: the Drill and Drop Sentek moisture meter probe and the iMetos soil moisture station with Echo Probe EC-5 sensors [21]. Statistical analysis of research results was carried out by dispersion, correlation, and regression methods using the Statistica 6.0 program.

Research results and their discussion. Data on crop evapotranspiration (ETs), and sunflowers in particular, are the basis for specifying irrigation regimes [22]. The study of irrigation regimes and ETs parameters based on the method of soil water balance showed that the water regime and ETs were formed depending on the initial soil moisture reserves, productive precipitation during the growing season, and irrigation elements – structures of drip irrigation systems (method of laying IP) (Table 1).

Meteorological conditions of the growing season (primarily productive precipitation) significantly influenced the formation of evapotranspiration (ETs). For example, for the Ukrainian F1 hybrid in the extremely dry year 2020 (68 mm of precipitation) on the irrigated experimental plots, the share of precipitation in the formation of evapotranspiration was from 9.2% to 13.1%. At the same time, in the abnormally wet 2021 (393.8 mm), the share of precipitation in the formation of ETs increased sharply – up to 65.8–73.4%. In the moderately dry year (2022), the share of precipitation in the formation of ETs was from 23.5% to 31.0%. For a more correct analysis of the data on the evapotranspiration of sunflower crops, data for individual years were averaged. It was determined that, on average, for 2020–2022, on the irrigated experimental plots, productive precipitation and irrigation water formed ETs in almost equal proportions. Thus, the share of irrigation water was in the range from 39.2% (subsoil irrigation, the distance between IP was 1.0 m) to 45.8%, and productive precipitation – from 41.3% (drip irrigation,

1. Drip irrigation regimes, evapotranspiration (ETs), and yield of sunflower hybrids (2020–2022)

Variant of experiment			Number of waterings	Irrigation rates, m³/ha	Precipita-tion, m³/ha	Soil mois-ture, m³/ha	ETs, m³/ha	Yield, t/ha
A factor	B factor	C factor						
Rimisol F1	DI	0.7	18	1960	2098	670	4728	4.19
		1.4	14	2313		827	5238	3.70
	SDI (–30 cm)	1.0	13	1667		597	4362	4.01
		1.4	11	1872		490	4460	3.64
	control (W/I)		–	–		840	2938	1.59
Ukrainian F1	DI	0.7	19	2140		624	4862	4.41
		1.4	14	2427		557	5082	3.91
	SDI (–30 cm)	1.0	14	1803		703	4604	4.09
		1.4	11	1963		563	4624	3.69
	control (W/I)		–	–		950	3048	1.66
Impulse mode of water supply when applying subsoil drip irrigation								
Ukr. F1	PSDI (–30 cm)	1.0	148	2222	2098	530	4850	4.50

the distance between IP was 1.4 m) up to 45.6% (subsoil irrigation, the distance between IP was 1.0 m) (Figure 1).

Naturally, productive precipitation was the basis of ETs formation on the control variant of the experiment (without irrigation) – 68.8%, while the share of soil moisture was only 31.2%.

One of the important criteria for determining the efficiency of water use by plants is the so-called water consumption coefficient (WCC) – the ratio of total water consumption to the formation of a unit of the yield of productive organs of a certain crop [23]. An additional criterion for determining the efficiency of irrigation measures is water use efficiency (WUE) [24, 25] and the irrigation efficiency coefficient (IEC) [26]. The irrigation efficiency coefficient is the physical amount of irrigation water that provides an increase in the yield of a unit of productive organs compared to non-irrigated conditions, and the efficiency of irrigation water use is the total amount of agricultural products produced by a unit of used irrigation water.

To analyze the efficiency of water use by sunflower hybrids, three coefficients were calculated (Table 2) [25].

According to the calculations given in Table 2, the highest water consumption for the formation of a product unit (WCC was equal to 1839.8–1848.8 m³/ton) was in the control plot in non-irrigated conditions. On the other hand, water was more effectively used by sunflower hybrids on the plot with sub-soil laying of irrigation pipelines (–30 cm), where the weighted average coefficient of water consumption was equal to 1157.55 m³/t (hybrid Rimisol F1) and 1189.95 m³/t (hybrid Ukrainian F1); 1.94–2.41 and 1.88–2.27 kg of grain were got for 1 m³ of irrigation water, respectively. In these variants of the experiment, the irrigation efficiency coefficient was 688.8–913.2 m³ of irrigation water for obtaining an additional ton of grain yield of Rimisol F1 hybrid and 742.0–967.0 m³ of water for obtaining 1 ton of grain of Ukrainian F1 hybrid.

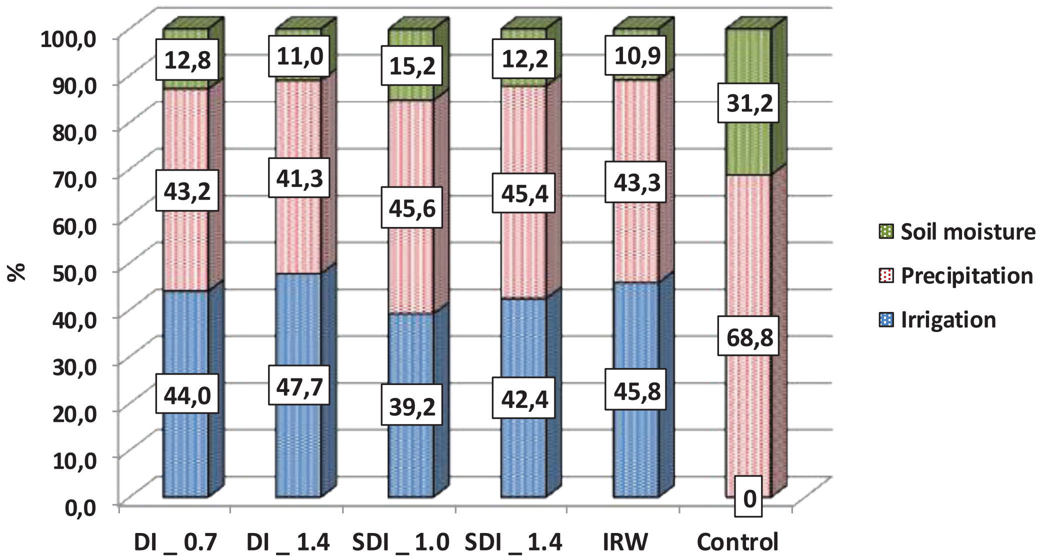

Fig. 1. The structure of evapotranspiration (ETs) formation for the Ukrainian F1 sunflower hybrid, depending on design of micro-irrigation systems (the method of irrigation system laying)

2. Efficiency of water use by sunflower hybrids depending on the designs of drip irrigation systems (2020–2022)

Variant of experiment			ETs, m³/ha	Water consumption coefficient, m³/t	Irrigation efficiency coefficient, m³/t	WUE, kg/m³	Yield, t/ha
A factor	B factor	C factor					
Rimisol F1	DI	0.7	4728	1127.5	753.8	2.14	4.19
		1.4	5238	1414.4	1096.2	1.60	3.70
	SDI (–30 cm)	1.0	4362	1088.7	688.8	2.41	4.01
		1.4	4460	1226.4	913.2	1.94	3.64
	control (W/I)		2938	1848.8	–	–	1.59
Ukrainian F1	DI	0.7	4862	1102.5	778.2	2.06	4.41
		1.4	5082	1298.6	1078.7	1.61	3.91
	SDI (–30 cm)	1.0	4604	1125.7	742.0	2.27	4.09
		1.4	4624	1254.2	967.0	1.88	3.69
	control (W/I)		3048	1839.8	–	–	1.66
Search experiment – pulse mode of water supply when applying subsoil drip irrigation (2021–2022)							
Ukr. F1	SDI (–30 cm)	1.0	4850	1077.8	782.4	2.05	4.50

A certain “intermediate” place was occupied by the variants of a field experiment with the surface laying of irrigation pipelines, namely: 1127.5–1414.4 m³ and 778.2–1078.7 m³ of water were used for the formation of 1 ton of sunflower seeds of Rimisol F1 and Ukrainian F1 hybrids, respectively. For 1 m³ of irrigation water, an additional 1.60–2.14 kg of sunflower seeds of Rimisol F1 hybrid and 1.61–2.06 kg of Ukrainian F1 hybrid were obtained, and 753.8–1096.2 m³ and 778.2–1078.7 m³ of irrigation water were used to form 1 ton of additional products, respectively.

The search variant with a pulse water supply mode for subsoil drip irrigation was the most expedient (effective) from the point of view of total water consumption. Thus, only 1077.8 m³ of moisture was spent on the formation of 1 ton of sunflower seeds. However, slightly less production (2.05 kg of grain) was obtained per 1 m³ of irrigation water than when applying the usual subsoil regime of irrigation. The coefficient of irrigation efficiency also had a certain tendency to increase the consumption of irrigation water to obtain additional production from irrigation (IEC = 782.4 m³/t).

Conclusions. The results of experimental research proved that the method of irrigation pipelines laying of drip irrigation systems has an effect on the parameters of irrigation regime formation and the yield of sunflower hybrids in the conditions of the Dry Steppe zone. It was proved that the application of subsoil drip irrigation with the IP laying to a depth of 0.3 m with a distance between the pipelines of 1.0 m is the most appropriate for growing sunflower hybrids, which is explained by the drought resistance of this crop. In the field experiments, the variant with sub-soil laying of irrigation pipelines provided almost identical yield (4.01–4.09 t/ha) with lower crop water consumption coefficients (1088.7–1125.7 m³/t) and higher efficiency of irrigation water use (WUE – water use efficiency) – 2.27–2.41 kg of grain per 1 m³ of irrigation water.

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РЕЖИМИ КРАПЛИННОГО ЗРОШЕННЯ ТА ЕФЕКТИВНІСТЬ ВИКОРИСТАННЯ ВОДИ ГІБРИДАМИ СОНЯШНИКУ

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Анотація. *У статті наведено результати експериментальних досліджень із вивчення впливу конструкцій систем краплинного зрошення на формування режимів зрошення, продуктивності та ефективність використання води гібридами соняшнику. За цього враховано основні складові евапотранспірації, а у якості критеріїв ефективності краплинного зрошення обрано коефіцієнти водоспоживання (КВ), ефективності зрошення (Кез) та ефективності використання поливної води (WUE – water use efficiency). Польові короткотермінові дослідження проведено протягом 2020–2022 рр. на землях Брилівського дослідного поля Інституту водних проблем і меліорації НААН (Херсонська область, підзона Степу Сухого). Для обробки експериментальних даних використано аналітичні та математично-статистичні методи. Схемою трифакторного польового експерименту було передбачено різні варіанти укладання поливних трубопроводів систем краплинного зрошення (у горизонтальній та вертикальній площині), а також реалізація імпульсного режиму водоподачі (еталон). Контрольним був варіант з природним вологозабезпеченням (без зрошення). Результатами експериментальних досліджень доведено, що спосіб укладання поливних трубопроводів систем краплинного зрошення достовірно впливав на параметри формування режимів краплинного зрошення та врожайність гібридів соняшнику в умовах Степу Сухого. Встановлено закономірності формування структури евапотранспірації посівів соняшнику у зрошуваних та незрошуваних умовах. Статистично доведено, що впровадження підґрунтового краплинного зрошення з укладанням поливних трубопроводів на глибину 0,3 м і відстанню між ними 1,0 м є найбільш доцільним за вирощування гібридів соняшнику. Це пояснюється біологічними особливостями, а саме – посухостійкістю цієї культури. Так, у польових дослідах варіант із внутрішньогрунтовим укладанням поливних трубопроводів краплинного зрошення забезпечив практично ідентичні параметри врожайності (4,01–4,09 т/га) за нижчих коефіцієнтів водоспоживання культури (1088,7–1125,7* $м^3$*/т) та вищій ефективності використання поливної води– 2,27–2,41 кг зерна на 1* $м^3$ *поливної води.*

Ключові слова: *краплинне зрошення, підґрунтове краплинне зрошення, коефіцієнт водоспоживання, коефіцієнт ефективності зрошення, евапотранспірація, режим зрошення, соняшник*

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ANALYSIS OF THE HYDROCHEMICAL REGIME OF THE DNIPRO RESERVOIRS

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Abstract. *A complex of issues was considered, namely: hydro-chemical pollution of catchment landscapes, bottom sediments of river basins and groundwater, slowing down of underground flow due to the regulation of the river network, regional development of flooding, presence of landscapes contaminated with radionuclides, and the growth of global climate change. All above as well as the ongoing war in the territory of Ukraine affect the conditions of the formation of the hydro-chemical regime and contribute to the changes in the quantitative and qualitative water indicators in the Dnipro River basin and the Dnipro reservoirs, as the main sources of water supply for Ukraine. The research determined the changes in the hydro-chemical regime of the surface water of the Dnipro reservoirs during 2016–2022 to specify the impact of climate change and anthropogenic factors on the drinking water supply. The dynamics of changes were analyzed for individual qualitative indicators of the surface water of the Dnipro reservoirs in the cold (January) and warm (July) months of the year. It was proven that the accumulation of flood water affects the mineralization of the Dnipro reservoirs along their longitudinal axis, and the mineralization rate and the content of the main ions are significantly affected by the water content of the year. It was established that, in the Dnipro reservoirs, the lower limit of mineralization relative to natural conditions increased by 55%, and the upper limit decreased by 30%. It was determined that despite the seasonal changes in the concentration of ions in the water of the Dnipro reservoirs, their ratio for each reservoir remains practically constant and only sometimes changes in the case of a shift in the carbonate balance and in the confluence of more mineralized waters, which increase the content of* Mg^{2}, Na^{+}, K^{+}, *and* SO_4^{2-}. *The predominant water cation is* Ca^{2+}, *the anion is* HCO_3^{-}, *and the absolute and relative content of other ions is much smaller. The metamorphism of the water of the Dnipro reservoirs changed the ratio of ion concentrations, namely the relative amount of* SO_4^{2-}, Cl^{-}, Na^{+}, *and* K^{+} *ions increased. The obtained results of changes in the quality indicators of surface water in the Dnipro reservoirs have proved the dependence of the formation of the hydro-chemical regime of the reservoirs on the impact of climate change, economic activity, and the consequences of military actions.*

Keywords: *water resources, reservoir, Dnipro, river basin, water quality*

Relevance of research. Global climate change, which is manifesting in a change in the amount of atmospheric precipitation, an increase in the amount of evaporation due to global warming, an increase in anthropogenic load, and unbalanced water use affect the hydrochemical composition of the Dnipro reservoirs water.

Based on hydro-ecological zoning, where hydrogeological structures with dynamic parameters are decisive, hydrochemical pollution of catchment landscapes, bottom sediments of river basins and groundwater, slowing down of underground flow due to the river network regulation, regional development of flooding, presence of radionuclide-contaminated landscapes, and the increasing effect of global climate change become very important, as all these contribute to the change in the conditions of the formation of the hydrochemical regime, which in its turn leads to a change in the quantitative and qualitative characteristics of water the Dnipro River basin.

Russia's full-scale war in Ukraine, starting in February 2022, directly affected the quality of the country's water resources: water intake facilities, water supply, and drainage treatment facilities, water supply networks were destroyed, dams were blown up and water was supplied to Crimea without complying with regulatory standards. The hostilities harmed the water quality of the Dnipro River and Dnipro reservoirs, as the main sources of Ukraine's water supply. Therefore, an urgent

task is to identify a mechanism of changes in the hydrochemical composition of the Dnipro water, primarily the water of the Dnipro reservoirs to characterize the state of water resources, which will enable to specify the possibility of using the water of the reservoirs as a source of drinking water supply.

Analysis of recent research and publications. The formation of water quality of the Dnipro River is changing significantly as a result of the impact of climate change, ongoing hostilities, and the economic activity in the territory of Ukraine.

Back in the 50s of the 20^{th} century O.O. Alekin [1], the author of "Fundamentals of Hydrochemistry" revealed the general foundations of studying the chemical composition of river water in the territory of the former USSR, the unity of chemical processes occurring in all natural waters, the systemic conditioning of a complex of natural and anthropogenic factors. When the scientific school of hydrochemical research was developed, the process of hydrochemical regime formation and hydrological characteristics were described. The study of the total anthropogenic impact on the chemical composition of the water of the Dnipro River basin and its reservoirs as well as the differentiated assessment of the impact was given attention to [2–5]. Research on changes in the water quality of the Dnipro River basin is thoroughly covered in the works of V.I. Vyshnevsky, hydrological and hydrochemical characteristics – in the works of O.I. Denysova, processes of formation of the chemical composition of surface waters of reservoirs – in the works of P.M. Lynnyk [6–12]. N.M. Osadcha, V.D. Romanenko, V.M. Timchenko, V.K. Khilchevskyi, et al. developed research on the hydrochemistry of regional basin systems, among which the main place was occupied by both the Dnipro basin as a whole and the basins of some of its tributaries [13–16], however, in the last decade there was a need to update the available data.

The requirements of the EU Water Framework Directive 2000/60/EC in the Dnipro River Basin Management Plan (within Ukraine) [17] provide for ensuring a good ecological and chemical state for surface water bodies and performing an analysis of the hydro-chemical regime of reservoirs to implement actions aimed at improving the hydro-ecological situation in the basin, avoiding degradation of regenerative and cleaning capacity of water ecosystems, and establishing the restrictions on water use [18].

The purpose of the research is to specify the mechanism of changes in the hydro-chemical composition of water in the Dnipro reservoirs to characterize the state of water as a source of drinking water supply.

Research materials and methods. Empirical and theoretical methods of scientific research were used, namely collection and analysis of quantitative and qualitative indicators of surface water of the Dnipro reservoirs. The conditions of water use from the Dnipro reservoirs are defined by DSTU4808:2012 "Sources of centralized drinking water supply. Hygienic and ecological requirements for water quality and water withdrawal rules", as well as by the State sanitary standards and rules "Safety indicators and separate indicators of the quality of drinking water in conditions of martial law and emergencies of a different nature" (DSanPiN No. 683) developed for martial law conditions [19; 20].

The change in some quality characteristics of the surface water of the Dnipro reservoirs in 2016–2022 was determined at 6 observation posts, which are characterized by the largest range of data: 1 post – Kyiv Reservoir (Dnipro River, 897 km, Vyshhorod town, tail-water of the Kyiv HPP, Kyiv city potable water intake); 2 post – Kaniv reservoir (Dnipro River, 854.5 km, 500 m downstream the Bortnytska aeration station); 3 post – Kremenchug Reservoir (Dnipro River, 678 km, Sokyrne village, potable water intake of Cherkasy city); 4 post – Kamyanske Reservoir (Dnipro River, 550 km, Horishni Plavni town, town potable water intake); Post 5 – Dnipro Reservoir (Dnipro River, 328 km, Zaporizhzhia city, headwater of the Dnipro HPP, city potable water intake); Post 6 – Kakhovka Reservoir (Dnipro River, 106 km, Lyubymivka village, MPS of the Kakhovka Canal).

Surface water samples were taken by the monitoring service of the State Water Resources Agency of Ukraine and the Central Geophysical Observatory named after Borys Sreznevskyi, the analysis was carried out by an accredited laboratory by general sanitary chemical parameters: the content of ammonium ions (NH_4^+), mg/dm³, hydrogen indicator, units of pH, water hardness, mg-eq/dm³, total iron (Fe_{tot}), mg/dm³, dissolved oxygen, mgO_2/dm^3, color, degree, total alkalinity, mg-eq/dm³, the content of magnesium ions (Mg^{2+}), mg/dm³, nitrate- (NO_3^-) and nitrite- (NO_2^-) ions, mg/dm³, sulfate ions (SO_4^{2-}), mg/dm³, dry residue (dissolved substances), mg/dm³, phosphate ions (PO_4^{3-}), mg/dm³, chemical oxygen demand (COD), mgO_2/dm^3, chloride ions (Cl^-), mg/dm³.

Research results and their discussion. The hydrochemical regime of the reservoir is determined by the following factors: intensity of water exchange; the nature of the soils and vegetation in the areas of flooding and sub-flooding of the catchment area; mode of filling and drawdown of the reservoir; amplitude and intensity of water level fluctuations. An important role in the formation of the hydrochemical regime is also played by: the geographical location of the reservoir, its morphological structure, position in the cascade, atmospheric precipitation, anthropogenic factors (absorption and discharge of water, operation of hydroelectric power stations, water transport, etc.), intrareservoir hydrological and biogeochemical processes.

From the moment the reservoirs are filled, the hydrochemical composition of the Dnipro River water gradually transforms into a lake water type. This transformation is the more pronounced, the slower the water exchange is in the reservoir. Decomposition of the remains of flooded vegetation and disturbing bottom sediments during the operation of reservoirs affect the quality of water entering the upper basin of the reservoir. In reservoirs, in contrast to the river, during their lifetime, shallow, sometimes stagnant zones appeared, in which the oxygen regime deteriorates and organic substances accumulate.

Following DSTU4808:2012, surface sources with water quality of 1–3 classes are used for centralized drinking water supply, the assessment of which is obtained by hygienic and ecological criteria [19]. Within the cascade of the reservoirs, the quality of surface water by the specified indicators varies from 1 to 4 class (class 4 is observed by the content of NH_4^+, NO_3^-, NO_2^-, PO_4^{3-}, COD in separate periods), and the highest values of the average annual water quality indicators are observed by: NH_4^+ (2.775 mg/dm³), NO_3^- (18.15 mg/dm³) and NO_2^- (0.427 mg/dm³) in Kaniv reservoir, hydrogen index (8.183–8.471 units of pH), in Kyiv reservoir and (8.185–8.313 units of pH) in Kakhovka reservoir, Fe_{tot} (0.094–0.574 mg/dm³) in Kremenchuk reservoir, dissolved oxygen (6.884 mgO_2/dm^3) in Kamianske reservoir, PO_4^{3-} (0.969 mg/dm³) in Kyiv reservoir, COD (50.275 mgO_2/dm^3) in Kaniv reservoir (Fig. 1).

Within the cascade of reservoirs, the highest values of average seasonal water quality indicators in the cold period are observed by dissolved oxygen (11.075 mgO_2/dm^3) in Kyiv reservoir, the content of Ca^{2+} (69.625 mg/dm³), Mg^{2+} (22.55 mg/dm³), suspended substances (8.75 mg/dm³), NH_4^+ (0.945 mg/dm³), PO_4^{3-} (0.635 mg/dm³), Fe_{tot} (0.29 mg/dm³), SO_4^{2-} (69.8 mg/dm³), Cl^- (35.675 mg/dm³) in Kaniv reservoir, color (42 degrees) and COD (31.43 mgO_2/dm^3) in Kamianske reservoir, temperature (2.5 °C) in Kakhovka reservoir.

In the summer months, the highest average seasonal indicators are observed by temperature, the content of Ca^{2+} (49.85 mg/dm³), NH_4^+ (0.636 mg/dm³), Fe_{tot} (0.408 mg/dm³) in Kaniv reservoir, PO_4^{3-} (0.473 mg/dm³) in Kremenchuk reservoir, COD (35.978 mgO_2/dm^3), color (51.75 degrees) in Kamianske reservoir, Mg^{2+} (15.85 mg/dm³), dissolved oxygen (8.65 mgO_2/dm^3), Cl^- (35.45 mg/dm³) in Dnipro reservoir, SO_4^{2-} (52.6 mg/dm³) in Kakhovka reservoir.

Comparison of average monthly data with normative ones allowed to plot changes in the content of dissolved oxygen, mgO_2/dm^3, Fe_{tot}, mg/dm³ and COD, mgO_2/dm^3 (Figs. 2–4) [21–23].

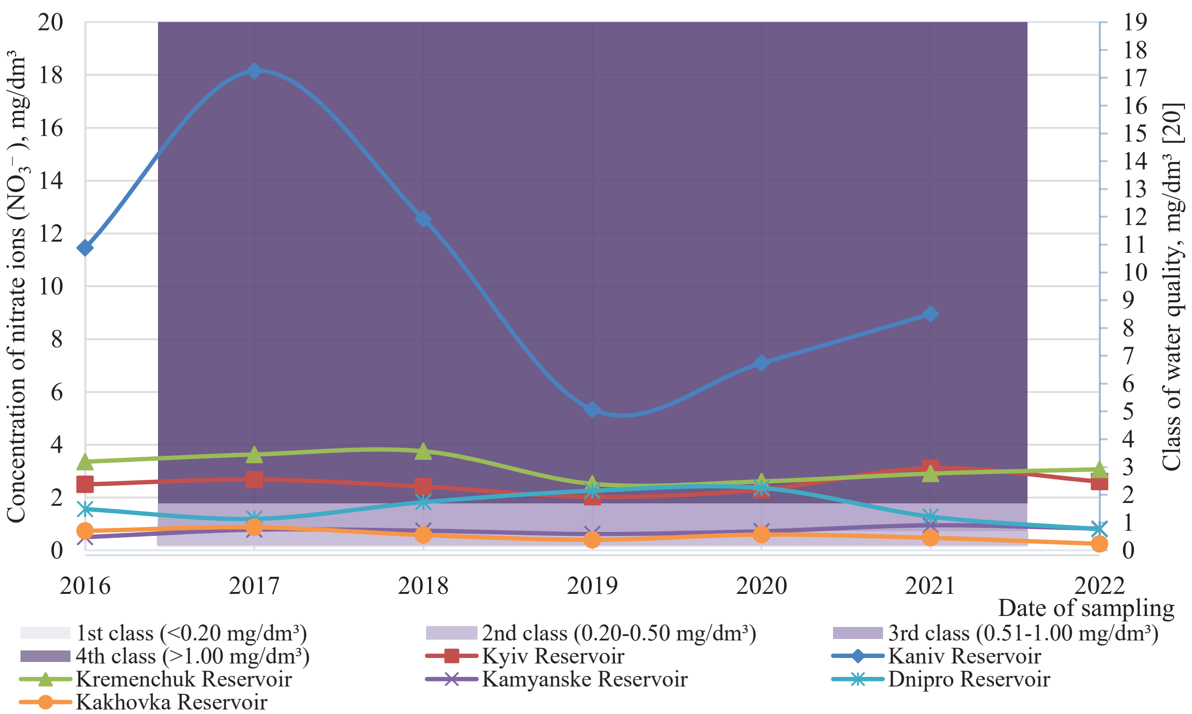

Fig. 1. Average annual change in the content of nitrate, mg/dm³, in the surface water of the Dnipro reservoirs in 2016–2022 (samples were taken from the Kakhovka reservoir in 2016–2021)

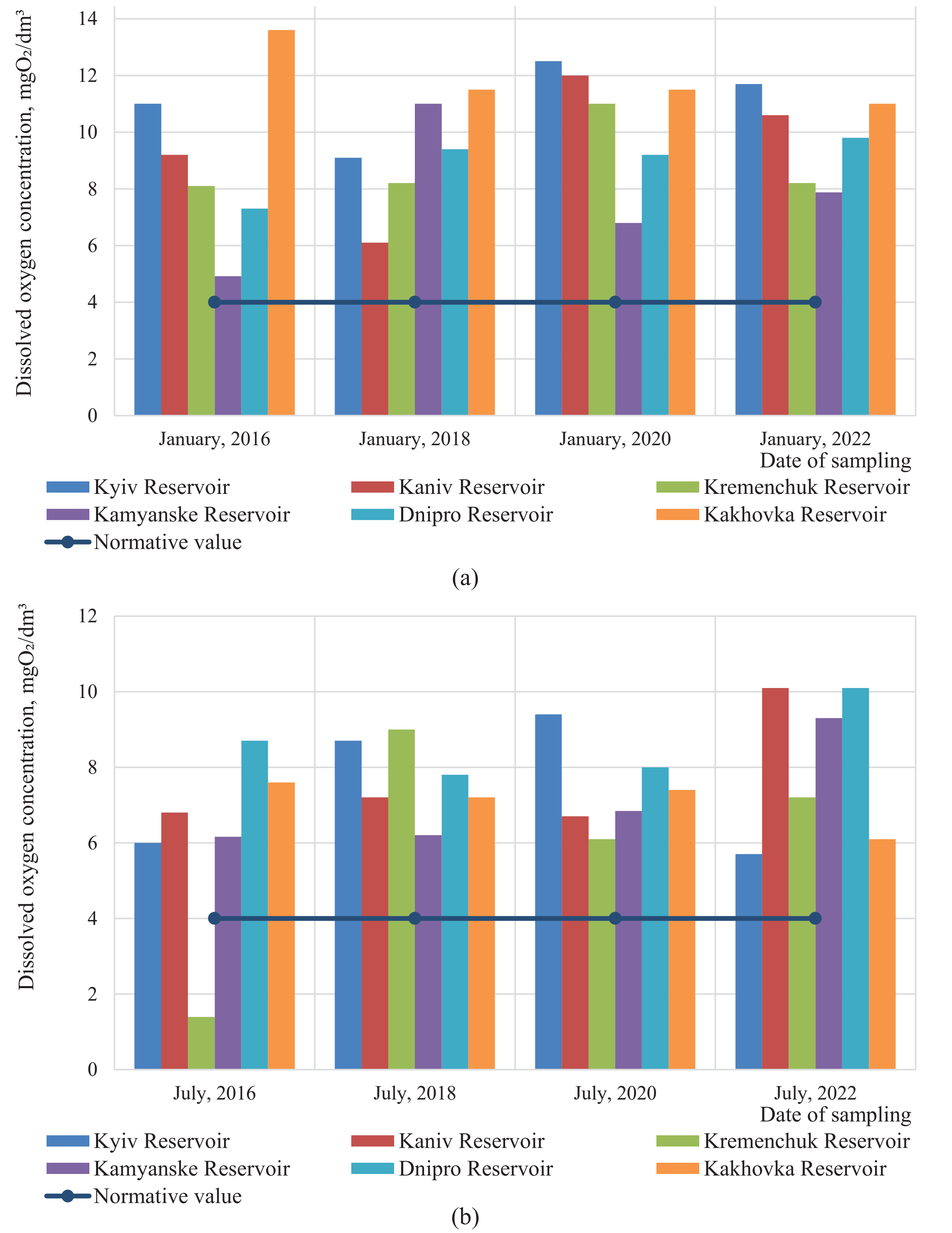

Fig. 2. Changes in the content of dissolved oxygen, mgO_2/dm^3, in the water of the Dnipro reservoirs in the cold (a) and warm (b) months of 2016–2022 (samples were collected in the warm months from the Kakhovka reservoir in 2016–2021)

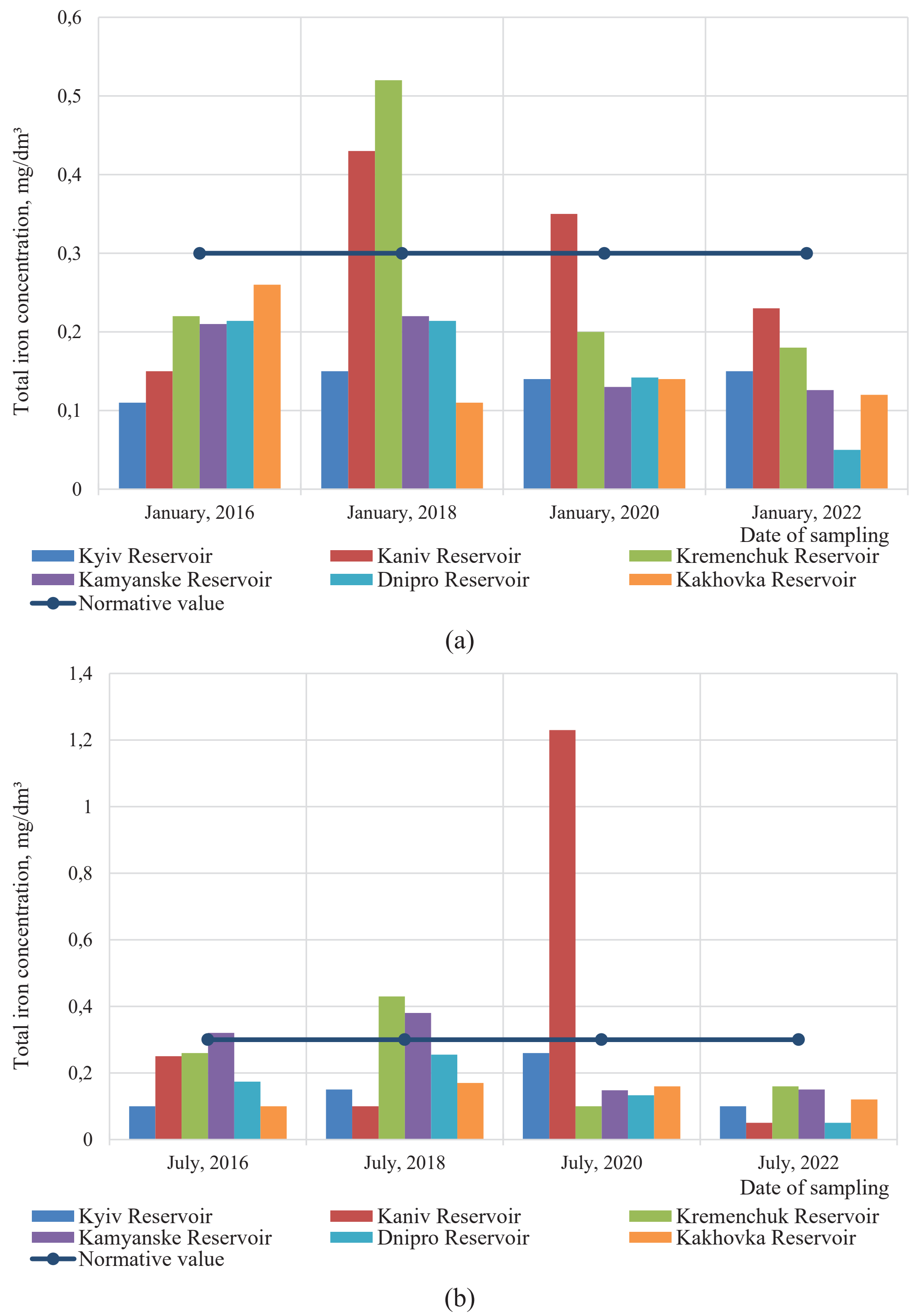

Fig. 3. Changes in the content of total iron, mg/dm³, in the water of the Dnipro reservoirs in the cold (a) and warm (b) months of 2016–2022 (samples were collected in the warm months from the Kakhovka reservoir in 2016–2021)

It is known that the construction of reservoirs leads to a seasonal or multi-year redistribution of river runoff. Changes in the dynamics of mineralization and the concentration of the basic ions occur along with the redistribution of river runoff.

As a result of the accumulation of low-mineralized floodwater in the reservoirs and their mixing with more mineralized river water arriving in subsequent seasons, the annual amplitude of fluctuations in mineralization and the concentration of individual ions decrease. The accumulation of flood water leads to a change in the mineralization of reservoirs along their longitudinal axis. The surface and bottom water

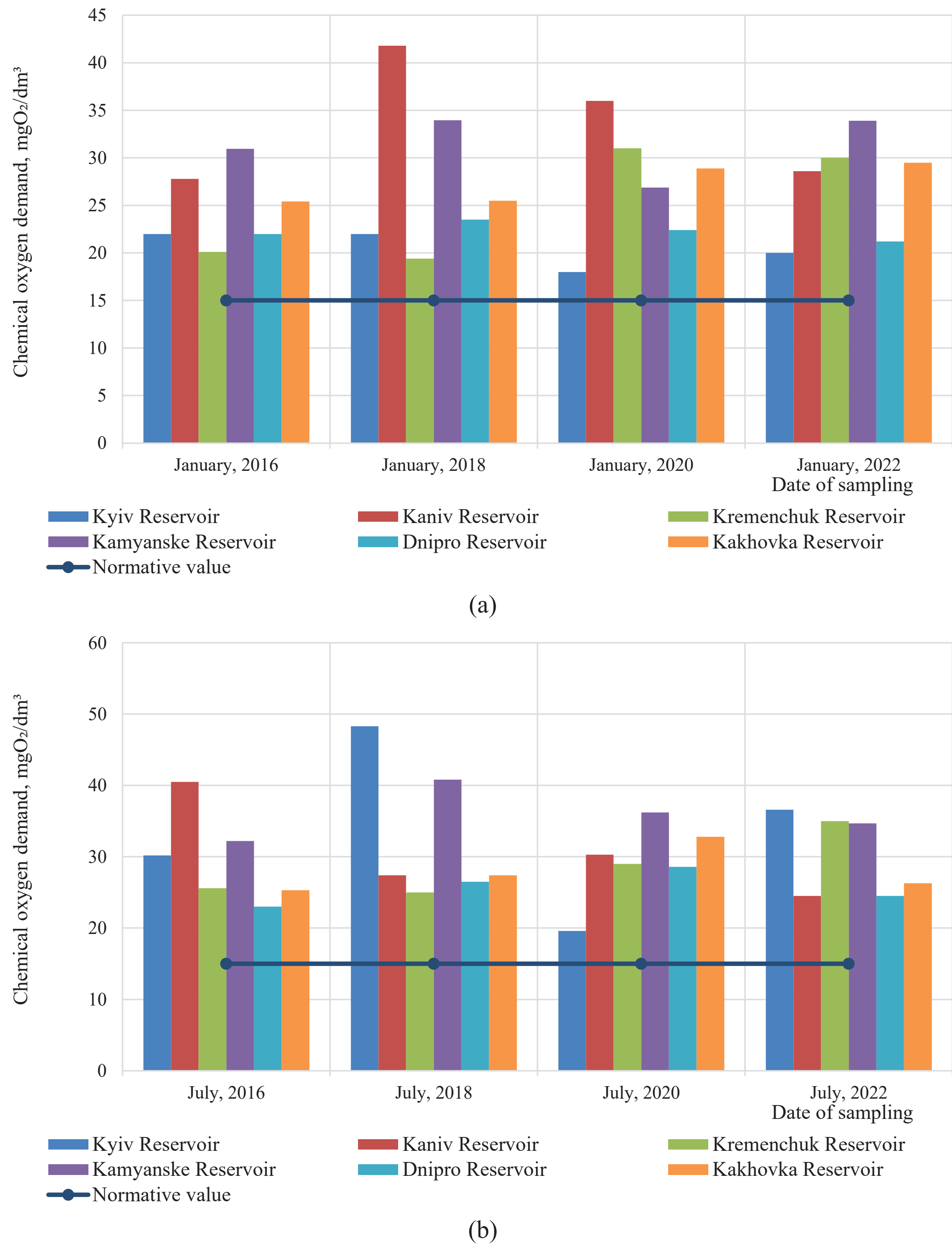

Fig. 4. Changes in COD, mgO_2/dm^3, in the water of the Dnipro reservoirs in the cold (a) and warm (b) months of 2016–2022 (samples were collected in the warm months from the Kakhovka reservoir in 2016–2021)

layers of the Dnipro reservoirs usually have the same mineralization. The level of mineralization and the content of basic ions is significantly affected by the water content of the year. In medium-water and high-water years, the water mineralization of the Dnipro reservoirs is lower than in low-water years [21]. Thus, in the Dnipro reservoirs, the lower limit of mineralization relative to natural conditions increased by 55%, and the upper limit decreased by 30%. Currently, the upper limit of mineralization down the Dnipro cascade increases from 400 mg/dm³ in the Kyiv reservoir to 460 mg/dm³ in the Dnipro reservoir (Table 1).

1. Range of the concentration of basic ions and water mineralization of the Dnipro reservoirs in 1985–2021, mg/dm³ [24]

Reservoir	Ca^{2+}	Mg^{2+}	Na^+ i K^+	HCO_3^-	CO3⁻	SO_4^{2-}	Cl^-	Sum of ions
Kyiv	17.0–70.0	5.0–27.0	5.0–25.0	106.0–246.0	0.0–15.0	11.0–89.0	1.0–29.0	196.0–394.0
Kaniv	31.0–79.0	5.0–35.0	9.0–59.0	106.0–217.0	0.0–27.0	19.0–112.0	11.0–59.0	198.0–398.0
Kremenchug	29.0–70.0	5.0–30.0	3.0–40.0	109.0–220.0	0.0–28.0	17.0–54.0	11.0–41.0	216.0–420.0
Kamyanske	29.0–59.0	5.0–17.0	9.0–35.0	88.0–219.0	0.0–12.0	20.0–54.0	17.0–31.0	171.0–393.0
Dnipro	33.0–62.0	5.0–22.0	1.0–43.0	131.0–219.0	0.0–21.0	26.0–86.0	21.0–44.0	207.0–460.0
Kakhovka	31.0–55.0	5.0–22.0	7.0–59.0	73.0–217.0	0.0–25.0	33.0–94.0	21.0–54.0	210.0–450.0

The predominant cation in the water in the Dnipro reservoirs is Ca^{2+}, and the anion is carbonate (HCO_3^-). The absolute and relative content of other ions is much lower. Despite the seasonal changes in the concentration of ions in the water of reservoirs, their ratio for each reservoir remains practically constant and only sometimes changes in the case of a shift in the carbonate balance and in the confluence of more mineralized water, which increases the content of Mg^{2+}, sodium (Na^+), potassium (K^+) and SO_4^{2-}. The metamorphism of the water of the Dnipro reservoirs changed the ratio of ion concentrations, namely the relative amount of SO_4^{2-}, Cl^-, Na^+, and K^+ ions increased.

The analysis of the obtained results proved that the position of the individual reservoir in the cascade and the features of its hydrological regime largely determine the seasonal and multi-year dynamics of water mineralization and the content of the basic ions, which change significantly along with the seasonal redistribution of the river runoff [21; 24].

Today, the surface water of the Dnipro reservoirs, as a source of water supply, is characterized by long-term and seasonal fluctuations in the chemical composition and physical properties, water pollution degree, etc., which occur under the effect of climatic change, economic activity and ongoing hostilities on some adjacent territories to the Dnipro reservoirs cascade.

Improper water use and agricultural pollution of water bodies against the background of the increase in average annual temperature led to the scarcity of water capacity of water ecosystems in the Dnipro basin and its reservoirs.

The water of the Dnipro River, as the main source of drinking water supply, was especially acutely affected by the war unleashed by Russia, namely the uncontrolled discharge of water at the Kakhovka HPP. The volume of water discharge from the Kakhovka Reservoir at the moment exceeds the filling volume; there is irrational use of water from the reservoir, which causes the need to provide alternative technological solutions for the uninterrupted operation of water intakes in the Kherson, Zaporizhzhia, and Dnipropetrovsk regions. Toxins that appear after all aquaculture in the Kakhovka Reservoir dies, which is already happening, will begin to spread and threaten other countries.

Conclusions. The conducted research on the hydro-chemical regime of the surface water of the Dnipro reservoirs for 2016–2022 showed:

– the ionic composition is dominated by hydro carbonate ions, there is a decrease in the number of calcium ions due to an increase in the concentrations of magnesium and sodium;

– there are above-limit values of certain quality characteristics of the surface water of the Dnipro reservoirs in the cold (January) and warm (July) months of the year compared to the normative ones (by the content of NH_4^+ twice, COD in three times and by color twice) [19]. In certain periods, the quality of the surface water of the Dnipro reservoirs corresponds to 4 class 4 by the content of NH_4^+, NO_3^-, NO_2^-, PO_4^{3-}, and COD [20].

The obtained data proved the need to improve water treatment technologies with the use of biological methods of water treatment, the use of membrane technologies, etc.

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АНАЛІЗ ГІДРОХІМІЧНОГО РЕЖИМУ ДНІПРОВСЬКИХ ВОДОСХОВИЩ

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Анотація. *Розглянуто комплекс питань, а саме: гідрохімічне забруднення водозбірних ландшафтів, донних відкладів річкових басейнів та ґрунтових вод, уповільнення підземного стоку внаслідок зарегулювання річкової мережі, регіональний розвиток підтоплення, наявність забруднених радіонуклідами ландшафтів, зростання глобальних змін клімату, за яким зміна умов формування гідрохімічного режиму та війна на території України сприяють зміні кількісних та якісних показників водних ресурсів у басейні річки Дніпро та дніпровських водосховищ, як основного джерела водопостачання України. Дослідженнями визначено зміни гідрохімічного режиму поверхневих вод дніпровських водосховищ упродовж 2016–2022 років для встановлення впливу кліматичних змін та антропогенних чинників на питне водопостачання. Проаналізовано динаміку змін окремих якісних показників поверхневих вод дніпровських водосховищ у холодні (січень) та теплі (липень) місяці року. Засвідчено, що накопичення повеневих вод продовжує призводити до зміни мінералізації дніпровських водосховищ по їх повздовжній осі, а на її рівень та вміст головних іонів значно впливає водність року. Встановлено, що, на дніпровських водосховищах нижня межа мінералізації відносно природних умов підвищилась на 55%, а верхня – знизилась на 30%. Визначено, що незважаючи на сезонні зміни концентрацій іонів у воді дніпровських водосховищ, їх співвідношення для кожного водосховища залишається практично сталим і лише інколи змінюється в разі зміщення карбонатної рівноваги та в місцях впадіння більш мінералізованих вод, які збільшують вміст Mg^{2}, Na^{+}, K^{+} і SO_4^{2-}. Переважним катіоном води є Ca^{2+}, аніоном – HCO_3^{-}, абсолютний і відносний вміст інших іонів значно менший. Метаморфізація вод дніпровських водосховищ змінила співвідношення концентрацій іонів: підвищилась відносна кількість іонів SO_4^{2-}, Cl^{-}, Na^{+}, K^{+}. Отримані результати зміни якісних показників поверхневих водних ресурсів у дніпровських водосховищах підтвердили залежність формування гідрохімічного режиму водосховищ від впливу кліматичних змін, господарської діяльності та наслідків військових дій.*

Ключові слова: *водні ресурси, водосховище, Дніпро, річковий басейн, якість води*

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PROSPECTS AND PROBLEMS OF USING LOCAL WATER RESOURCES FOR IRRIGATION IN THE BASINS OF SMALL RIVERS OF THE FOREST-STEPPE OF UKRAINE

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Abstract. *On the example of a separate agricultural farm located in the basin of the small Manzhelia River within the Left Bank Forest Steppe, the approaches to the selection of potential sources of irrigation and the specifics of determining the volumes of local water resources intended to be used for irrigation, as well as the areas of possible irrigation in the absence of existing irrigation systems, are given. The results of the research indicate that the prospects for the development of land irrigation on farmland can be mainly provided subject to the combined use of surface runoff accumulated in ponds on the Manzhelia River and groundwater admissible for extraction, taking into account their quality. It was determined that influenced by a complex of anthropogenic factors, the river runoff sharply decreased compared to natural conditions, and the feeding of river course ponds during the entire low water period occurs only due to lateral inflow. Based on calculations it was determined that in average and low-water years, the volumes of surface and ground inflow to the cascade of ponds for the period from June to September are smaller than evaporation losses. Under such conditions, the use of the river runoff for irrigation is possible only due to the accumulation of flood and, partially, high water runoff. The calculations of flood runoff volume for March – April at the gate of the lower pond indicate the impossibility of using water from it for irrigation in very low-water years, as well as the dependence of runoff use for irrigation in low-water years on the pre-flood filling level of the ponds. It was determined that up to 0.8 million m^3 of water can be used for irrigation in medium-water years, and up to 1.4 million m^3 in high-water years, which will provide irrigation on an area of 400 and 700 hectares, respectively (having an irrigation rate of 2000 m^3/ha). The possibility of installing at least 40 water intake wells within the territory of the farm with a total flow rate of 20–24 thousand m^3/day and a total water intake during the irrigation period of about 1.5 million m^3 has been substantiated. This will make it possible to irrigate 750 hectares of land having an irrigation rate of 2000 m^3/ha, and at least 1000 hectares having an irrigation rate of 1500 m^3/ha. It is focused on the mandatory preliminary investigation of water quality for irrigation, which for many small rivers and aquifers is a limiting factor when using local water resources for the construction of irrigation systems.*

Key words**:** *water resources, climate change, irrigation, groundwater, river runoff, river course ponds, water quality*

Formulation of the problem. Climate change, primarily the progressive increase in its aridity in all natural and climatic zones of Ukraine, significantly worsens the conditions of the natural water supply for crop production. It increases the need for irrigation on an increasing number of land plots [1–3]. The need to restore and increase the areas of actual irrigation is emphasized in the “Irrigation and Drainage Strategy in Ukraine for the period until 2030” [4].

At the same time, climatic transformations have a significant negative impact on the provision of the territories with water resources, which manifested in the reduction of the water content of rivers and reservoirs, their shallowing, lowering of the groundwater level, deterioration of water quality, etc. [5–7]. This makes it difficult to choose reliable sources of irrigation, especially in the basins of small rivers, due to the significant distance of potential irrigation areas from large reservoirs and irrigation canals.

Such a situation is now particularly typical for the territory of the forest-steppe zone of Ukraine. A significant increase in the average annual air temperature was recorded within its area, which exceeded the climatic norm (1961–1990) by almost 3.0°C in 2019 (one of the warmest years), and there was almost unchanged insignificant amount of precipitation. Thus, in 2019, its annual amount in the zone was 73% of the norm on average, and in some regions, it did not exceed 50% of the rate. Therefore, in recent years, in the forest-steppe zone, there has been a tendency both to restore irrigation of land on existing irrigation systems and to apply irrigation in new areas, primarily in Vinnytsia, Cherkasy, and Poltava regions, using different methods and sources of irrigation. In addition, the choice of the latter is a rather urgent problem from the point of view of providing the necessary water volumes of appropriate quality from them, especially in the context of the impact of climatic transformations on water resources.

The features of choosing potential sources of irrigation, determining the volume of local water resources that can be used for irrigation, as well as the area of possible irrigation under transformed climatic conditions in the forest-steppe zone were considered on the example of LLC "Promin-Lan", a separate agricultural farm located in the basin of the small Manzhelia River within Kremenchuk (until 2020 – Globynsk) district of Poltava region.

Analysis of recent research and publications. Some scientific works [1; 2; 5–16] were devoted to certain aspects of climate change and the resulting decrease in water resources available for use, which negatively affects the natural water supply of soils in various physical and geographical zones of Ukraine. Ukrainian climatologists observe the gradual "migration" of climatic zones to the north (on average by 100 km when average annual air temperature increases by 1°C) [9; 10]. A significant increase in air temperature and the frequency of abnormally high temperatures in the summer months led to a sharp increase in evaporation from the land and water surface, which, having a relatively stable amount of precipitation, negatively affected the water balance of river catchments. The decrease in river runoff and the shallowing of water bodies has become a characteristic phenomenon for almost all plain regions of Ukraine [13–16]. For example, the runoff coefficient (the ratio of the runoff layer to precipitation) of the Irpin River for the period from 2015 to 2019 decreased by 1.7 times compared to the period before 2010 [17].

The shallowing of surface water bodies and the depletion of groundwater, the reduction of fresh water available for use is recognized by the recently adopted Water Strategy of Ukraine for the period until 2025 [18] as one of the main problems in the area of water use, protection, and restoration.

The issue of using the flow of small rivers to ensure the development of irrigation in their basins, taking into account the transformation of climatic conditions, the current ecological state of water bodies, their water (hydrological and hydrochemical) regime, etc., is currently poorly researched, and the available publications mainly relate to determination and evaluation of the changes in some of these indicators or characteristics, rather than the actual water resource potential of small rivers and underground waters. The implementation of the procedure for assessing the impact on the environment of planned activities related to the design and construction of irrigation systems, following the Law of Ukraine "On Environmental Impact Assessment" [19] became a certain stimulus for researching determining the latter and possible volumes of its use for irrigation.

It should be noted that in Ukraine at the end of the 20th century and the beginning of the current century, there were more than 63.000 small rivers (about a third was in the forest-steppe zone), 93% of which had a length of less than 10.0 km with the prevailing catchment areas from 200 up to 500 km^2 [20; 21]. Significant transformations of the water regime in catchment areas caused by climate change and economic activity have caused a significant deterioration in the ecological condition of small rivers. Regulation of their runoff as a result of the construction of numerous ponds and reservoirs led to a sharp decrease in river runoff, degradation of rivers, and sometimes to their complete disappearance [14–16; 22–26].

In this regard, the use of runoff from small and medium-sized rivers for irrigation nowadays requires the study of both conditions of surface runoff formation and its quantitative and qualitative assessment as well as its intra-annual distribution. The same applies to groundwater.

The purpose of the research is to quantitatively assess local water resources and determine the prospects for the development of irrigation with surface and underground water at the LLC "Promin-Lan" farm of the Kremenchuk district in the Poltava region.

Research materials and methods. Today, the farm cultivates about 1.7 thousand hectares of leased land, scattered on both sides of the Manzhelia River near the village of Vesela Dolyna. The Manzhelia River is a right tributary of the Psel River and belongs to the Middle Dnieper sub-basin of the Dnieper River basin area. The length of the river is now 23 km, and the catchment area is 117 km^2. The river bed is winding, 0.5–3.0 m wide, on average 2 m. The river is fed through snow, rain, and soil. Surface rain and melt inflow come mainly through numerous ravines and gullies, as well as small streams, which mostly dry up in the low water periods. The Manzhelia River is an anthropogenically altered water body due to its significant regulation with ponds (11 ponds). A cascade of four ponds has been arranged on the river flowing through the farmlands. As of the end of 2019, only one pond from the four ones was filled with water – № 4 (Fig. 1).

In terms of hydrogeology, the area of the land plots of Promin-Lan LLC belongs to the Dnieper-Donetsk artesian basin, in particular the Dnieper artesian basin of the II order with the spread of some aquifers and complexes in the Neopleistocene, Pliocene, Kharkiv, and Kaniv-Buchatsk deposits within the zone of active water exchange.

Research on determining potential sources of irrigation, volumes of surface and underground water that can be used for irrigation farm plots, as well as the areas of possible irrigation included determining the runoff of the Manzhelia River, assessing the impact of anthropogenic factors on the state of water bodies, the presence of groundwater for irrigation and the quality of surface and underground waters regarding their suitability for irrigation, establishing modern morphometric and bathymetric parameters of artificial reservoirs in the river course, determining the expediency and possibility of cleaning the riverbed, silted and overgrown reservoirs to increase the river runoff.

Methodologically, the research was based on field surveys of water bodies and their adjacent territory, system and cartographic data analysis, Earth remote sensing materials, and hydrological calculations. Assessment of water quality for irrigation according to agronomic criteria was carried out by the provisions of DSTU2730:2015 [27].

Research results and their discussion. The performed hydrological calculations show that the natural runoff of the Manzhelia River is characterized by significant unevenness of its distribution throughout the year. The spring period accounts for more than 70% of the annual runoff, while in the summer months, it is less than 5%. It was determined, that under the influence of a complex of anthropogenic factors, the river

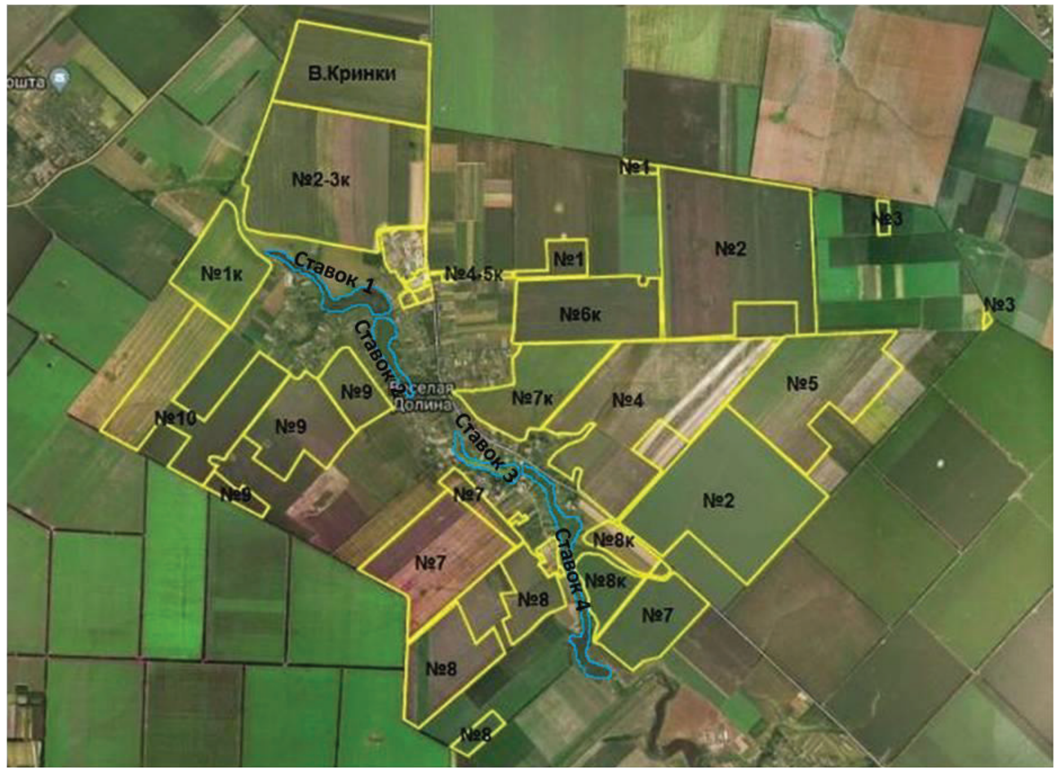

Fig. 1. Scheme of field location within the land plots used by Promin-Lan LLC and ponds on the Manzhelia River near the village of Vesela Dolyna of the Kremenchuk district in the Poltava region

runoff decreased sharply compared to natural conditions, and the constructed artificial river course ponds turned into closed reservoirs, the feeding of which during the entire low water period occurs only due to lateral inflow, that is, from the local part of the catchment directly adjacent to them. Inflow from the upper reaches of the catchment occurs only during floods and heavy rain floods. Selective in-situ measurements in the beds of the ponds proved that the latter are silted up on average up to 30–40 cm in the central part and up to 50–70 cm in the near-dam areas. There are no bottom drains in the ponds, so they are not washed. Due to significant siltation and frequent drying out of reservoirs, the main sources of soil and pressure feeding are silted up and mudded.

The value of the natural average annual runoff, determined based on the regionalized map of the average long-term runoff module, built based on long-term observations at stationary hydrological stations, for each pond and side tributary, is given in Table 1.

The rates given in Table 1 show the average multi-year values of runoff, however, its volumes significantly differ both by year and in different months and seasons throughout the year. Thus, according to the observation data at the Myrhorod hydrological station in the basin of the Khorol River, on average for the long-term period since 1919, 58.9% of the runoff, i. e. more than half, arrives in March – April period. During the next six months of the growing season (from May to October inclusive), only 25.2% of the annual runoff arrives, and the part of the runoff for the last three months of the period is only 7.3%.

The possibility of using surface water from the cascade of ponds in the river course of the Manzhelia River largely depends on the water content of the year, the levels of pre-flood filling of the ponds, and the groundwater tables. The assessment of the intra-annual runoff distribution of the Manzhelia River was made based on zoned values (as a percentage of the annual) for the Vorsklo-Pselsky hydrological district [28]. Calculations were made for four ranges of river water content: high (P = 25%), medium (P = 50%), low (P=75%), and very low (P = 95%). The results of calculations for different cross-river points are shown in Fig. 2. It was determined that under the current anthropogenically changed conditions of runoff formation, the inflow of water to the dam site of the lower pond № 4for four months from June to September will be 45 thousand m^3 in a high-water year, in a medium-water it will be 31 thousand m^3, in a low-water year it will be 23 thousand m^3, and in an extremely low-water year, it will be 14 thousand m^3 (Table 2).

Table 2 shows the results of calculating the inflow to the ponds in the summer-autumn period, taking into account the annual distribution of the runoff of the Manzhelia River and the actual catchment areas of each of the ponds, testify that even in high-water years, the total lateral inflow during the warm period of the year to all four ponds in the village Vesela Dolyna will be only 192.000 m^3. In extremely low-water years, when the greatest need for irrigation arises, the total inflow into the ponds will be 115.000 m^3, in particular, for the entire summer period – only 26.000 m^3. The total area of the four ponds is about 50 hectares, and the total evaporation in the basin during the summer period is equal to 220 mm, accordingly, the evaporation from the surface of the ponds will be 110 thousand m^3, which is more than four times higher than the inflow to the ponds. A practically zero balance of summer inflow and evaporation will be observed only in high-water years.

In the case of restoration of the natural flow of the river as a result of clearing the riverbed and ponds from the source of the river to the dam site, the corresponding volumes of runoff for the period from June to September will increase to 211 thousand m^3 in a high-water year, to 149 thousand m^3 in a medium-water year, in low water-year – up to 106 thousand m^3 and in extremely low water-year – up to 66 thousand m^3.

1. Catchment areas and water inflow rates of the Manzhelia River before the specified cross river points

Pond №	Distance from the mouth of the Manzhelia River, km	Total catchment area, ha	Local catchment area, ha	Natural average annual runoff, m^3/s	Local (lateral) average annual runoff, m^3/s
Pond dam №0	22.7	2251	2251	0.038	
Pond dam №1	20.5	3376	1125	0.057	0.019
Pond dam №2	19.6	3626	250	0.062	0.004
Pond dam №3	18.3	4102	476	0.070	0.008
Pond crossing dam № 4	16.3	5218	1116	0.089	0.019
Pond dam №4	15.9	5600	382	0.095	0.006

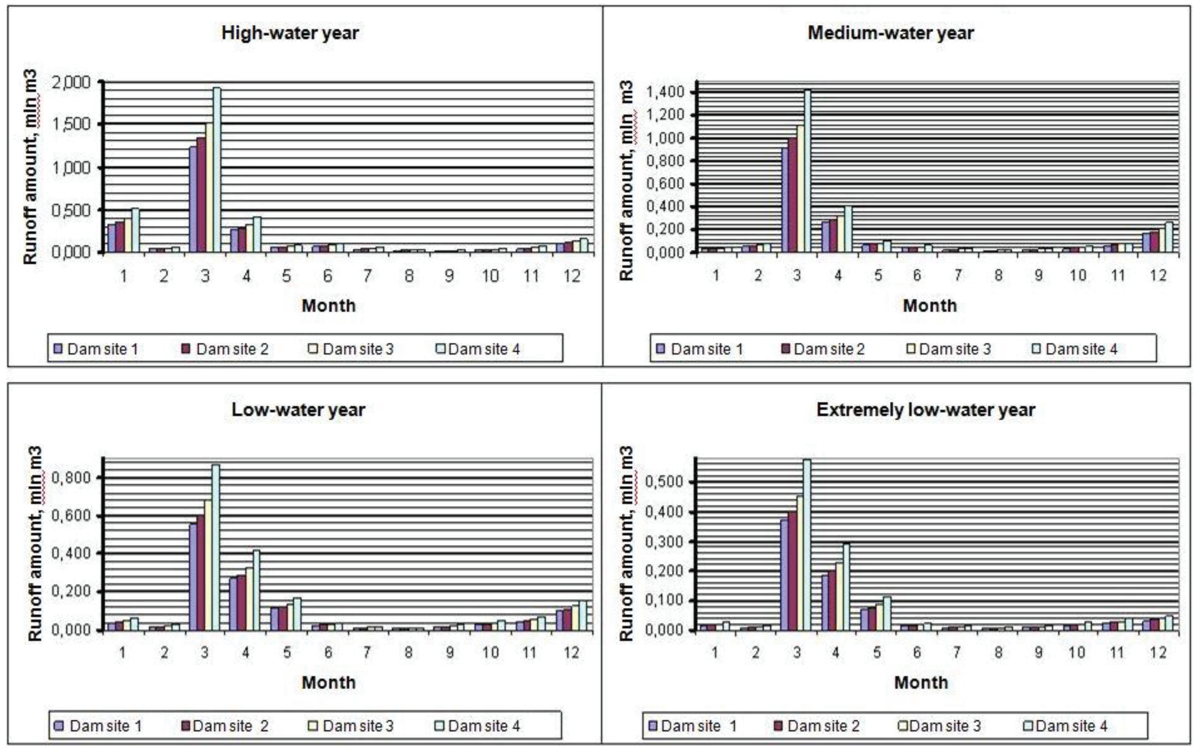

Fig. 2. Intra-annual distribution of the Manzhelia River runoff in the specified cross river points in different water content years, million m^3

2. Distribution of intra-annual inflow to river course ponds on the Manzhelia River for the period from May to November, million m^3

Month	May	June	July	August	September	October	Total amount
High-water year, P=25%							
Dam 1	0.019	0.022	0.011	0.007	0.005	0.009	0.073
Dam 2	0.004	0.005	0.002	0.001	0.001	0.002	0.015
Dam 3	0.008	0.009	0.005	0.003	0.002	0.004	0.031
Dam 4	0.019	0.022	0.011	0.007	0.005	0.009	0.073
In total							0.192
Medium-water year, P=50%							
Dam 1	0.022	0.013	0.007	0.004	0.007	0.012	0.065
Dam 2	0.005	0.003	0.002	0.001	0.002	0.003	0.016
Dam 3	0.009	0.005	0.003	0.002	0.003	0.005	0.027
Dam 4	0.022	0.013	0.007	0.004	0.007	0.012	0.065
In total							0.173
Low-water year, P=75%							
Dam 1	0.037	0.009	0.005	0.003	0.006	0.010	0.070
Dam 2	0.008	0.002	0.001	0001	0.001	0.002	0.015
Dam 3	0.015	0.004	0.002	0.001	0.003	0.004	0.029
Dam 4	0.037	0.009	0.005	0.003	0.006	0.010	0.070
In total							0.184
Extremely low-water year, P=95%							
Dam 1	0.024	0.005	0.003	0.002	0.004	0.006	0.044
Dam 2	0.005	0.001	0.001	0.000	0.001	0.001	0.009
Dam 3	0.010	0.002	0.001	0.001	0.002	0.002	0.018
Dam 4	0.024	0.005	0.003	0.002	0.004	0.006	0.044
In total							0.115

Since the greatest need for irrigation water occurs in low-water years, the clearing of silted riverbed and ponds for irrigation is not very effective, as it will provide an insignificant additional water inflow in low water (by 83 thousand m^3) and extremely low water (by 52 thousand m^3) years. At the same time, cleaning the ponds from silting will allow increasing both their useful volume and the lateral inflow of runoff due to the opening of pressure-feeding sources. Thus, clearing the pond № 4 of siltation up to 0.6 m will increase its useful volume by 108.000 m^3.

Calculations have determined that in medium and low-water years, the volumes of surface and soil inflow to the cascade of ponds near the village of Vesela Dolyna for the period from June to September are very small, and evaporation losses are smaller. Under such conditions, the use of river runoff for crop irrigation is possible only due to the accumulation of surface and, partially, flood runoff.

The performed calculations show that in extremely low-water years (P = 95 %) the runoff volume for March – April at the cross point of pond № 4 is only 870 thousand m^3, which is commensurate with the total volume of the cascade of four ponds within the village (865 thousand m^3), and in low-water years (P = 75 %), the flood runoff volume will be 1.284 million m^3, that is, the transit runoff outside the cascade will be only 419 thousand m^3. Accordingly, in very low-water years, the use of water for irrigation will be impossible due to the need to provide partial water transit to downstream ponds. In low-water years, the possibility of using runoff for irrigation will be determined by the pre-flood filling level of the ponds. The use of runoff for irrigation in the volume of up to 400.000 m^3 will be possible only when the pre-flood filling of the ponds is more than half. In case of pre-flood emptying of the ponds to dead volume levels, water withdrawal for irrigation will be impossible due to the need to provide sanitary spring discharges and fill the downstream ponds.

In medium-water (P = 50 %) and high-water (P = 25 %) years, the volume of the river runoff for March – April will be 1.84 million m^3 and 2.35 million m^3, respectively. Taking into account that the filling of ponds will be high in medium and high-water years, up to 0.8 million m^3 of water can be used for irrigation in medium-water years, and up to 1.48 million m^3 – in high-water years, which will allow providing irrigation on an area of 400 and 700 hectares respectively, having an irrigation rate of 2000 m^3/ha).

Therefore, the calculations of the volume of flood runoff for March – April at the cross point of the lower pond indicate the impossibility of using water from it for irrigation in extremely low-water years, as well as show the dependence of the use of runoff for irrigation in low-water years on the pre-flood filling level of the ponds.

In low-water periods, the groundwater tables in the Manzhelia River basin in the summer-autumn period are below the usual banked-up water level of ponds. Thus, in the autumn of 2019, the recorded groundwater table in the area of the pond between the villages of Stepove and Vesela Dolyna was on average 2.0 m below the bottom of the pond, therefore, in cases of a significant decrease in groundwater tables, significant water losses may occur in the ponds due to intensive filtration on replenishment of groundwater.

To use the accumulated volumes of runoff in the summer months, it is necessary to develop filling ponds, which should be filled during the flood period. Filtration losses and, accordingly, the intensity of the decrease of pond levels in the post-flood period depend on the groundwater table in the adjacent territory, which must be taken into account when planning water intake for irrigation.

The main technical measures to increase the water content of the Manzhelia River include the following:

– clearing and deepening to the base level of the riverbed in the upper reaches of the Manzhelia River;

– restoring the riverbed of the Manzhelia River between the Stepove and Vesela Dolyna villages with the construction of a tubular crossing in its river course;

– clearing and deepening to the base level of the southern part of river course pond № 1 (1/3 of the length and area) within the village of Vesela Dolyna in the middle course of the Manzhelia River, which will provide a decrease in the area of evaporation from the water surface while preserving its useful volume;

– clearing and deepening the pond № 3 within the village of Vesela Dolyna;

– restoring to service water culverts and discharge structures on ponds and in the Manzhelia river course within the villages of Syrenky and Stepove;

– restoring to service the culverts of ponds № 1, 2, 3, and 4 within the village of Vesela Dolyna in the middle course of the Manzhelia River.

Prospects for irrigation development on farmland in general can be based on the use of both surface and underground water. The availability of underground water and the possibility of its use for irrigation are determined, first of all, by the hydrogeological conditions of the territory and the suitability of water for irrigation in terms of its quality.

The analysis of the general hydrogeological conditions and filtration parameters of the main aquifers proves the possibility of using groundwater mainly from Lower Neopleistocene alluvial deposits, primarily on the right bank of the river and north of the settlement, i. e. within the distribution of this aquifer for irrigation of the land cultivated by Promin-Lan LLC near the village Vesela Dolyna. It is also possible to have a compatible water intake from Buchach sediments. Within the fields located to the east of the village (№ 2, 4, 5) and related to the V terrace, it is advisable to consider the prospects of using the water of the Pliocene alluvial horizon.

Taking into account water supply and water quality, the main potential source of irrigation with groundwater on the "Promin-Lan" farm can be an aquifer in the Lower Neopleistocene alluvial deposits, which lies at a depth of 30–40 m with an average capacity of 10 m. Its productivity allows local water intakes from the wells with a discharge rate of from 300 to 600 m^3/day (approximately at a distance of 300 m from each other) in the form of linear rows or concentrated points around the places of accumulation of produced water. Within individual fields with an area of 150–200 hectares, it is possible to arrange water intakes from 12–15 wells with a total discharge from 3.6–4.5 to 7.0–9.0 thousand m^3/day.

The use of groundwater for irrigation on the land of "Promin-Lan" LLC is possible provided that it is previously accumulated in storage tanks, the volumes of which are determined during irrigation design. It is advisable to arrange storage reservoirs near the places of groundwater extraction and the location of potential irrigation areas. As preliminary options, it is proposed to construct such reservoirs in the territory of dairy farms № 1 and № 2, as well as in the area of the natural decline in the western part of the village behind the garden near the field № 9. As of 2022 a groundwater storage reservoir and four water intake wells were built near farm № 2 (near the pond № 4).

Based on the water supply capacity of aquifers, territorial possibilities, and minimization of the general spatial decrease of groundwater tables due to water intake for irrigation, within the area of the farm, at least 40 water intake wells with a total discharge rate of 20–24 thousand m^3/day and a total water withdrawal during the irrigation period of about 1.5 million m^3 can be arranged. That will make it possible to irrigate 750 hectares of land with an irrigation rate of 2000 m^3/ha, and at least 1000 hectares can be irrigated with an irrigation rate of 1500 m^3/ha.

Based on the results of selective hydrochemical studies, it was determined that the limiting factor for the use of both surface and underground water for irrigation in certain areas may be its low quality due to alkalization (II class – limitedly suitable) and soil salinization (III class – unsuitable) according to DSTU2730:2015 [27], which requires additional assessment of water quality and implementation of water and irrigated land reclamation measures.

Conclusions. The increase in the aridity of the climate in the forest-steppe zone of Ukraine leads to a growing need for irrigation, as the most effective means of minimizing the negative impact of climate change on the sustainability and efficiency of agriculture in this region.

The main limiting factors for the expansion of irrigation areas in the forest-steppe zone are the relatively low natural supply of local water resources in the basins of small rivers, the limited suitability of surface and underground water for irrigation due to soil alkalization and salinization, toxic effects on plants, as well as (primarily for drip irrigation systems) due to high iron content. In the basins of many small rivers, there is a high probability of a situation when small amounts of local water resources or their low quality will limit the areas of possible irrigation, up to the emergence of competition for water and conflict situations, especially in low-water periods.

The decision on the possibility, prospects, and scope of irrigation application in the basins of small rivers of Ukraine should be based on the results of a comprehensive assessment of the possible accumulated volumes of river runoff in artificial reservoirs and the amount of groundwater permissible for withdrawal, taking into account their quality. Therefore, priority should be given to the construction of drip irrigation systems in the areas located near water sources, such as ponds or suitable places for water storage reservoirs, primarily underground.

According to expert assessments, the available local water resources are sufficient to provide irrigation for 10–20 % (1.3–2.6 million hectares) of arable land in the Forest-Steppe zone.

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ПЕРСПЕКТИВИ ТА ПРОБЛЕМИ ВИКОРИСТАННЯ МІСЦЕВИХ ВОДНИХ РЕСУРСІВ ДЛЯ ЗРОШЕННЯ В БАСЕЙНАХ МАЛИХ РІЧОК ЛІСОСТЕПУ УКРАЇНИ

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Анотація. *На прикладі окремого агрогосподарства, розташованого в басейні малої річки Манжелія в межах Лівобережного Лісостепу, наведено підходи до вибору потенційних джерел зрошення та особливості визначення обсягів місцевих водних ресурсів, які можуть бути використані для поливу, а також площ можливого зрошення за відсутності існуючих зрошувальних систем. Результати досліджень свідчать, що перспективи розвитку зрошення земель у господарстві можуть бути пов'язані переважно з сумісним використанням накопиченого в ставках на річці Манжелія поверхневого стоку та допустимих для вилучення підземних вод з урахуванням їхньої якості. Визначено, що під впливом комплексу антропогенних чинників стік річки різко зменшився порівняно з природними умовами, а живлення руслових ставків упродовж усього меженного періоду відбувається лише за рахунок бокового притоку. Розрахунками визначено, що в середні за водністю і маловодні роки об'єми поверхневого і ґрунтового притоку до каскаду ставків за період із червня по вересень є меншими ніж втрати на випарування. За таких умов використання стоку річки для зрошення можливе лише за рахунок акумуляції повеневого і, частково, паводкового стоку. Розрахунки об'єму повеневого стоку за березень – квітень у створі нижнього ставу свідчать про неможливість використання води з нього для зрошення у дуже маловодні роки, а також залежність використання стоку для зрошення у маловодні роки від рівня передповеневого наповнення ставків. Визначено, що у середньоводні роки для зрошення можна буде використати до 0,8 млн м³, а в багатоводні до 1,4 млн м³ води, що дозволить забезпечити зрошення на площі 400 га і 700 га відповідно (при нормі зрошення 2000 м³ /га). Обґрунтовано можливість влаштування у межах території розташування господарства не менше 40 водозабірних свердловин із сумарним дебітом 20–24 тис. м³/добу та загальним водовідбором протягом зрошувального періоду близько 1,5 млн м³. Це дозволить за норми зрошення 2000 м³/га поливати 750 га земель, а за норми зрошення 1500 м³/га – не менше 1000 га. Акцентовано на обов'язковому попередньому дослідженні якості води для зрошення, яка для багатьох малих річок та водоносних горизонтів є лімітуючим чинником використання місцевих водних ресурсів для влаштування зрошувальних систем.*
Ключові слова: *водні ресурси, зміни клімату, зрошення, підземні води, річковий стік, руслові ставки, якість води*

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TILLAGE EFFECTS ON SOIL FUNCTIONAL PROPERTIES: A REVIEW

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Abstract. *Soil is the foundation of all-natural production systems. There is a necessity to study the management systems impact on soil functional properties and crop productivity in response to climate change effects. Our review was conducted using published databases of Ukrainian and worldwide peer-reviewed publications, including high-quality databases in Scopus, Web of Science, ResearchGate, Ukrainian specialized publications, and other web sources to evaluate the effects of tillage, with- and without cropping diversity, cover crops, and chemigation, on soil functional properties associated with soil health and crop productivity. Globally used different types of tillage practices (plowing vs. no-till) affect soil biology, nutrient cycling and organic matter accumulation, water, nutrient, and air ecosystems, changes in the soil structural and hydrological properties, and factors responsible for soil erosion and degradation were evaluated. The relevance of the research is appropriate due to global climate change and the transition of farmers converting from plowing to minimum tillage technologies, including no-till in order to achieve economic crop production with enhanced agroecosystem services. While both plowing and minimum tillage technologies have contrasting benefits and limitations, there is a lacking of consistent advantages of one tillage technology over the other one to support economic crop production, regenerate soil health, and enhance agroecosystem services. Currently, no-till technologies are increasingly adopted by farmers in Ukraine; however, farmers are looking for evidence-based knowledge and the government to remove roadblocks. The issue is increasingly becoming more relevant in connection with climate change effects, which require further studies.*
Key words: *climate change, soil health, cover crop, chemigation, Scopus, Ukraine*

The relevance of the study. Soil is a complex dynamic ecosystem essential to support and provide ecosystem services. Currently, agricultural soils are under the immense pressure of intensification to achieve food security to meet the demands of increasing population growth in the world. In response to the effects of global climate change on ecosystem productivity, the study of the influence of management and environmental factors on the soil-plant-water systems is becoming urgent. There is a need for a comprehensive review of scientific research on changes in soil's performance under various tillage systems. It is expected to allow improving current and upcoming new management practices to modernize the compatibility of the agricultural production systems and create market opportunities for various produce and commodities. The improved soil cultivation technologies in conjunction with minimum or zero-tillage, precision fertilization and chemical protection against pests and diseases, land reclamation and adaptation of sustainable practices, and proactive genetics, breeding, and biotechnology are expected to regenerate or maintain soil's capacity to support crop production.

Analysis of recent research and publications. Currently, scientists around the world [10; 28; 58] emphasize the need to minimize soil cultivation (plowing) or adaptation of conservation tillage to improve soil health by enhancing biological diversity, increasing soil organic carbon sequestration, accumulating essential plant nutrients, improving soil structural stability, controlling soil erosion, and decreasing soil compaction and greenhouse gas emissions. It is believed that conventional tillage-induced subsoil compaction (plow pan) is a detrimental consequence to affect soil hydrological properties, crusting and poor infiltration, secondary salinization and drought, and restricted root growth of plants. It is reported that frequent cultivation that contributes to the loss of plant available moisture, depletion of soil organic carbon, and reduction of soil biodiversity and efficiency, leading to degraded soil functional properties [5; 41]. As a result, the agrogenic (regenerative) activities of the soil severely affected over time [8].

Changing from frequent and intensive plowing to conservation tillage is an environmentally compatible and economically viable approach to regenerate soil health with increased ecosystem services (Fig. 1). With conservation tillage especially zero or no-till, undisturbed surface accumulation of crop residue acts as a mulch to improve biodiversity, decrease soil temperature and evaporation, and store moisture for a longer period of time [50]. Potential benefits include enhanced fungal dominance in food webs, increased carbon sequestration, accumulation of nutrients, reduced greenhouse gas emissions, improved soil aggregate formation, decreased soil erosion, and ameliorate soil health [38; 50]. In contrast, it is reported that the no-till transition process is slow, especially in the first few years which can lead to debatable results depending on the type of soils and crops [7; 54]. Several studies have reported that it may take about 5 to 6 years to overcome the no-till transition process and achieve the expected results on soil's performance [20; 30]. Islam et al. [30] suggested that introducing cover crops into the crop rotation, as one of the measures to improve the no-till adaptation and performance while residues exerted positive effects to increase albedo – protect soil against overheating, prevent capillary loss of moisture from deeper soils, retain carbon, promote biodiversity, and improve functional properties associated with soil health.

Several studies [23; 40] have emphasized that the prospects of modeling the critical processes associated with the influence of tillage operations on changes in the functional properties of soil, and argued that the use of the concept of its homeostasis will be a holistic approach to evaluate soil's performance [8]. The proactive nature of the concept is explained by the fact that its change has an energetic nature – it is the intensity of subordinate processes of transformation of external energy flows of matter. Any changes in soil properties, for example, compaction, lead to a different level of soil enrichment with surface energy, and accordingly, the availability of moisture and nutrients to plants. The availability of water and nutrients to plants depends on the level of homeostasis: the higher soil homeostasis, that is, the use of the flow of external energy in it, the higher the availability of plant nutrition and water availability from the soil. Soil homeostasis, as a manifestation of the interaction of the thermodynamic system of the soil with the environment, depends on three components: the structure of the soil, as a design of the thermodynamic system, the presence of requirements as a working body in the system, and the intensity of external weather disturbances. The approach of homeostasis is promising to consider most of the factors affecting the soil's performance – tillage, irrigation, fertilization, climate changes, etc. [8].

Despite the relevance of research, there are no existing national programs to support the implementation of minimum or no-till practices. Based on practical experiences to achieve sustainable production, these technologies are greatly needed to implement for diverse soils and climate zones in Ukraine. The goal of our research was to evaluate the impact of various tillage systems and crop rotation with cover crops on the dynamics of soil functional properties.

Fig. 1. Effects of conventional- and no-tillage practices on soil health

Research materials and methods. The methodology of our research was based on published databases of Ukrainian and worldwide publications, including high-quality databases of peer-reviewed literatures in Scopus, Web of Science, ResearchGate, Ukrainian specialized publications, and other web sources, by keywords. All the selected publications were sorted out by title and abstract, and then by a full text available for review against the specified keywords. Duplicate articles have been removed. About 22% of the non-English-language articles published in other journals were included in the study.

Research results and their discussion. *The influence of soil cultivation on changes in its properties.* It is widely suggested that minimum tillage combined with crop residue mulching is be a promising agricultural management practice to ameliorate soil properties to support increased crop productivity [34]. As noted by researchers [6; 15], the zonal features of the minimum tillage are determined by the features of the soil cover. Tillage minimization is recommended on soils with an equilibrium antecedent density close to the optimum level for growing field crops; on these soils, the intensity of cultivation may be minimum, and certain methods may be discarded altogether [3; 16]. Minimum tillage or no plowing is a promising and easy-to-implement approach on well-drained structurally stable and potentially fertile soils, particularly chernozems. Also, minimum tillage is a highly effective agromelioration method for the retention and preservation of soil moisture and precipitation for a longer period of time [14]. A number of studies indicated that the annual soil moisture-accumulating effect is 30–50 mm, which contributes to the stabilization of processes, especially during severe drought events. Therefore, the most promising zone for the introduction of minimum tillage or no-till is the Steppe zones and a large part of the Right Bank Forest Steppe of Ukraine [2; 11; 13; 17].

Quirk [46] investigated that the soil moisture dynamics, in particular the processes of wetting and drying, freezing and thawing, and plant water consumption that underlie the soil physical properties. Potential impacts included changes in soil hydrological processes and water flows, including the timing and magnitude of surface runoff, discharge of runoff and percolation, and evaporation, which may affect other environmental variables, including the flow of nutrients and sediments [52].

Russell [6] indicated that when the soil oxygen concentration drops to 9–12%, plant root growth significantly affected, and when oxygen content is less than 5%, it stops functioning altogether. The absorption of water and nutrients by plants via roots significantly decreased with increasing soil anaerobiosis (oxygen content (9–12%). Plants respond to oxygen deficiency during their maximum vegetative growth: winter plants – before and during earing; roots and tubers – during the formation of their productive organs and deposition of nutrients in them. Leguminous crops responded critically, because, in addition to root respiration, they require oxygen for bacteria that exist on it in symbiosis and absorb atmospheric nitrogen, which is later transformed into nitrogen compounds available to plants [4]. Hula et al. [35] reported that frequent tillage operations can contribute to soil erosion along the slopes. It is suggested that with minimum tillage, the off-site movement of soil particles from slopes can be fixed at a shorter distance than with the plowing.

A field experiment at the Institute of Sugarcane in India (ICAR-Indian Institute of Sugarcane Research, Lucknow), where different tillage technologies and their influence on soil hydrological properties were studied, results showed that plowing to different depths (45–50 cm and 25–30 cm depths) increased porosity and the soil bulk density decreased when compared to minimum tillage. Thus, at a depth of 0–15 cm, the bulk density decreased by more than 6% during the budding phase of the sugarcane plants. Likewise, the highest nitrogen uptake of 158.5 kg/ha was recorded in plowed treatment; besides, increased soil biological and chemical properties along with sugarcane yield [32].

Based on the results of a three years study, both minimum tillage and plowing increased the moisture holding capacity by 3.1 to 7.9% at 0–200 cm soil depths, when compared to the transitional no-till. The highest water holding was reportedly between 100–200 cm depth, while deep plowing showed the highest moisture holding at 0–100 cm depth. In contrast, the yield and protein content of grain were lower with minimum tillage and deep plowing when compared to the no-till [29].

Field research was conducted to study the different methods of main tillage by chiseling with different types of chisels looseners and plowing effect on the agro- and water-physical indicators of light chestnut soil, results showed that the methods of main tillage had better regulating impact on the agro- and water-physical condition of the soil with a significant impact on crop productivity [36; 37]. Other studies [12] conducted over a period of 11 years indicated that while the mesoporosity was more developed in the plowed soil, the macroporosity, in contrast, was higher in the no-till soil. Moreover, the highest values of moisture conductivity were observed in the no-till at deeper depths (700–850 cm) which was decreased at the soil surface. In contrast, the plowed soil had the highest values of moisture conductivity at 0–15 cm depth, which decreased with an increase in soil depth. The profile distribution of moisture conductivity in the no-till contributes to the higher infiltration of the groundwater and the capillary supply of the root layer of the soil from deep depths.

The soil hydrological properties under the transitional no-till lead to a decrease in the water infiltration and lower hydraulic conductivity rates due to the consequence of initial surface compaction when compared to conventional plowing. An initial soil compaction under short-term no-till (1 to 3 years) decreased porosity due to the lack of disturbance and inversion of soil, while frequent plowing breaks down compacted soil layers and increased porosity [50]. However, several studies have shown that long-term no-till significantly reduced surface soil compaction by adding greater amounts of residues from agronomic and cover crops with different root systems in crop rotation [18; 39; 50].

Blanco-Canqui and Ruis [22] discussed the implications of no-till management for assessing organic carbon dynamics, fertility, and yield, but a current synthesis of no-till impacts on soil physical properties. They argued that understanding changes in soil physical properties following the adaptation of no-till is important for soil management, agricultural production, and environmental quality.

The results of a simulated scenarios [33], included long-term (30 years) corn growth in a rainfed regime, the modeling have shown significant effects of tillage on crop yield and soil water balance. The chisel plowing increased corn yield by 14%, but this positive effect of chiseling lasted only one cropping season. Under different tillage options (chiseling and no-till), root length density and stratification of soil hydrological properties within the profile generated different patterns of soils response to drought events during the harvest season.

According to Beltrao et al. [21], the highest crop yields were obtained at the most favorable ratios of the air and water in the soil during the critical periods of crop culture. They reported that all the components in the soil-plant-atmosphere system must be balanced to mitigate the consequences of climate change, while its can't be completely eliminated [27]. However, the added impact on soil properties under different tillage practices depends primarily on certain conditions at the soil-atmosphere interface, which requires a more detailed study.

The influence of cultivation on soil nutrients and microbiological activities. There is a close relationship between the availability of soil moisture and the assimilation of nutrients by plants as the intensity of absorption of nutrients and their movement along the plant decreases with a lack of moisture. It is known that under drought, the absorption of nutrients (such as phosphorus) by plants decreases by 7–28% and precedes the decrease in the rate of absorption of potassium, especially nitrogen. However, the deficiency of phosphorus is a limiting factor for the development of the root system and grain formation [1]. Soil cultivation transiently improved the crop productivity of agricultural land by effective control of weeds, pests, and pathogens to optimized plant nutrition [25; 43].

Surface application of nutrients (either by chemical fertilization or amendments), under no-till, leads to the stratification of organic carbon and nutrients [42; 55]. However, cropping diversity with mixed cover crops under minimum tillage or no-till reduce stratification, control soil degradation, and consequently, mitigate the negative impacts of conventional agriculture on the environment. However, the combined effect of these measures on greenhouse gas emissions, particularly nitrous oxide and ammonia volatilization from soil ecosystems remains highly debated [44].

A field research study [32] to determine the tillage effects on corn nitrogen uptake and utilization, no-till results showed significant increase in phosphorus-use efficiency at the initial stages on the low-input plants. The effect of tillage was constant at all stages of crop growth and development, with higher plant phosphorus-use efficiency under the plow and chisel disc options than under the no-till. However, plants grown under the no-till had the highest phosphorus concentration in the shoots.

Other research results showed that the potential denitrification activity and the total number of denitrifying bacteria increased by 66 and 116%, respectively, in response to the effects of no-till, while soil denitrification under the no-till led to an increase in nitrous oxide emissions [58]. When comparing tillage technologies, results indicated a significant decrease in soil pH with a variation of ± 0.28% under the no-till, when compared to the conventional tillage. Thus, lower relative changes in soil pH observed on clayey loam (–2,44%) were recorded for the long-term no-till [49].

Skaalsveen et al. [50] have reported that the no-till has great potential as a soil erosion mitigation with significant reductions in soil loss, providing beneficial effects on loading sediments and particulate phosphorus into fresh waterbodies. However, the no-till increased the edge-of-field loss of dissolved reactive phosphorus [48] but have a minor effect on nitrogen leaching. Sustainable soil management practices, in general, increased soil respiration (by 81.1%), microbial biomass (by 104%), and dehydrogenase enzymatic activity (by 59.2%) when compared to the combination of other soil cultivation technologies [51].

Under climate-smart agricultural practices, the transitional no-till decreased the soybean and winter wheat yields (by 14.9% and 20.7%), than under the conventional tillage in Ukraine [9]. However, soybean yield increased by 14% and winter wheat by 5.1% in response to salicylic acid chemigation under no-till compared to the control. The water-use efficiency of soybean increased by more than 2% under no-till when compared to conventional tillage. Likewise, microbial biomass increased by 19% and earthworm numbers increased by 8% under the no-till soil than that of the plowed soil. Soil moisture accumulation increased by 18% under the no-till, when compared to conventional plowing [9].

Froslev et al. [46] indicated a significant difference in the composition of the soil biology associated with the intensity of tillage, where plowing, minimum tillage, and no-till were compared. Despite the significant influence of tillage on biota composition, comparisons with natural ecosystems showed that experimental fields were much more similar in composition to other rotational fields than to more natural habitats, old fields, and forests, respectively. Long-term no-till farming practices (14 years) significantly increased the size of soil microbial communities and the activity of β-glucosidase, which is associated with the decomposition of soil organic matter and at the same time negatively affects the bacterial diversity due to lack of soil disturbance and accumulation of residues on the soil surface [57].

Reducing tillage and cover crops, which are widely recommended to improve soil health, significantly affect the functional diversity of microorganisms [45]. However, decreased the nutrient availability with soil depth under the no-till with uneven nutrient supply and homogenization than that of the conventional tillage.

Conclusions. Intensive tillage practices, while supporting greater food security, have adverse effects on soil biology and associated properties, disperse structural stability, and decrease organic matter associated with degraded soil health. Together with climate change, conventional tillage practices are expected to accelerate soil health degradation and affect global food security. In contrast, conservation tillage such as minimum tillage or no-till is a proactive approach to regenerate soil health properties. Despite no-till's importance in soil functionality, the major barriers to transitional no-till are nitrogen immobilization, transient soil compaction, weed pressure, and stratification of organic carbon and essential nutrients. Cropping diversity with cover crops, as a biological primer, is expected to complement no-till soil functionality. The water and nutrient contents, the activity and diversity of microbiota, and the influence of cover crops in crop rotation under different tillage technologies are all the issues that have not been thoroughly studied and further research is needed, taking into account climate changes and the characteristics of soils, in particular degraded ones.

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ВПЛИВ ОБРОБІТКУ ҐРУНТУ НА ЙОГО ВЛАСТИВОСТІ: ОГЛЯД ЛІТЕРАТУРИ

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Анотація. *Ґрунти є основною природною системою. Біологічна продуктивність сільськогосподарських культур серед усіх параметрів агроценозу є найбільш мінливим і інтегральним показником життєздатності сівозміни, яка акумулює генетичний потенціал культур, здоров'я ґрунту, погодні умови та агротехнічну ефективність. Обробіток ґрунту є основною технологічною операцією, яка є частиною більшості сільськогосподарських практик протягом багатьох років. Різні технології обробітку ґрунту впливають на його якісні характеристики, змінюючи водний, поживний, повітряний режими, а в окремих випадках призводять до низки негативних явищ, наприклад, зміни структурного складу ґрунтів, зниження стійкості до зовнішніх чинників, деградації та ерозії. Актуальність дослідження підсилюється змінами клімату та переходом виробників від використання оранки на мінімальні і нульові технології з метою економії та екологізації виробництва. Метою роботи було оцінити доступність і змістовність публікацій з даної теми у базах даних українських і закордонних видань, включаючи наукометричні бази рецензованої літератури Scopus i Web of Science, ResearchGate, українських спеціалізованих видань та перевірених вебджерел, за ключовими словами. Усі відібрані публікації перевірялися за назвою та анотацією, а потім за доступним повним тестом для перегляду за вказаними ключовими словами. Публікації-дублікати було вилучено із аналізу. Крім того, до аналізу було включено 22 % неангломовних рукописів, опублікованих у нерецензованих журналах. Визначено, що питанням впливу різних технологій обробітку ґрунту на зміну його властивостей з охарактеризуванням позитивних і негативних сторін, встановлення закономірностей процесів приділено увагу багатьох вчених усього світу та висвітлено у численних роботах, проте спільного висновку щодо переваг однієї технології над іншою та змістовного обґрунтування агротехнологій не існує. Щодалі питання набуває все більшої актуальності у зв'язку зі змінами клімату та потребує детального вивчення.*

Ключові слова: *зміна клімату, здоров'я ґрунту, покривні культури, хімічний обробіток, Scopus, Україна*

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INFLUENCE OF SHORT-TERM CROP ROTATIONS WITH DIFFERENT PROPORTIONS OF SUNFLOWER ON SOIL WATER REGIME

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Abstract. *The article analyses the features of water consumption of sunflower in short-term crop rotations. Presents the results of the 2020–2021 research carried out in the experimental field of Kharkiv National Agrarian University named after V.V. Dokuchaev, located in the area of the Left Bank Forest-Steppe of Ukraine. The soil cover of the experimental field is represented by typical chernozem heavy loam on loess-like loam. Soil moisture was determined by gravimetric technique. Sunflower water consumption was calculated using the water balance method. The sunflower yield was recorded manually. The purpose of our research was to determine how short-term crop rotations with different sunflower saturation affect the formation of the soil water regime and the yield of the crop itself. The experimental design included five-field crop rotations with sunflower saturation of 0, 20, 40 and 60%. The control in the experiment was a five-field crop rotation without sunflower. It was determined that the yield of sunflower seeds depended on the variants and ranged from 3.21 to 3.57 t/ha. The increase in the share of sunflower in crop rotation was accompanied by a decrease in its yield, in particular, due to the deterioration of moisture supply. Soil moisture consumption was the highest in crop rotation with sunflower saturation of 60% (2969 m^3/ha). Against the background of reducing the share of sunflower to 40 and 20%, moisture consumption was 2713 and 2824 m^3/ha. The water consumption coefficient was high due to an increase in the share of sunflower in short-term crop rotations. It was determined that in crop rotation with sunflower saturation of 40% the coefficient of water consumption was the lowest. At the same time, this variant has the highest yield of sunflower seeds (3.57 t/ha). Increasing the saturation of short-term crop rotations with sunflower up to 60% should occur under conditions of the high culture of agriculture. Therefore, ways of efficient use of soil moisture to increase the yield of sunflower in short-term crop rotations are being developed.*
Key words**:** *sunflower, water consumption, soil moisture, saturation, yield*

The relevance of the study. Crop rotation plays a major role in crop yielding [1; 2]. The preceding crops must be carefully chosen for obtaining higher yields and seed quality. Some scientists are working to determine the optimal crop rotation and the influence of the predecessor [3–6]. Sunflower has a leading place in the agrarian sector of Ukraine. Ukraine fully meets its own needs in sunflower seed processing products and is also an exporter of sunflower oil on the world market. Over the past 10 years, the area under this crop has increased almost 3 times [7; 8]. Sunflower is a very cost-effective crop. According to Grain Trade, prices in Ukraine for its seeds are $700 per ton [9].

According to Johnston et al. [10], sunflower is usually grown in 3–4-year rotations with cereals, oilseed rape, and legumes. Production programs of agrarian enterprises are aimed at obtaining high incomes. This is manifested in the design of short-term crop rotations, where the share of sunflower can reach 50%. The integration of sunflower in the cropping system has many advantages [11]. This crop is simple, flexible, adaptable to a wide range of pedoclimatic situations and cropping systems, appreciated for its environmental impact, and for leaving the soil in a favorable condition for subsequent crops. At the same time, it is necessary to take into account soil and climatic conditions, precursors, cultivation technologies, mineral nutrition and plant protection systems [12].

Adaptation to a changing climate is something that modern agriculture is facing. In such circumstances, water management is particularly important [13–15]. During the growing season, field crops use a significant amount of moisture. At the same time, the reserves in the soil decrease, reaching a minimum at the time of harvesting [15]. It is important to prevent this process at the beginning of the growing season of agricultural crops [16–19]. One of the ways to regulate the water regime of the soil is the use of drought-resistant sunflower hybrids, science-based crop rotations and tillage systems. This ensures the accumulation and most rational use of moisture [20].

Analysis of the latest research and publications. Crop rotation is an appropriate measure to increase crop yields, and reduce adverse environmental impacts [21]. According to the results of scientific research, it is proved that crop rotation is an inviolable basis for the stability of agriculture. They have a positive effect on all important soil indicators, in particular soil moisture.

Agricultural crops do not use soil moisture equally for crop formation. Crops that intensively use moisture from the soil do not create agroecological negative. The less moisture remains in the soil after harvesting, the better it will be absorbed during precipitation. Total moisture consumption from early spring to harvesting by sunflower is higher than in other crops. It is known that soil moisture reserves in sunflower agrocenoses in crop rotation during the period of intensive plant development are lower than at the beginning of the growing season [22; 23]. Scientists note that in sunflower crops moisture consumption in the period from sowing to 5–6 leaves are 1250–1330 m^3/ha. By the end of the vegetation period, plants grow intensively and moisture consumption increases to 3140–3160 m^3/ha. Given the residual moisture reserves in the soil at harvest time, sunflower is very drying to the soil [24]. After it, insignificant reserves of available moisture remain in the soil – 890–930 m^3/ha [25]. In the post-harvest period, the processes of moisture accumulation in the soil begin to prevail. The accumulation of precipitation during this period in the fields after sunflower is 52–62%.

The purpose of the research was to determine the influence of the share of sunflower in short-term crop rotations on water consumption and crop yield.

Materials and methods of the research. Research to determine the water consumption of sunflower in 2020–2021 was conducted on the basis of the chair of Farming named after O.M. Mozheiko of the experimental field of Kharkiv National Agrarian University named after V.V. Dokuchaev (KhNAU). The complexity of the climatic conditions of the Kharkiv region of Ukraine for agriculture is also revealed in not existing guaranteed annual sufficient moisture. In addition, in some years, thermal resources are much less than the needs of crops. According to the meteorological station of KhNAU, during the growing season of sunflower, the average long-term precipitation was 278 mm, and the air temperature was +17.7 °C. During the growing season of sunflower in 2020, precipitation was 114 mm less than normal, and the average air temperature was 19.8 °C, which is 2,1 °C higher than the climatic norm. Atmospheric precipitation during the growing season of sunflower in 2021 was showery in June – 81.9 mm, which is 22.9 mm higher than the average long-term norm. In July and August, precipitation was less than the long-term average by 51.5 and 44.2 mm, respectively. Precipitation in 2021 was 197.7 mm, which is 81.3 mm less than the long-term average, and the excess of the average daily air temperature by 2.5 °C compared to the long-term average. Therefore, sunflower vegetation during this period took place in relatively unfavorable conditions.

The physical properties of the soil are affected by many factors that change vertically with depth, laterally across fields and temporally in response to climate and human activity [26]. Different soils have distinct physical and chemical properties depending on the nature of mineral and organic components, their relative amounts, and how minerals and organic matter interact [27]. The soil cover of the experimental field is represented by typical chernozem heavy loam on loess-like loam. In terms of agrophysical and agrochemical properties, it is one of the most favorable soils for growing field crops. It is characterized by high reserves of nutrients available to plants, high humus content and intense biological activity. The arable layer of the soil (0–30 cm) contains humus (according to Tyurin) – 4.9–5.1%, easily hydrolyzable nitrogen (according to Kornfield) – 81 mg/kg of soil, mobile forms of phosphorus and potassium (according to Chirikov) – 100 and 200 mg/kg of soil. Content of exchangeable cations: calcium – 37.8%, magnesium – 6.6%, sodium – 0.49%, potassium – 0.5%, hydrogen – 21 mg-equiv./kg soil. The soil reaction – pH: aqueous – 7.0, salt – 5.2–5.6. Groundwater lies at a depth of about 18 m [28].

Sunflower hybrid – Cruiser LG59580. The size of the sowing area is 750 m^2, the accounting area is 100 m^2. Variants of short-term (5-field) crop rotations with different proportions of sunflower in the structure of the sown areas were studied (Table 1). The control in the experiment was a five-field crop rotation without sunflower.

Soil moisture was determined by Gravimetric Technique [29]. The formula for calculating moisture:

$$W_d,\%=\frac{W2-W3}{W3-W1}\times 100, \quad (1)$$

where W1 – the weight of the container (g), W2 – the weight of moist soil + container (g), and W3 – the weight of dried soil + container (g).

The determination of moisture reserves in the soil was carried out taking into account the known field moisture (% moisture by weight of

1. Crop rotation structure, %

Pea	Winter wheat	Corn	Winter rye	Fallow	Sunflower
20	20	20	20	–	**20**
20	20	–	20	–	**40**
–	20	–	20	–	**60**
–	20	40	20	20	**0**

absolutely dry soil), a certain soil layer (h, cm) and its density (dv) on an area of 1 ha (10 000 m^2).

The formula for calculating soil moisture reserves in m^3/ha:

$$W = h \times dv \times Wt, \quad (2)$$

where W – moisture reserves in the soil, m^3/ha; h – thickness of a certain soil layer, cm; dv – density of soil composition, g/cm^3; Wt, – actual field moisture of the soil, determined by the gravimetric method,% of the completely dry mass of the soil.

The total water consumption was determined by the difference between the spring supply of available moisture and its balance at the end of the growing season of the crop. To this indicator, we added precipitation that fell during the vegetation period. The end result is the calculation of the water consumption coefficient. Two variants can be used to determine the water consumption coefficient: calculation per unit of dry aboveground biomass and per unit of main production [30]. In our study, the efficiency of moisture use for crop formation was assessed taking into account seed yield. Statistical data processing was performed using the CORREL function, which is included in the data analysis package in MS Office Excel 2017.

Research results and discussion. The results of our research show the content of available moisture in the soil layer 0–150 cm. On average, in 2020–2021, at the time of sowing sunflower, it was within 1562–1763 m^3/ha (Table 2). Most moisture (1763 m^3/ha) was accumulated in the crop rotation with a share of sunflower 20 %, and the least – in the crop rotation with a saturation of 40 %. During the spring-summer period of sunflower vegetation, there was a predominance of moisture consumption from the soil over its accumulation. Before harvesting sunflower, the most moisture in the soil remained under control. High moisture accumulation (749 and 658 m^3/ha) was recorded in crop rotations with sunflower saturation of 20 and 40 %. When the share of sunflower increased to 60 %, moisture reserves decreased (488 m^3/ha).

In 2020, at the beginning of sunflower sowing, moisture reserves in the 1,5-meter soil layer were high. They were the highest in the field of crop rotation with sunflower saturation of 20 % – 1840 m^3/ha (Fig. 1). At the end of the growing season of sunflower, moisture reserves acquired minimum values (254 m^3/ha) in crop rotation, where its share was 60 %. Crop rotation without sunflower ensured the residual amount of moisture in the soil at the level of 1094 m^3/ha.

The year 2021 was more favourable in terms of humidity due to sufficient precipitation in the autumn-winter period. At the time of sunflower sowing, moisture reserves in the 1.5-meter soil layer were in the range of 1518–1721 m^3/ha. Most of the available moisture was accumulated in crop rotation with a share of sunflower 60 %. The lowest amount of moisture was in the control variant – 1518 m^3/ha. In the phase of full ripeness of sunflower, the most moisture was recorded in the variant with a share of 20 % (985 m^3/ha). Crop rotation with 60 percent saturation of sunflower was characterized by minimal moisture reserves in the soil – 721 m^3/ha.

Due to the root system sunflower has a rather high level of water consumption. For the formation of a high yield of sunflower, 1650–1850 m^3/ha of moisture in the root layer (0–150 cm) and a sufficient amount of precipitation (300–400 mm) during the growing season are necessary [31]. Gorobets et al. [32] draw attention to the inverse relationship

2. Available moisture reserves in the soil under sunflower, (average for 2020–2021)

Share of sunflower in crop rotation, % (variant)	Available moisture content in the soil layer 0–150 cm, m^3/ha	
	during sowing	before harvesting
20	1763	749
40	1562	658
60	1647	488
0 (control)	1649	985
LSD0.5	116	69

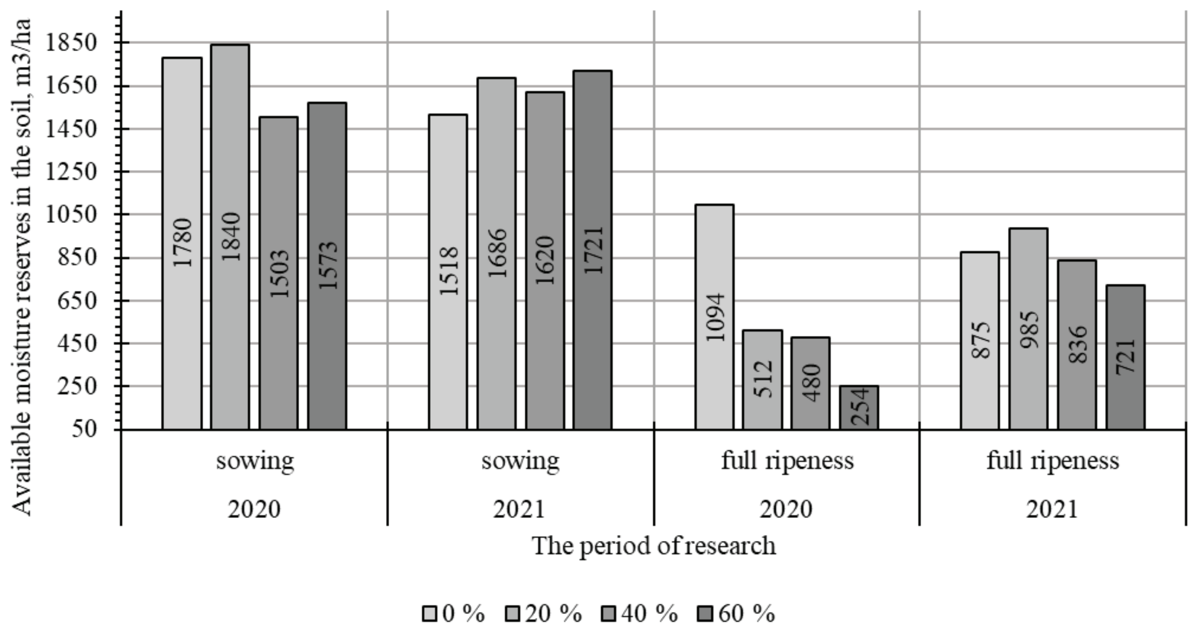

Fig. 1. Available moisture content in the 150-centimeter soil layer, in 2020 and 2021
Note: 20 %, 40 %, 60 %, 0 % – the share of sunflower in crop rotation

between the amount of residual (during sunflower harvest) and accumulated moisture in the soil. If moisture in the soil layer 0–150 cm contains 1580 m^3/ha, it will accumulate at the level of 530–580 m^3/ha. With residual reserves of 350 m^3/ha, the soil absorbs 1880–1920 m^3/ha of available moisture. It was found that after sunflower, the reserves of available moisture in the soil in spring were in the range from 1800 to 1840 m^3/ha. Scientists note that the coefficient of water consumption of sunflower is 450–600 m^3/t, and this is much higher than that of corn, sugar beet and cereals [33; 34].

Kovalenko [35] determined that during the growing season sunflower spends 2581–2764 m^3/ha of moisture on evaporation from the soil. While the share of moisture from the soil is 33.3–37.4 %, and from precipitation – 62.3–66.7 %. Moisture loss from the topsoil (0–10 cm) during the growing season was 49–91 m^3/ha or 5.0–12.6 % of total water consumption. The highest water consumption occurred when placing sunflower in crop rotation with fallow – 12.6 %, and the lowest – with peas – 5.0 %. Domaratsky and Kozlova [30] determined that during sunflower sowing, the available moisture reserves in the meter layer of soil were 1300 m^3/ha. This qualifies as the lower threshold of average moisture availability. When plants reach full ripeness, moisture reserves decreased to 150–300 m^3/ha. During the growing season, sunflower plants used 1150–1000 m^3/ha of moisture from the soil. Together with precipitation, moisture reserves determine the size of the total water consumption, which in the LG 5580 hybrid was 2556 m^3/ha.

The Left-Bank Forest-Steppe of Ukraine is characterized as a subzone of unstable moisture. Therefore, it is important that crops effectively use the moisture reserves accumulated in the soil during the sowing period and precipitation that fell during the growing season. In our studies, sunflower water consumption was closely related to its share in crop rotation.

On average, in 2020–2021, the maximum water consumption (2969 m^3/ha) was observed in crop rotation with its share of 60 % (Table 3). In the variant of 40 % saturation, the level of moisture consumption decreased by 256 m^3/ha. The process of water consumption had an impact on the yield of sunflower plants. With a sunflower yield of 3.21 t/ha in crop rotation with a saturation of 60 %, the water consumption coefficient was at the level of 926 m^3/t. In other crop rotations with sunflower yields of 3.43 and 3.57 t/ha, the water consumption coefficient was 823 and 761 m^3/t. Thus, when the crop rotation is saturated with sunflower 20 and 40 %, the plants used soil moisture more efficiently to form a unit of the main product.

In 2020, the amount of precipitation during the growing season of sunflower was 164 mm. Taking this into account, the total water consumption varied by experimental variants in the range of 2326–2968 m^3/ha (Table 2). The maximum water consumption (2968 m^3/ha) was in crop

3. Sunflower water consumption depending on the saturation of short-term crop rotations

Share of sunflower in crop rotation, % (variant)	Soil moisture, m³/ha	Total water consumption, m³/ha	Sunflower yield, t/ha	Water consumption coefficient, m³/t
2020				
20	1328	2968	3.73	796
40	1023	2663	3.77	706
60	1319	2959	3.24	913
0 (control)	686	2326	–	–
2021				
20	701	2678	3.13	856
40	784	2761	3.36	822
60	1000	2977	3.17	939
0 (control)	643	2620	–	–
Average for 2020–2021				
20	1015	2824	3.43	823
40	904	2713	3.57	761
60	1160	2969	3.21	926
0 (control)	665	2474	–	–

rotation with sunflower saturation of 20%. The level of culture water consumption decreased by 305 m³/ha in crop rotation with a share of 40%. At the same time, its yield level was the highest – 3.77 t/ha. To form this amount of yield, sunflower plants used 1187 m³/ha of moisture, of which 38% is soil moisture and 62% is precipitation. A similar trend was observed for all variants in both years of research. Crop rotation with the share of sunflower 60% provided the minimum yield – 3.24 t/ha.

In 2021, during the growing season of sunflower, 198 mm of precipitation fell. Under such conditions, the lowest total moisture loss was characterized by the variant of crop rotation without sunflower – 2620 m³/ha. Sunflower plants on the field with a share in the crop rotation of 60% had the maximum need for water for the formation of the yield. The difference with the control variant was 357 m³/ha. Reducing the saturation of sunflower crop rotation to 20% provided the most efficient use of moisture by plants (2678 m³/ha).

We have established a direct relationship between water consumption and sunflower yield, as evidenced by the correlation level – 0.99. This corresponds to the calculations of Kovalenko et all [36]. According to their data, the correlation coefficient between soil moisture and sunflower seed yield averaged 0.85±0.12. In the experiment Neshev [37] higher and more stable yields were found when the sunflower was sown after winter wheat – 2.54 t/ha. A severe yield decrease was observed when the sunflower was grown as a monoculture. In the first year of the study (2018) the seed yields were 2.53 t/ha and diminished to 1.64 t/ha in the third experimental year (2020).

When evaluating the studied variants for crop rotation, it is also necessary to take into account the moisture consumption for the formation of a unit of the main product. Calculations of water consumption coefficients per 1 t of seeds make it possible to estimate changes in total water consumption and crop yields from the share of sunflower in crop rotations.

In 2020, a high-water consumption coefficient was determined in the variant of crop rotation with 60% saturation with sunflower – 913 m³/t. And the plants used moisture less efficiently and formed a low yield (3.24 t/ha). In crop rotations with a saturation of 20 and 40%, there was a decrease in the coefficient of water consumption (by 117 and 207 m³/t) for the formation of sunflower yield.

In 2021, sunflower crops used moisture least efficiently in the field of crop rotation with a share of 60% – 939 m³/t. The introduction of crop rotations with sunflower saturation of 20 and 40% led to a decrease in the consumption coefficient by 83 and 117 m³/t. Thus, a saturation of crop rotation at the level of 40% provides a high yield of sunflower and reduces water consumption per 1 t of seeds.

Conclusions. Research data indicate a decrease in the efficiency of moisture use by sunflower in case of increasing its share in crop rotation. Saturation of crop rotations with sunflower at the level of 60% leads to an increase in water consumption coefficient (2969 m³/t). There is a relationship between sunflower yield and total water consumption within the studied variants. The yield of sunflower seeds was the highest (3.57 t/ha) in the crop rotation

with a share of 40%. At the same time, the water consumption coefficient was the lowest – 761 m³/t. So, with the increase in the saturation of short-term crop rotation with sunflower, the moisture consumption for the formation of its yield increases. Further research will be aimed at studying the dynamics of the influence of saturation of short-term crop rotations with sunflower on agrophysical indicators of soil fertility, which were not reflected in this work. Also, variance analysis will be conducted and correlations between sunflower seed yield and agrophysical indicators of soil fertility will be established depending on the research variants.

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ВПЛИВ КОРОТКОРОТАЦІЙНИХ СІВОЗМІН З РІЗНОЮ ЧАСТКОЮ СОНЯШНИКУ НА ВОДНИЙ РЕЖИМ ҐРУНТУ

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Анотація. *В статті проаналізовано особливості водоспоживання соняшнику у короткоротаційних сівозмінах. Представлено результати досліджень 2020–2021 рр., проведених на дослідному полі Харківського національного аграрного університету ім. В.В. Докучаєва, розташованому в зоні Лівобережного Лісостепу України. Ґрунтовий покрив дослідного поля представлений чорноземом типовим важкосуглинковим на лесоподібному суглинку. Вологість ґрунту визначали гравіметричним методом. Водоспоживання соняшника розраховували за методом водного балансу. Облік врожайності проводили вручну. Метою наших досліджень було встановити як впливають короткоротаційні сівозміни із різним насиченням соняшнику на формування водного режиму ґрунту та урожайність самої культури. Схема досліду передбачала п'ятипільні сівозміни із насиченням соняшнику 0, 20, 40 і 60%. Контролем у досліді була п'ятипільна сівозміна без соняшнику. Визначено, що врожайність насіння соняшнику залежала від варіантів і коливалася від 3,21 до 3,57 т/га. Збільшення частки соняшнику у сівозміні супроводжувалося зниженням його врожайності, зокрема, за рахунок погіршення вологозабезпеченості. Загальні витрати вологи з ґрунту виявилися найбільшими у сівозміні з насиченням соняшнику 60% (2969 м³/га). На фоні зменшенням частки соняшнику до 40 і 20% витрати вологи становили 2713 і 2824 м³/га. Коефіцієнт водоспоживання був високим за рахунок збільшення частки соняшнику в короткоротаційних сівозмінах. Тому волога, яку рослини витрачають на формування одиниці врожаю, використовувалася менш ефективно. Визначено, що у сівозміні із насиченістю соняшником 40% коефіцієнт водоспоживання був найнижчим. При цьому на даному варіанті спостерігається найвища врожайність насіння соняшнику – 3,57 т/га. Насичення польових сівозмін соняшником можна розглядати у межах 20–60% до загальної посівної площі. Це слід робити за умов високої культури землеробства, використання високопродуктивних гібридів соняшнику, стійких до ураження хворобами, шкідниками та бур'янами. На підставі даного дослідження розробляються шляхи ефективного використання ґрунтової вологи для підвищення врожайності соняшнику в короткоротаційних сівозмінах.*

Ключові слова: *соняшник, водоспоживання, вологість ґрунту, насиченість, урожайність*

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THE INFLUENCE OF PHOSPHOGYPSUM ON THE SALT COMPOSITION OF SALINATED SOIL

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Abstract. *Global climate changes in many countries of the world lead to the need to use irrigation as a driving factor for obtaining guaranteed and stable harvests of agricultural crops. Irrigation with water of different quality leads not only to an increase in the yield, but also to a change in the salt composition of the soil. The change in the salt composition of soils occurs much faster during irrigation with mineralized water, which leads to the accumulation of soluble salts in the arable layer of the soil and the deterioration of the composition of the soil absorption complex. Accumulation of sodium ions leads to salinization of irrigated soils. It is possible to stop or suspend the salinization processes by introducing chemical melioration with calcium-containing meliorants. As an ameliorant in this work, the use of a by-product of the mineral fertilizers production – phosphogypsum, which contains a significant amount of calcium (up to 95%), replacing exchangeable sodium in the soil absorption complex is proposed. Our researches are related to the establishment of optimal calculation norms and terms of phosphogypsum application, their influence on the change in the components of the soil's saline extract. The research was conducted on soils that had been irrigated with mineralized water from the Samara River (Ukraine) for a long time (over 50 years). According to the amount of exchangeable sodium, the soils of the experimental sites belonged to low-sodium soils with physical signs of salinization processes, and according to the content of toxic salts-moderately saline. For phosphogypsum in the soil-ameliorative conditions of the Northern Steppe of Ukraine, the ameliorative, agronomic, and ecologically safe rates of introduction in spring and autumn were calculated. The scheme of experiments provided options with sprinkler irrigation and without irrigation. The composition of the aqueous extract was determined by indicators of anion-cation content. During the research, a gradual decrease in the number of sulfates was observed: by 1.5% in the second year after exposure, and by 7.5% in the third year after exposure to phosphogypsum. The number of hydrocarbons decreased in irrigated areas where phosphogypsum was applied, and an increase in their content was observed in areas where irrigation was not carried out. Irrigation options were characterized by a significant increase in the content of chlorine ions, which is explained by the arrival of these ions exclusively with irrigation water. The degree of salinity was determined by pH and sodium adsorption ratio (SAR). Based on these indicators, it was established that the soils are slightly saline in all variants of the experiments. As a result of multi-year research, a positive effect of phosphogypsum melioration on the anion-cation composition of water extract and the degree of soils salinity irrigated with mineralized water for a long time was noted. According to the anionic composition, the chemistry of the soils in the experimental plots was sulfate in the variants where phosphogypsum was applied and vegetation irrigation was carried out and without irrigation, while in the control plots (without phosphogypsum and without irrigation) soda-sulfate chemistry was characterized. The chemistry of the soils in the experimental areas according to the cationic composition was sodium in all versions of the experiments. According to the sodium-adsorption ratio (SAR), the degree of soil salinization belonged to the slightly saline type, while the average type of salinity remained in the control plots without phosphogypsum.*

***Key words**: anionic-cationic composition, soil water extraction, phosphogypsum, sodium adsorption ratio*

Introduction. The global food crisis is growing every year due to global climate change. The year 2022 showed that the lives of almost 120 million people depend on agricultural products produced on the territory of Ukraine. Therefore, more and more agricultural producers in the Steppe and Forest-Steppe zones of Ukraine are switching to irrigated agriculture to obtain guaranteed stable and high yields of agricultural crops. The role of irrigation reclamations and their impact on the environment will increase every year [1].

According to the strategic ecological assessment of irrigation and drainage in Ukraine by 2030, in order to overcome the deficit of water supply, it is necessary to carry out permanent irrigation on the area of 18.7 million hectares (60%) of arable land and periodic irrigation on the territory of 4.8 million hectares (15%). The area of insufficiently humid, arid, dry, and very dry wetlands has increased by 10% over the past 25 years. The change in climatic conditions led to the expansion of the natural and climatic zones boundaries of Ukraine in the northern direction by 100–150 km [2].

The quality of irrigation water in Ukraine changes significantly every year (Rudakov et al., 2020; Andrieiev et al., 2022) [3–5]. The area with irrigation water of the II quality class "limitedly suitable" according to agronomic criteria increased by 14% (compared to 2014), which in 2018 amounted to 388,739 thousand ha (84.2%) [2].

The practice of irrigating mineralized surface soils in the world is quite accepted [6; 7] and groundwater [8]. Such irrigation is always accompanied by certain processes of soil degradation [9]. Saltation occurs [10], physical properties deteriorate, and soil fertility significantly decreases.

One of the well-known methods of chemical soil reclamation to combat negative processes during irrigation is the use of gypsum [11; 12]. Many scientific works in the world and domestic practice of irrigated agriculture devoted to this issue are highlighted [13–16].

Experiments on plastering of soils irrigated with mineralized waters were conducted by many domestic scientists [17–19]. As a result of the conducted research, it was established that plastering increases the content of metabolizable and absorbed calcium and significantly reduces the amount of absorbed sodium. When applying even high doses of gypsum, it is not possible to bring the degree of saturation of the soil solution with calcium to the required level in the absence of watering. In the scientific works by the authors from Europe and Asia, patterns of changes in soil properties under the influence of irrigation were established and methods were developed to reduce the adverse effect of low-quality irrigation water on soils [9; 15; 20–23]. Among them, plastering and deep plantation plowing remain the most studied. Scientists emphasize that plastering is a method that limits or weakens the process of salting, but does not eliminate it completely [24; 25].

The effect of chemical meliorants consists in squeezing out or creating an obstacle for the entry of sodium into the soil absorption complex. Due to that, the physical properties of the soil change, and the productivity of agricultural crops increases. Due to the displacement of sodium from the soil absorption complex by calcium or other di- or three-charged cations, the mobility of soil colloids decreases, alkalinity decreases, the availability of nitrogen, phosphorus, potassium, and calcium for plants increases, and microbiological processes are activated [14; 26–29].

Taking into account the accumulated scientific and practical experience, the problem of chemical reclamation of irrigated soils and irrigation water remains insufficiently studied and relevant today. The questions about the expediency and effectiveness of plastering chernozems with a weak degree of salinization are not resolved. There are objections to approaches to the calculation of meliorant doses. The quantitative component of the gypsum interaction with soil and water, depending on variable natural and climatic conditions, is insufficiently covered. Environmental aspects of the meliorants usage are problematic, which necessitates the search for new, more effective measures from the point of view of resource and energy conservation and environmental safety [24; 30].

The need for chemical reclamation of irrigated lands is due to salinization of soils and their degradation: compaction, destructuring, crust formation, etc. [27; 31; 32]. Uncontrolled irrigation in the 1960s and 1980s with high rates of low-quality water and non-compliance with irrigation technology caused a decrease in soil fertility and deterioration of the ecological and reclamation status of irrigated areas. Unfounded irrigation regimes on chernozems are often accompanied by such degradation processes as flooding, secondary salinization, salinization, violation of the gas regime, dehumification, etc. [33]. Thus, there is a need for a comprehensive study of changes in the agroecological state of soils that have been under the influence of mineralized water irrigation for a long time. As a result of long-term irrigation with water of different quality in the territory of the Northern Steppe of Ukraine, an acute problem of secondary salinization and salinization of lands arose [34].

Material and methods. Degradation processes of irrigated soils were studied thanks to the systematic analysis of the results by domestic and foreign scientists. Methods of analysis and synthesis were used to solve the set goal. To establish the optimal rate and method of applying phosphogypsum, experimental studies were conducted in field and laboratory conditions. The influence of calcium-containing ameliorants on the physical properties of the soil was determined in the field, and the chemical composition of the soil was determined in the laboratory. The reliability of the obtained results was checked by statistical evaluation methods.

The experimental researches covered plots with a total area of 60 hectares in the state enterprise "the Dnipro research station's experimental farm of the institute of vegetable and melon growing of the Ukrainian national academy of sciences" in the village of Oleksandrivka, Dnipro district, Dnipropetrovsk region (2010–2021) near the lake on the samara river (Fig. 1).

The anion-cation composition of the water extract of the arable soil layer (30 cm) indicates the type or chemistry of salinization [35]. Laboratory studies were carried out in certified laboratories in Dnipro according to the regulatory and methodological bases in Ukraine.

The farm has been irrigated with Irtec hose-drum sprinklers with mineralized water (more than 2 g/l) from the Samara River for 50 years [36]. During the three years of research, the irrigation rate during the growing season was 1150 m^3/ha, 1300 m^3/ha and 1700 m^3/ha, respectively. Irrigation water belongs to the II quality class in terms of toxic effects on plants and the danger of salinization and salinization. In accordance with agronomic criteria, the chemical type of water was established as chloride-sulfate sodium-magnesium for almost the entire period, and chloride-sulfate magnesium-sodium (Table 1).

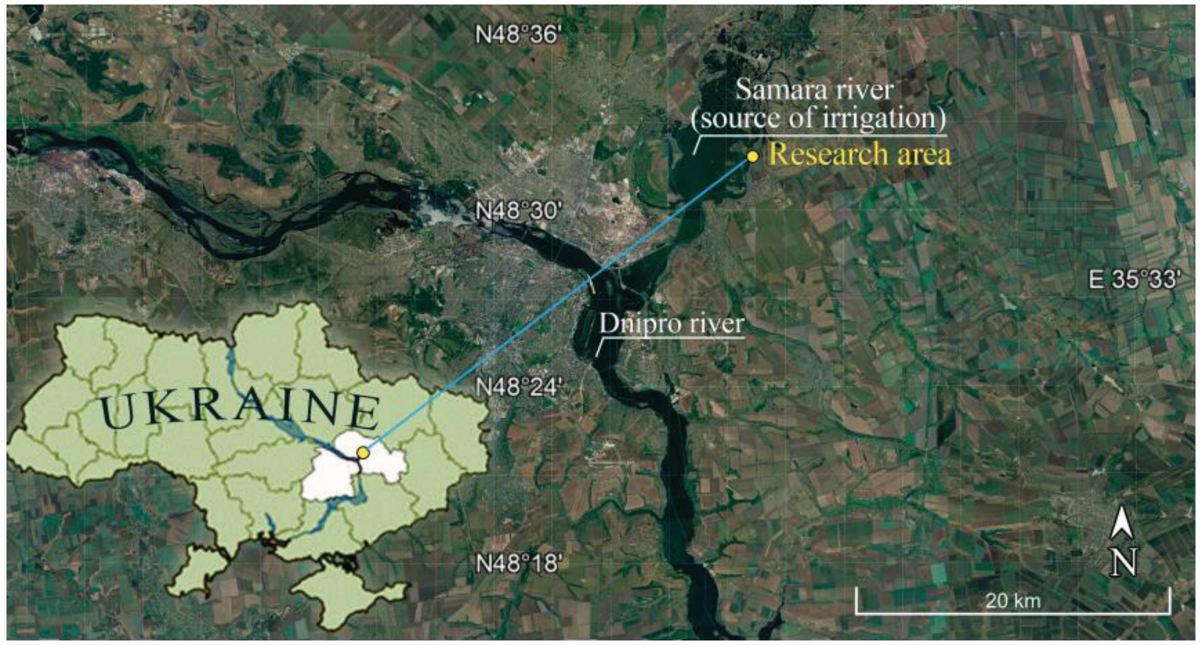

Fig. 1. The place of research

1. Chemical composition of irrigation water by years of research

№	Main indicators (irrigation source – reservoir on the Samara River)	Unit of measurement	Results of water analysis by year		
			First year	Second year	Third year
1	pH	–	8.10	8.01	8.33
2	Rigidity	meq/dm^3	23.9	24.7	25.2
3	Alkalinity	meq/dm^3	5.50	5.53	6.25
4	Dry residue	mg/dm^3	2290.0	2670.0	3090.0
5	Sulfates	mg/dm^3	889.4	920.2	1154.0
6	Chlorides	mg/dm^3	493.8	490.2	520.0
7	Hydrocarbons	mg/dm^3	336.5	380.6	551.0
8	Calcium	mg/dm^3	176.1	220.9	203.0
9	Magnesium	mg/dm^3	182.1	200.7	201.4
10	Potassium + sodium	mg/dm^3	322.7	460.5	470.3
11	Sum of ions	mg/dm^3	2229.8	2670.0	3089.0

During the research, agricultural crops were alternated in the following crop rotation: spring barley, winter wheat, winter wheat, corn for grain, winter wheat.

The soil cover is represented by ordinary low-humus chernozems leached from the loam forest. This is confirmed by the morphological and physico-mechanical indicators of the soil: the 0–45 cm soil layer contains 71.02–74.0% of physical sand and 28.98–26.0% of physical clay, which, according to N.A. Kachinsky, corresponds to light loamy soil; the content of humus in the arable layer (0–30 cm) is 2.01–2.50%, with depth the content of humus gradually decreases (at a depth of 90–105 cm – 0.3%). Salinity processes are observed: pH = 7.5, the content of toxic salts changes to 0.48% (medium salinity).

The soils of the experimental areas have signs of salinity: in a wet state, the soil is highly plastic, viscous, sticky, swells strongly, and easily peptizes; when drying, the soil mass is compressed, which gives low water permeability. At the same time, the amount of exchangeable sodium is 3.64%; the absorption capacity of the soil absorption complex is 20.1–26.47 meq per 100 g of soil, which are not characteristic indicators of saline soils. In order to determine the reasons for such an unsatisfactory physical condition of the experimental soils and establish measures to stop the degradation processes, many years of field research were laid. The searches are related to the analysis of the physical and chemical parameters of the soil through the control of the values of the soil's water extract characteristics during the years of research.

During the research, large amplitudes of fluctuations in daily and annual air temperatures were observed. Over the years of observation, a greater amount of atmospheric precipitation fell in the warm period of the year, but it was characterized by high intensity, which is ineffective for growing agricultural crops. The hydrothermal coefficient varied from 0.95 (2012) to 3.52 (2014).

As a calcium-containing meliorant, phosphogypsum was chosen like a by-product of the mineral fertilizers production. To prevent irrigation salinization of the soil, phosphogypsum from the Dnipro Mineral Fertilizer Plant (Kamyanske), Ukraine was used.

Norms of phosphogypsum application were calculated according to the Pfeffer method in the modification of Molodtsov and Ignatova, 1990 for the displacement of exchangeable sodium for low-sodium brines; according to O.M. Grinchenko, 1980, determined by the method of additional absorption of calcium by the soil; the norm was calculated by the coagulation-peptization method according to B.I. Laktionov, 1963. The reclamation norms are 1.4 t/ha, 3 t/ha, 6 t/ha, respectively, according to the methods proposed above. For the climatic zone of the Northern Steppe of Ukraine, the recommended agronomic norm is 6 t/ha. Since a by-product of the mineral fertilizers production containing specific impurities was chosen as a chemical ameliorant, an environmentally safe application rate of 10.3 t/ha was calculated. The calculated norms should not exceed the ecologically safe ones.

Phosphogypsum was applied to the soil with a reserve for three years with and without irrigation (Table 2). Ameliorant was applied in 2010, 2014, and 2018 under spring barley, grain corn, and winter wheat, respectively. Phosphogypsum was applied for cultivation in the spring (at the rate

2. Scheme of the field experiment

Providing moisture	Variant	The rate of phosphogypsum application
Without irrigation	V1	Control without phosphogypsum
With irrigation	V2	Control without phosphogypsum
Without irrigation	V3	With the introduction of phosphogypsum under cultivation in the spring at the rate of 1.4 t/ha
	V4	With the introduction of phosphogypsum under cultivation in the spring at the rate of 3 t/ha
	V5	With the introduction of phosphogypsum in the fall under the main tillage at the rate of 6 t/ha
With irrigation	V6	With the introduction of phosphogypsum under cultivation in the spring at the rate of 1.4 t/ha
	V7	With the introduction of phosphogypsum under cultivation in the spring at the rate of 3 t/ha
	V8	With the introduction of phosphogypsum in the fall under the main tillage at the rate of 6 t/ha

of 1.4 and 3 t/ha) and in the fall for the main tillage (at the rate of 6 t/ha).

Results and discussion. Irrigationally saline soils (irrigated with water of the II quality class for 50 years) and the change in their chemical composition when phosphogypsum was applied were chosen as the object of research.

The subject of research is the salt regime of the soil, the change of chemical and physical properties of irrigated soils under the influence of chemical melioration with phosphogypsum.

The main goal of the research is to evaluate the effect of phosphogypsum as a chemical ameliorant on the chemical composition of soils with signs of salinity during long-term irrigation with water of the II quality class.

The chemical composition of the aqueous extract of the soil during the years of research was controlled by indicators of anion-cation composition. In Fig. 2 shows the average values of the analyzes of the aqueous extract by anions, and Fig. 3 – cation composition of the soil in meq/100 g of soil.

Over the years of observation, there was a decrease in sulfate ions in the control variant during irrigation (Table 1, variant V2). This can be explained by the process of washing out sulfates with irrigation water. The absence of irrigation on the control option led to an increase in SO_4 ions in the second year by 0.20 meq/100 g of soil, compared to the first, and a further decrease in the third year. The trend of increasing sulfates for the second year can be explained by the increase in the average annual air temperature compared to multi-year values. This made it possible to draw up sulfates from the lower layers of the soil profile during this period.

It can be seen from the graphs (Fig. 1) of the anionic composition that there is an increase in sulfate ions in relation to the control without irrigation and without the addition of phosphogypsum for all years of observation. The average indicators of the number of SO_4^{-2} ions compared to the control in the absence of watering increased by 18%. This trend proves the theory of sulfates entering the soil during irrigation together with irrigation water. On the control options without irrigation, the amount of sulfates in the arable layer of the soil gradually decreased, with their highest value in the second year of observations (2.51 meq/100 g of soil).

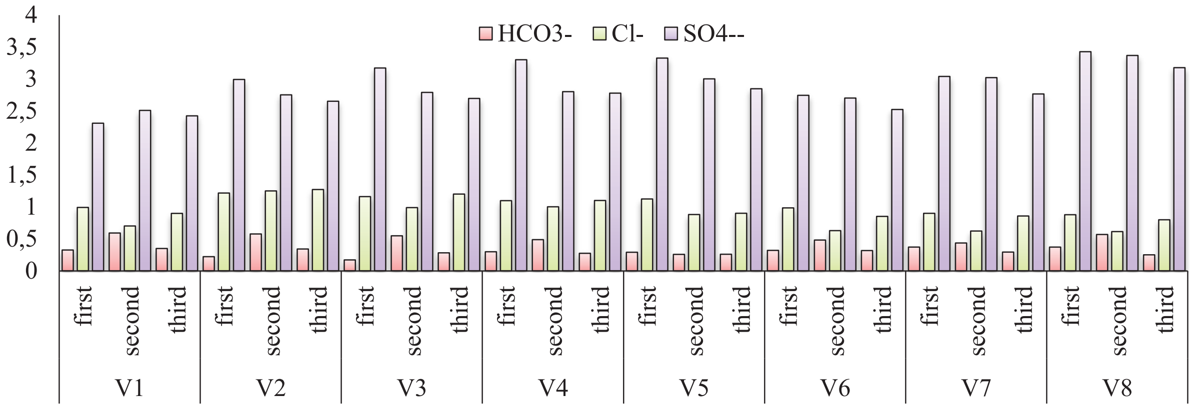

Fig. 2. Anionic composition of aqueous soil extract in the first three years of research, meq/100 g of soil

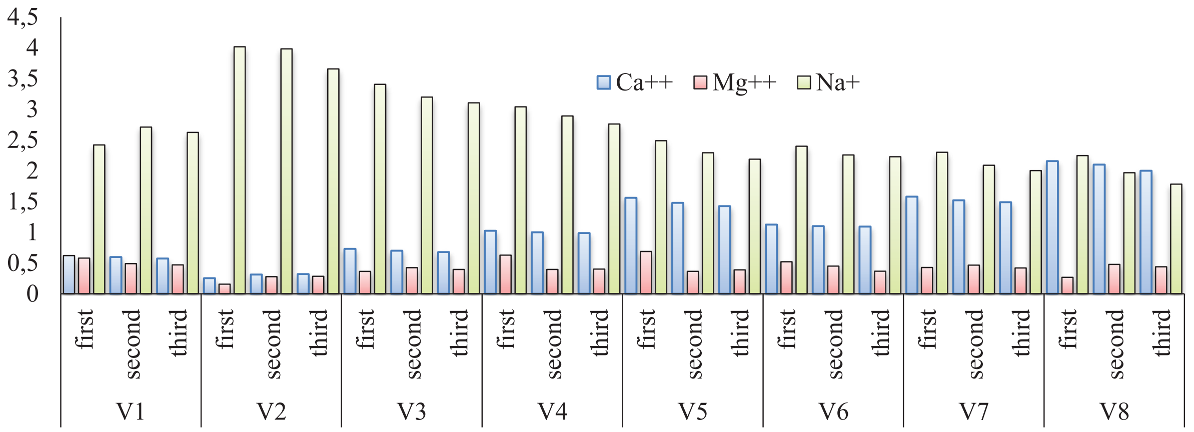

Fig. 3. Cationic composition of the soil's aqueous extract in the first three years of research, meq/100 g of soil

The addition of phosphogypsum in areas without irrigation (Table 1, option V8) led to an increase in the concentration of SO_4^{-2} at all application rates, compared to the control option. In numerical form, the average values are 2.67–3.43 meq/100 g of soil, which is 0.31–1.07 meq/100 g of soil more compared to the option without irrigation. Options 6, 7 and 8 tend to increase the sulfate ion in proportion to the increase in the rate of phosphogypsum application. A decrease in concentration was observed in the long-term effect: a decrease of up to 1.5% in the second year after exposure, and by 7.5% in the third year after exposure.

During irrigation with the addition of phosphogypsum, the average values of SO_4^{-2} ions increased by 0.11–0.35 meq/100 g of soil over the entire observation period, compared to the irrigated control, and by 0.53–0.77 meq/100 g of soil in the control without irrigation. The content of SO_4^{-2} in the absence of irrigation is proportional to the rate of the phosphogypsum addition and decreased over the years of research. The content of sulfates decreased by 17.8% compared to the first year in the 3rd option in the third year of the post-action, and by 18 and 16.9% in the options 4 and 5, respectively, which is 4.5–27% more compared to options without irrigation. This is explained by the process of leaching SO_4^{-2} ions with irrigation water [33].

During the observation period, the number of hydrocarbons changed chaotically without a clear pattern. A certain regularity of the decrease in the amount of HCO_3^{-1} during irrigation with the addition of phosphogypsum, and the increase of indicators in the absence of irrigation with the addition of phosphogypsum, was established. Thus, the amount of HCO_3^{-1} decreased by 0.04–0.06 meq/100 g of soil in the areas where irrigation was carried out and phosphogypsum was applied in relation to the control areas where only irrigation was carried out without ameliorants. Compared to non-irrigated control options, the absence of irrigation with the addition of phosphogypsum led to a decrease in HCO_3^{-1}indicators by 0.03–0.07 meq/100 g of soil.

The concentration of hydrocarbons did not change significantly when the rate of phosphogypsum application was changed. In the irrigated variants, there was an increase in HCO_3^{-1} at the rate of application of 3 t/ha to 3% compared to the rate of 1.4 t/ha, and a decrease of 10.7% at the rate of 6 t/ha, while in the absence of irrigation this difference increased gradually by 8% and then by 4%.

It is known that chlorine ions are the most toxic for plants. Hypothetical toxic compounds formed with chlorine slow down the growth and development of plants. All chlorine salts are toxic to crops [27], but Na_2SO_4 is more toxic to some crops than NaCl, and vice versa to corn [14]. Whereas sulfur, which is part of the SO_4 ion, is more important in the development of plants and is a component of many cell components. Sulfur takes part in redox processes and energy exchange, plays a major role in the formation of properties and structural transformations of protein molecules [37].

Chlorine ions increased their concentration in irrigated areas during the entire period of observation, which is explained by the arrival of ions exclusively with irrigation water. There was a 1.5-fold increase in chlorine when irrigated in control plots compared to plots where irrigation was not carried out. Chemical amelioration with phosphogypsum on irrigated areas showed a positive tendency to decrease chlorine concentration by 13–34%, compared to the irrigated control option (V2). While the introduction of phosphogypsum in the absence of irrigation did not significantly affect the concentration of chlorine in the soil, namely: at the norm of 1.4 t/ha, the average indicators in the years of research compared to the non-irrigated option remained at the level of 0.85 meq/100 g of soil, and at rates of 3 and 6 t/ha decreased by 8.5 and 14.7%, respectively. Also, different rates of phosphogypsum application did not affect the change in chlorine concentration, although without irrigation a slight decrease in Cl was observed when the rate was increased by 0.085 and 0.022 meq/100 g of soil. The absence of irrigation in the control areas did not show a significant pattern of changes in chlorine concentration, while in the reclamation area, a decrease of the ion was observed in the second year after the action by 32–15% due to the redistribution of salts with an increase in SO_4 ions.

The type or cheminism of salinization was determined by the ratios of the largest anions-cations given in the Table 2. Application of phosphogypsum with and without irrigation, according to the anionic composition of the aqueous extract of the soil, has a sulfate type of salinization. The soda-sulfate type (SST) of salinization was observed in the control plots without the phosphogypsum addition and without irrigation in the first year, and in the other years of observation, only the sulfate type (ST) of salinization was noted.

The degree of salinity equivalent to chlorine and the amount of toxic salts in percentages in all variants of experiments were determined by combining anions and cations into hypothetical molecules of the appropriate amount (meq/100 g of soil), the results of which are shown in Table 3.

The SAR indicator for the set data range of all options except the first defines the degree of soil salinity as slightly saline. For the first option, according to the range of SAR ratios, salinity is characterized by an average degree. Control plots without irrigation were characterized by increased SAR values of 0.56 units in the second year. There was a similar trend with sulfates. The explanation of this phenomenon is due to the influx of sodium sulfate from the lower layers of the soil profile into the arable layer during this period.

The degree of soil salinization can also be determined according to FAO standards by the sodium-adsorption ratio (SAR) [38]:

$$SAR = \frac{Na^+}{\sqrt{0.5\left(Ca^{2+} + Mg^{2+}\right)}},$$

where Na^+, Ca^{2+} and Mg^{2+} – the content of the corresponding ions in the water extract of the soil, meq/100 g of soil.

For the first three years of research, the SAR values of the correspondingly obtained cation indicators are shown in Table 4.

The lowest SAR indicators were observed in the third year after the application of phosphogypsum as a chemical meliorant at a depth of 0–105 cm. The most significant decrease in SAR occurred with the application of phosphogypsum at rates of 3 and 6 t/ha with irrigation and without it at all rates (recommended rate of 6 t/ha).

The phosphogypsum addition had a positive effect on the physical properties of the arable layer of the soil (Table 5).

The phosphogypsum addition significantly affected the density indicators in the direction of improvement (Table 4). Even with the phosphogypsum addition, there was a tendency to increase the density in the irrigated options, compared to the non-irrigated areas. A tendency to increase soil density in dry years was also observed. The lowest density indicators in the variants without irrigation were noted in the first year after the effect when phosphogypsum was re-applied. The value of the density in this period was 1.17–1.2 g/cm^3, which is 0.04–0.96 g/cm^3 less compared to the aftereffect of the first year at the first application.

When irrigated, the effect of phosphogypsum as a chemical ameliorant on the density of the soil composition is more significant, compared to non-irrigated options. Over the years of research, the same trend was observed as in the absence of irrigation (increased density in dry years and the lowest values in the first year of the post-action when repeated application of phosphogypsum). The value of the density in the first year after the effect when phosphogypsum was re-applied was 1.18–1.21 g/cm^3.

The porosity of the soil in the control areas without the phosphogypsum addition and without irrigation varied in the ranges from 50.0 to 50.8% (Table 4). With irrigation according to the average indicators in all years of the research, the value of the sparability of the arable layer of the soil in the control areas was 47.14%, and in the absence of irrigation, this indicator was 3.24% higher. This is explained by the increased corresponding indicators of soil density. Over the years of research, under irrigation conditions, a tendency to decrease sparability was noted, while without irrigation, no clear dynamics were observed, i. e., the values changed randomly (Table 4).

The phosphogypsum addition significantly affected the indicators of soil porosity. An improvement in sparability indicators was observed in all variants of experiments, compared to the control. The best option in the absence of irrigation, as well as in the study of density, turned out to be the option with the phosphogypsum addition in the fall under the main tillage at the rate of 6 t/ha. The best indicators of soil sparability were noted in variants without irrigation when phosphogypsum was re-applied in the first year after the application. Cracking in the first year of the after-effect during repeated application increased by 0.17–0.35%, compared to the after-effect during the first application of phosphogypsum.

Irrigation did not lead to a drastic change in spariness, and over the years of research, the same trend was observed as in the absence of irrigation. The best value of spariness was observed in the first year after the application of phosphogypsum, which was 49.51–50.2%.

3. Cheminism and the soils salinity degree of the experimental site

Research variant		V1			V2			V3			V4		
Degree of salinity / chemistry (type) of salinity		eCl, meq	Stox.salts, %	cheminsim (type)	eCl, meq	Stox.salts, %	cheminsim (type)	eCl, meq	Stox.salts, %	cheminsim (type)	eCl, meq	Stox.salts, %	cheminsim (type)
A year of research	1st	0.61	0.21	SST	1.39	0.3	ST	1.39	0.37	ST	1.39	0.39	ST
	2nd	1.39	0.32	ST	1.69	0.35	ST	1.49	0.38	ST	1.52	0.39	ST
	3rd	0.76	0.29	ST	1.99	0.36	ST	1.63	0.35	ST	1.96	0.37	ST
Research variant		V5			V6			V7			V8		
Degree of salinity / chemistry (type) of salinity		eCl, meq	Stox.salts, %	cheminsim (type)	eCl, meq	Stox.salts, %	cheminsim (type)	eCl, meq	Stox.salts, %	cheminsim (type)	eCl, meq	Stox.salts, %	cheminsim (type)
A year of research	1st	1.7	0.4	ST	1.6	0.58	ST	1.5	0.42	ST	1.5	0.41	ST
	2nd	1.62	0.38	ST	1.51	0.41	ST	1.41	0.41	ST	1.48	0.41	ST
	3rd	1.88	0.38	ST	1.75	0.4	ST	1.56	0.4	ST	1.48	0.41	ST

4. Indicators of the sodium-adsorption ratio by research options in the years of observation

Research variant	Retrospective year	pH	SAR
V1	first	7.5	3.12
	second	7.4	3.68
	third	7.5	3.63
V2	first	7.4	8.87
	second	7.2	7.33
	third	7.4	6.65
V3	first	7.17	4.61
	second	6.7	4.26
	third	7.2	4.24
V4	first	7.29	3.34
	second	6.89	3.46
	third	7.26	3.31
V5	first	7.37	2.35
	second	6.97	2.39
	third	7.34	2.30
V6	first	7.22	2.64
	second	6.75	2.56
	third	7.21	2.61
V7	first	7.36	2.30
	second	6.91	2.10
	third	7.3	2.05
V8	first	7.43	2.04
	second	7	1.73
	third	7.38	1.61

5. Change of physical indicators of soil according to research options (soil layer 0–30 cm)

Research variant	Density of soil structures, g/cm^3			Soil porosity, %			Soil permeability, mm/min		
	1st year	2rd year	3th year	1st year	2rd year	3th year	1st year	2rd year	3th year
V1	1.37	1.35	1.35	50.20	50.40	50.50	2.14	2.07	2.00
V2	1.36	1.40	1.39	47.28	47.20	47.10	1.10	1.14	1.10
V3	1.24	1.25	1.20	52.00	52.00	52.35	2.48	2.45	2.50
V4	1.22	1.23	1.19	52.41	52.14	52.76	2.50	2.50	2.58
V5	1.21	1.21	1.17	52.83	52.02	53.00	2.51	2.52	2.60
V6	1.27	1.28	1.23	49.45	49.40	49.51	1.70	1.60	1.81
V7	1.25	1.24	1.20	49.98	50.00	49.91	1.73	1.71	1.89
V8	1.22	1.26	1.18	50.00	50.10	50.20	1.79	1.77	1.90

According to our data, the water permeability of the soil in the control without the phosphogypsum addition was higher in the non-irrigated variants, compared to the irrigated ones (Table 4). The phosphogypsum addition had a significant effect on the increase in water permeability of the soil in all variants of the experiment. When applying phosphogypsum without irrigation, the average indicators for all years of research increased by 2.46–2.54 mm/min. The increase in water permeability occurred in proportion to the increase in the application rate of phosphogypsum. This proves the theory of increasing water permeability of irrigated soils during chemical melioration with calcium-containing meliorants during coagulation of soil colloids with calcium cations. The best indicators of soil permeability were noted in variants without irrigation when phosphogypsum was re-applied in the first year after the application. Water permeability increased by 0.02–0.1 mm/min in the first year of the aftereffect during repeated application, compared to the aftereffect during the first application.

With chemical reclamation and irrigation, a decrease in water permeability was observed in comparison with non-irrigated options. As in the variants without irrigation, according to the years of research, the first year after the effect was the best with repeated application – 1.81–1.9 mm/min. This fact indicates the formation of water-resistant aggregates and a decrease in the mobility of silty particles when adding calcium with phosphogypsum. Due to this, the water resistance of the soil increases, filtration increases, which helps to wash salts from the soil. amelioration, it has acquired the status of good from satisfactory.

Conclusions. The use of phosphogypsum as a chemical ameliorant to prevent degradation processes occurring in ordinary chernozems has a positive effect on the anion-cation composition of the water extract and the degree of soil salinity. According to the "total effect" of toxic ions, the degree of soil salinity changes to a slightly saline type when phosphogypsum is applied at the rate of 3 and 6 t/ha with irrigation.

The increased ameliorative effect of phosphogypsum was observed precisely with irrigation because the sodium-adsorption ratio (SAR) in the third year after the application decreased by 10% in the variants without irrigation, and with irrigation – by 69% in relation to the control variants. According to the SAR indicators, the options with the application of phosphogypsum at the rate of 3 and 6 t/ha during irrigation turned out to be the best.

Under irrigation conditions, the improvement of the ecological condition of saline soils was noted when phosphogypsum was applied at the rate of 3 t/ha, which increased the water permeability of the soil by 0.66 mm/min and reduced the number of toxic salts to 0.41% in the third year after the effect. In non-irrigated conditions, the best option was the phosphogypsum addition in the fall under the main tillage at the rate of 6 t/ha, which increased the water permeability of the soil by 0.68 mm/min and reduced the amount of toxic salts to 0.38% in the third year after the action.

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ВПЛИВ ФОСФОГІПСУ НА СОЛЬОВИЙ СКЛАД ЗАСОЛЕНОГО ҐРУНТУ

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Анотація. *Глобальні зміни клімату в багатьох країнах світу призводять до необхідності використання зрошення як рушійного фактору для отримання гарантованих і стабільних врожаїв сільськогосподарських культур. Поливи водою різної якості призводять не лише до підвищення врожайності, а й до зміни сольового складу в ґрунті. Значно швидше відбуваються зміни сольового складу в ґрунті при зрошенні мінералізованою водою, що призводить до накопичення розчинних солей в орному шарі та погіршення складу ґрунтового вбирного комплексу. Накопичення іонів натрію призводить до засолення зрошуваних ґрунтів. Зупинити або призупинити процеси засолення можна шляхом проведенням хімічної меліорації використовуючи кальцієвмісні меліоранти. В якості такого меліоранту в цій роботі запропоновано використання побічного продукту виробництва мінеральних добрив – фосфогіпсу. Він містить значну кількість кальцію (до 95%) та здатний замінити обмінний натрій у ґрунтовому поглинальному комплексі. Наведеними дослідженнями встановлено оптимальні розрахункові норми і строки внесення фосфогіпсу, його вплив на зміну компонентів ґрунтової сольової витяжки. Дослідження проводили на ґрунтах, що тривалий час (понад 50 років) зрошувалися мінералізованою водою з річки Самара (Україна). За кількістю обмінного натрію ґрунти дослідних ділянок належали до малонатрієвих із фізичними ознаками процесів засолення, а за вмістом токсичних солей – до середньозасолених. Для використання фосфогіпсу в ґрунтово-меліоративних умовах північного Степу України розраховані меліоративні, агрономічні та екологічно безпечні норми внесення навесні та восени. Схема дослідів передбачала варіанти зі зрошенням шляхом дощування і без поливу. Склад водної витяжки визначали за показниками вмісту аніонів-катіонів. Під час досліджень спостерігали поступове зменшення кількості сульфатів: на 1,5% на другий рік після внесення в ґрунт, та на 7,5% на третій рік після внесення фосфогіпсу. На зрошуваних площах, де вносився фосфогіпс, кількість гідрокарбонатів зменшувалася, а на ділянках, де зрошення не проводили, спостерігали підвищення їх вмісту. Варіанти на поливі характеризувались значним збільшенням вмісту іонів хлору, що пояснюється надходженням цих іонів виключно з поливною водою. Ступінь солоності визначали за pH і коефіцієнтом адсорбції натрію (SAR). За цими показниками встановлено, що у всіх варіантах дослідів ґрунти виявилися слабозасоленими. У результаті проведених багаторічних досліджень відзначено позитивний вплив фосфогіпсу як меліоранта на аніонно-катіонний склад водної витяжки та ступінь засолення ґрунтів, що поливали мінералізованою водою протягом тривалого часу. За аніонним складом хімічний склад ґрунтів на дослідних ділянках у варіантах із внесенням фосфогіпсу і вегетаційними поливами та на ділянках без зрошення був сульфатним, а на контрольних ділянках (без внесення фосфогіпсу та без поливів) – содово-сульфатним. Хімічний склад ґрунтів на дослідних ділянках за катіонним складом був натрієвим у всіх варіантах дослідів. За натрій-адсорбційним коефіцієнтом (SAR) ступінь засолення ґрунту відноситься до слабозасоленого типу, тоді як на контрольних ділянках без фосфогіпсу залишався середній тип засолення.*

Ключові слова: *аніонно-катіонний склад, водна витяжка ґрунту, фосфогіпс, коефіцієнт адсорбції натрію*

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KINETIC MODEL OF THE INITIAL STAGE OF THE PROCESS OF COLLOID RETENTION BY THE PORE SPACE OF SOKYRNITE

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Abstract. *The physicochemical phenomena occurring on the surface of sokyrnite grains in complex system "medium grain surface – dispersion medium – surface of suspended particles" have been studied. The framework structure of the sokyrnite structure (rough surface, presence of pores and channels, entrance windows) enables it to work as a "molecular sieve" and to be a highly efficient sorbent-ion exchanger. The porosity of the filter media was determined. Namely: the porosity of the media grains (also called the internal porosity) and the porosity of the intergranular space (media layer). The internal surface area, which is an important quality parameter for sokyrnite as a physical adsorbent, was determined. Several other properties associated with sokyrnite and retained colloidal particles, which affect the strength of the physical adsorption, were investigated. The relationships characterizing the parameters of the zeolite filter media layer were formulated and given. In these studies, the requirements for determining the filter charging time and the optimal technological and design parameters of the filter, according to the operating conditions at a specific water treatment facility, were considered. They determined the need for more detailed research and development of a kinetic model for the initial stage of filtering an aqueous suspension through a filter containing zeolite media. A differential material balance expression for the zeolite filter was formulated. Based on the developed kinetic model, comparative experiments on iron removal from underground natural waters using the above-mentioned filter material were planned and carried out. The mechanism of the distribution of iron ions in the filter space due to the phenomenon of diffusion, in accordance with Fick's first law, is given. The mechanism of iron flake retention by the zeolite media pore space, the consolidation of which occurs during the transition of iron from a divalent to trivalent form, is described. The factors that interfere with autocatalytic processes in iron sediments were described. The dynamics of changes in the concentration of iron in the filtrate after the end of the ion-exchange resource of sokyrnite were studied.*

Key words: *kinetic model, filtration, pore space, sokyrnit, iron removal*

Relevance of research. Despite the wide range of physical properties of the existing granular filter medium, most stages of filtering through them are similar for different medium materials. An exception is the initial stage of filtering, which is usually called the "charging" of the filter. This is due to the fact that it is during it that all the diversity of the physical properties of the filtering medium is manifested. This entails a significant difference in the nature of the mechanisms and kinetics of the processes of interaction of the filter medium with colloidal particles contained in the purified water suspension. In the case of zeolite media, pore space plays a major role in filtering the colloidal suspension. The ion-exchange properties of zeolite are a determining factor in the process of iron removal from underground natural water. The study of the specified factors will allow the development of a kinetic model of the initial stage of the filtering process under given conditions.

Analysis of recent research and publications. Sokirnites are natural zeolites of volcanic origin with the general formula $K_2Na_2Ca \times Al_2Si_7O_{18} \times 6H_2O$. The sorption capacity of sokyrnite is due to its high content of clinoptilolite – more than 75 %; impurities – montmorillonite, quartz, feldspar, opal, and volcanic glass. The share of free intracrystalline volume for clinoptilolite is 34 % of the total volume [1; 2]. The sokyrnite had a rough surface and the size of the crushed stone ranged from 1 to 10 mm. The density of sokyrnites is 2,2–2,3 g/cm^3 and a hardness on the Mohs scale of 3,5–4 points. The specific surface area is 50–65 m^2/h. The colors are pink, white, gray, and light yellow.

The features of the sokyrnite structure (rough surface, presence of pores and channels, and entrance windows) are explained by the frame structure. The framework consists of tetrahedra that form eight-membered rings at their vertices,

thereby creating channels in the zeolite structure. Water molecules ("zeolite water") as well as cations of alkaline and alkaline earth metals (Ca^{2+}, Na^+, and K^+) located inside the channels. With a large number of entrance windows on the surface, a structure permeated with channels, and a complex of cations inside itself, it is possible to use sokyrnite as a "molecular sieve" and replace cations that can pass through the molecular window with structural cations of the mineral.

The outer surface of sokyrnite with a grain size of 0,8–1,2 mm has a surface area of 18 m^2/g. Considering that the micropore space of zeolite is inaccessible to suspended and colloidal particles, the surface available for the adhesion of suspended and colloidal particles is 1–2 m^2·g^{-1}. For comparison, the effective rough surface area of quartz sand grains is only 0,12 m^2·g^{-1}. It is important to note that the NH^+_4 ion exchange potential of sokyrnite is 1,23 mg-eq/g, and the size of the input windows is 3,5–4,8 Å. Indicators regarding the number of replaceable cations, mg-eq·g^{-1}: Ca^{2+} – 1,08; Na^+ – 0,13; K^+ – 0,02. Thus, sokyrnite is a highly effective ion-exchange sorbent [3–8].

The purpose of the study is to develop a kinetic model for the retention of colloids from an aqueous suspension in the pore space of zeolite media, as well as verifying its adequacy by conducting experimental studies on iron removal from underground natural waters.

Materials and methods of research. Field and laboratory experimental studies of physicochemical parameters of the investigated water suspensions; physico-mathematical modeling of the processes of filtration and purification of water suspensions using filter media from zeolite grains; use of experimental data obtained during experimental studies of the process of iron removal from underground natural waters.

Results of the study and their discussion. First, porosity of the researched filter media was determined. As a rule, the porosity determines the proportion of the cavity space from the total volume. Depending on the total volume under consideration, the porosity of the media grains ε_G and the porosity of the intergranular space (media layer) ε_I can be distinguished. Both porosities can be determined from the densities [9].

The grain porosity (also known as internal porosity) determines the cavity part of the zeolite grain volume. Therefore, it is defined as the ratio of the pore volume V_{por} and the zeolite grain volume V_G:

$$\varepsilon_G = \frac{V_{por}}{V_G} = \frac{V_{por}}{V_{zeol} + V_{por}}. \quad (1)$$

The grain porosity is related to the density of the media grain and the density of the zeolite skeleton of the grain:

$$\varepsilon_G = \frac{V_{por}}{V_G} = \frac{V_G - V_{zeol}}{V_G} = 1 - \frac{V_{zeol}}{V_G} = 1 - \frac{\rho_G}{\rho_Z}. \quad (2)$$

The porosity of the intergranular space (the outer part of the cavity space) ε_I is defined as the ratio of the water-filled volume of the cavities between the zeolite grains V_W and the filter volume V_F.

$$\varepsilon_G = \frac{V_W}{V_F} = \frac{V_W}{V_Z + V_W}. \quad (3)$$

The porosity of the intergranular space is related to media grain density and intergranular density as follows:

$$\varepsilon_G = \frac{V_W}{V_F} = \frac{V_F - V_Z}{V_F} = 1 - \frac{V_Z}{V_F} = 1 - \frac{\rho_I}{\rho_G}. \quad (4)$$

In the case of adsorption by a layer of filter media, instead of the porosity of the intergranular space, the term porosity of the filter media layer

1. Correlations characterizing the parameters of the zeolite filter media layer

Correlation	Expression
$\frac{\text{volume of water}}{\text{the total volume of the filter}}$	$\frac{V_W}{V_F} = \varepsilon_I$
$\frac{\text{volume of zeolite}}{\text{the total volume of the filter}}$	$\frac{V_Z}{V_F} = 1 - \varepsilon_I$
$\frac{\text{volume of zeolite}}{\text{volume of water}}$	$\frac{V_Z}{V_W} = \frac{1 - \varepsilon_I}{\varepsilon_I}$
$\frac{\text{mass of zeolite}}{\text{volume of water}}$	$\frac{m_Z}{V_W} = \rho_G \frac{1 - \varepsilon_I}{\varepsilon_I}$

is often used [10–15]. Table 1 presents the most important correlations.

The porosity of the intergranular space can be used to express various volume/volume or solid/volume correlations, which are characteristic of the conditions specified for a particular filter media. Therefore, they are often found in the equations that describe the parameters of the studied filter media.

Next, we determined the area of the outer surface of the researched filter media. The area of the outer surface of the zeolite grains has a strong influence on the mass transfer rate during physical adsorption. Thus, the area available for mass transfer in the mass transfer equation can be approximated by using the outer surface of the zeolite grains. The outer surface area can also be determined using a weighting method. In this method, the number of zeolite grains (Z_{gr}) in a representative sample is counted after weighing the sample (m_{Zgr}).

As a rule, porous adsorbents have internal surfaces that are significantly larger in area than external ones. In particular, zeolite sand has an extremely large internal surface area. Therefore, almost all its physical adsorption capacity is provided by its internal surface area. Therefore, the internal surface area is a very important quality parameter for zeolites as physical adsorbents. However, it should be noted that the internal surface area alone is not a sufficient parameter for characterizing or predicting the physical adsorption capacity of a zeolite because the physical adsorption power is additionally affected by a number of other properties related to the zeolite and retained colloidal particles.

The standard method for determining the internal surface area is based on low-temperature gas adsorption (usually nitrogen adsorption at 77 K) and subsequent application of the Brunauer-Emmett-Teller (BET) isotherm. This method is called the BET method, and the area of the inner surface determined by this method is often called the BET surface area, A_{BET} [9].

The internal surface area is related to the pore system size. The highly microporous adsorbents used for water purification have large internal surfaces.

A commercial BET surface analyzer is required to determine the BET surface area. As an alternative option, to save money, the iodine number was used to determine the BET surface area. The iodine number can be determined easily without expensive equipment. The determination is based on an adsorption experiment with iodine as adsorbate and with defined initial and residual concentrations (0,1 M and 0,02 M, respectively). The adsorbent dose should be varied to achieve a specified residual concentration. With the adsorbent dosage determined from the variation and initial and residual concentrations, the amount of adsorbed substance can be calculated using the material balance equation for isothermal studies. The amount of adsorbed substance, expressed in mg/g, was the iodine number. Because the numerical value of the iodine number is approximately equal to that of the BET surface area, the iodine number can be used as a compensating parameter to characterize the internal surface area, for example, to compare different types of adsorbents.

Next, a kinetic model for the initial stage of the colloid retention process in sokyrnite pore space was developed. In general, the kinetic model includes mass transfer equations, equilibrium relations, and material balance for the investigated filter. This is schematically illustrated in Fig. 1.

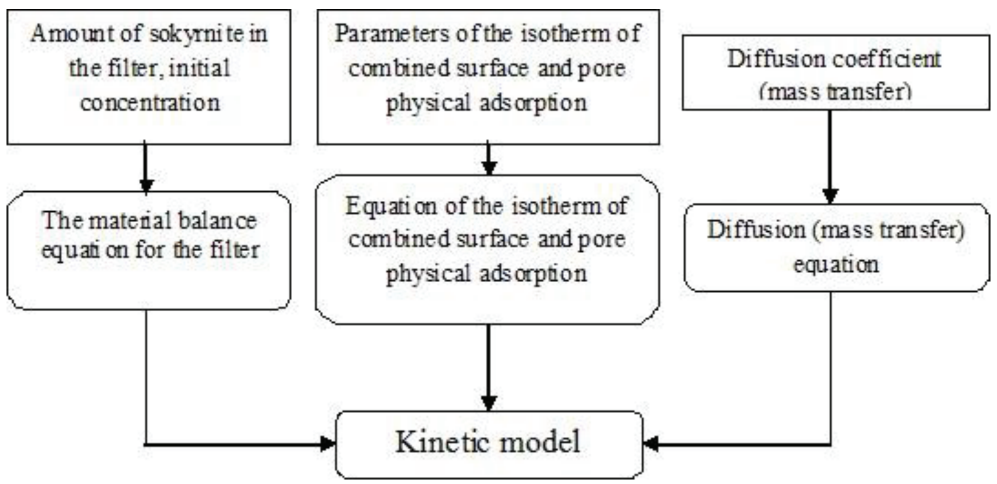

Fig. 1. General block diagram for modeling the kinetics of colloid retention in the pore space of sokyrnite. Model components and input data

The general assumptions in the kinetic model are as follows: (a) the colloidal suspension is assumed to be completely mixed, (b) the temperature is assumed to be constant, (c) the mass exchange with the zeolite surface and within it can be described as a diffusion process, (d) the attachment of colloids to the surface of the zeolite grains occurs much faster than the diffusion processes, and (e) zeolite grains are assumed to be spherical and isotropic.

The differential material balance for a zeolite filter can be expressed as:

$$m_Z \frac{d\bar{q}}{dt} = -V_W \frac{dc}{dt}, \qquad (5)$$

where m_Z is the mass of zeolite, and V_W is the volume of water in the filter. This equation relates the change in the average load on zeolite filter media with time to the change in the aqueous phase concentration over time. Integration of Equation (5) with the initial conditions $c(t = 0) = c_0$ and $\bar{q}\ (t = 0) = 0$ leads to the following form of the material balance equation:

$$\bar{q}(t) = \frac{V_W}{m_Z}\left[c_0 - c(t)\right]. \qquad (6)$$

During the process of iron removal from underground natural waters with the use of simplified aeration with atmospheric air and subsequent filtering, zeolite begins to retain iron ions almost immediately because of its ion-exchange properties. Figure 2 shows the curve of the averaged experimental data for iron removal using zeolite.

In the space of the filter, iron ions spread owing to the diffusion phenomenon in accordance with Fick's first law owing to the difference in their concentrations in the aqueous suspension. Adsorption of iron in the inner space of zeolite grains occurs owing to immobilization of its divalent soluble form. With the further transition of iron from divalent to less soluble trivalent form, iron flakes consolidate and are retained by the pore space of the zeolite media. Further filtering was accompanied by the process of contact coagulation of the iron flakes on the surface of the filter media. The process of fixing on it occurs because of the phenomenon of physical adsorption caused by London or Van der Waals forces. However, after the end of the ion exchange resource of the zeolite, the concentration of iron content in the filtrate increased sharply. This is due to the fact that the intensive extraction of iron ions from the purified aqueous suspension serves as an inhibitor of the autocatalytic process in the iron deposit, where the main part of the transformation of the iron form takes place. Therefore, a further decrease in the iron content of the filtrate can be explained by the disappearance of the factor that interferes with the autocatalytic process. Experimental studies have confirmed that the retention of colloids by the pore space of the zeolite media from an aqueous suspension occurs in accordance with the parameters of the developed kinetic model, which confirms its adequacy.

Conclusions. The parameters of the pore space of the filter media layer are described

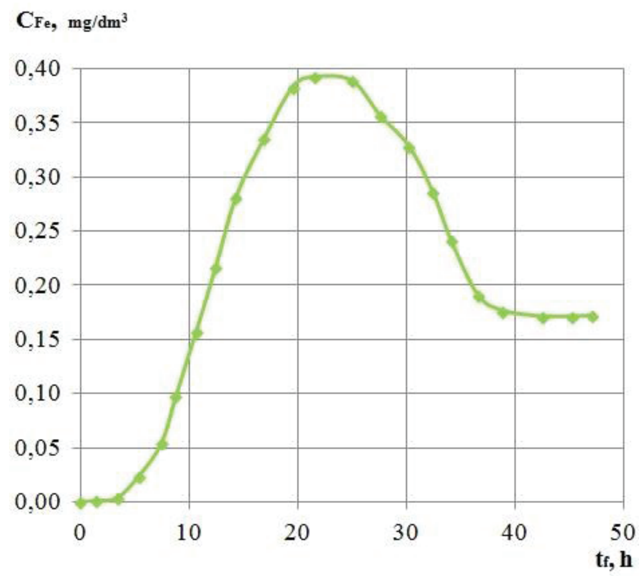

Fig. 2. Change in iron concentration C_{Fe} in the filtrate depending on the filtration time t_f (initial iron concentration – 1,2 mg·dm^{-3}, filtration speed – 7 m·h^{-1}) through zeolite-clinoptilolite grains (media fraction – 1,5–3 mm)

by the developed physico-mathematical model, which includes the determination of the porosity (grains of zeolite media and intergranular space) and the areas of the outer and inner surfaces of the zeolite grains.

Experimental studies have shown the high efficiency of zeolites during the initial stage of iron removal from water. This is because of its ion-exchange properties, significant internal porosity, and well-developed outer-grain surface.

The developed kinetic model for the retention of colloids in the pore space of sokyrnite from an aqueous suspension was verified through experimental studies that confirmed its adequacy.

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КІНЕТИЧНА МОДЕЛЬ ПОЧАТКОВОЇ СТАДІЇ ПРОЦЕСУ ЗАТРИМАННЯ КОЛОЇДІВ ПОРОВИМ ПРОСТОРОМ СОКИРНИТУ

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Анотація. *Досліджено фізико-хімічні явища, що відбуваються на поверхні зерен сокирниту в складній системі «поверхня зерна завантаження – дисперсійне середовище – поверхня зважених часток». Каркасна структура будови сокирниту (шорстка поверхня, наявність пор і каналів, вхідних вікон) дає йому можливість працювати як «молекулярне сито» і бути високоефективним сорбентом-іонообмінником. Було визначено пористість досліджуваного фільтрувального завантаження. А саме: пористість зерен завантаження (яку також називають внутрішньою пористістю) і пористість міжзернового простору (шару завантаження). Визначено площу внутрішньої поверхні, що є дуже важливим параметром якості сокирниту як фізичного адсорбенту. Досліджено низку інших властивостей, пов'язаних із сокирнитом та затримуваними колоїдними частинками, які додатково впливають на силу фізичної адсорбції. Сформульовано та наведено співвідношення, що характеризують параметри шару цеолітового фільтрувального завантаження. Під час даних досліджень враховано вимоги до визначення часу зарядки фільтра та його оптимальних технологічних і конструктивних параметрів відповідно до умов експлуатації на конкретному об'єкті водопідготовки. Вони обумовили необхідність більш детального дослідження та розробки кінетичної моделі початкової стадії фільтрування водної суспензії через фільтр із цеолітовим завантаженням. Сформульовано вираз диференціального матеріального балансу для цеолітового фільтра. На основі розробленої кінетичної моделі було заплановано та проведено порівняльні досліди із знезалізнення підземних природних вод за допомогою вищезазначеного фільтрувального матеріалу. Наведено механізм розповсюдження іонів заліза у просторі фільтра завдяки явищу дифузії, відповідно до першого закону Фіка. Описано механізм затримання поровим простором цеолітового завантаження пластівців заліза, консолідація яких відбувається при переході заліза із двовалентної у тривалентну форму. Описано чинники, що заважають автокаталітичному процесу в осаді заліза. Досліджено динаміку зміни концентрації вмісту заліза у фільтраті після закінчення іонообмінного ресурсу сокирниту.*

Ключові слова: *кінетична модель, фільтрування, поровий простір, сокирнит, знезалізнення*

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