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SOME ASPECTS OF REFORMING THE WATER MANAGEMENT SYSTEM AND EFFICIENT USE OF RECLAIMED LANDS IN UKRAINE

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Abstract. *The necessity and the basic directions of the scientific vision of further reforming the systems of water resources and land reclamation management are determined. The need for such a reform is dictated by the fact that, despite the adoption on October 4, 2016, by the Verkhovna Rada of Ukraine of the Law "On Amendments to Certain Legislative Acts of Ukraine on Implementing Integrated Approaches to Basin Management" and a number of by-laws, the system of water management and land reclamation management in Ukraine still remains virtually unreformed since post-Soviet times as two mutually exclusive functions remain in this system: the water management function and the land reclamation management function. Moreover, the statutory grounds for the introduction of integrated basin management have been deliberately used to eliminate economic entities which managed reclamation infrastructure, which has made it much more difficult to separate the above-mentioned functions, as required by Directive 2000/60/EC of the European Parliament and the Council of Europe "On establishing a framework for Community action in the field of water policy", the implementation of which into Ukrainian law is a mandatory task under the Association Agreement with the EU. Recent adoption (on February 17, 2022) by the Verkhovna Rada of Ukraine of the Law "On Organization of Water Users and Stimulation of Hydrotechnical Land Reclamation" was confirmed by the President of Ukraine on May 6, 2022. It is an important step towards reforming the water management as for the first time in Ukraine the law introduces a new organizational and legal form for the management of reclamation systems, namely water user organizations. But this Law does not address the main issue of the reform – the separation of the above-mentioned functions. Therefore, the success of further reforming of the systems of water resources and land reclamation management will directly depend not on the speed of development and adoption of bylaws to the Law "On Organization of Water Users and Stimulation of Hydrotechnical Land Reclamation". It will depend on the earliest possible adoption of the "Concept of reforming the water management system of Ukraine" by the Government of Ukraine, the project of which was prepared and approved by all interested ministries and departments in 2019, but was deliberately blocked by then leaders of the Ministry of Ecology and Natural Resources of Ukraine. Therefore, the work on reforming the systems of water resources and land reclamation management is unsystematic and, in many cases, the practical steps being implemented, especially in improving the structure of the State Agency Water Resources of Ukraine, are mostly destructive. Minimizing their negative impact will require considerable efforts and time. This article aims at scientific substantiation of the list and sequence of measures, including at the legislative level, the implementation of which will bring the systems of water resources and land reclamation management in Ukraine in line with European water legislation, and thus ensure full implementation of the provisions of integrated management on the basin principle not only formally but also in the spirit.*

Key words: *system, reform, management, efficiency, water resources, reclaimed lands, irrigation, drainage, water user*

Introduction. Resolving the tasks of sustainable provision of water resources and increasing the use of irrigation and drainage in Ukraine to fulfill the functions of a guarantor of world food security is impossible without radical reform of the existing, mostly still "Soviet" system of water resources and land reclamation management. This is especially important in the view of the extremely low level of own water resources provision; unacceptable inefficient use of the available irrigation and drainage potential; and dangerously high, the highest in Europe (over 0.6°C/10 years), growth rate of the average annual air temperature and, as a result, progressive reduction of the availability of water resources for the use with simultaneous increase of the need for them, including the expansion of irrigation areas and water regulation to minimize the negative impact of climate change on the sustainability and efficiency of agriculture.

First of all, an institutional reform should be implemented, the main aim of which should be, in accordance with the requirements of the "EU Water Directive", the separation of the functions of water resources and land reclamation management. Therefore, the system of water resources management through the adoption of the Water Strategy of Ukraine should be oriented towards achieving an acceptable level of water security through the full implementation of integrated water resources management on the basin principle. For the effective land reclamation management, it is necessary to create all necessary conditions for the involvement of landowners and land users to the management and operation of irrigation systems at both the intra-farm and on-farm levels. This problem should be solved by implementing the provisions of the already adopted Law of Ukraine "On Water User Organizations and Stimulation of Hydrotechnical Land Reclamation" and the adoption of the Law of Ukraine "On Amendments to Certain Legislative Acts Regarding the Improvement of Management Systems of Engineering Infrastructure of State-Owned Reclamation Systems". It is these laws and by-laws to them that should become the basis of a new system of management of the engineering infrastructure of irrigation and drainage systems, capable of ensuring not only effective management of the existing infrastructure, but also creating and implementing mechanisms for attracting investments for its modernization and further development. All these institutional and legislative changes should be based on the principles of harmonization of national legislation with the relevant EU legislation.

Actuality of research. One of the most important problems of sustainable development is the protection and preservation of natural resources, primarily water, in connection with their limitation at both the global level and directly in Ukraine. Today, about 2 billion people in the world lack access to safe drinking water. A significant part of them lives in vulnerable regions where various conflicts, including military ones, taking place. Since 2014, such regions include the regions of Ukraine – Donbas and Crimea, and from February 24, 2022 – almost all the territory of Ukraine. In addition, in terms of availability of water resources ready to use, Ukraine belongs to the countries with low water supply. According to this indicator, Ukraine ranks 111th among 152 countries of the world, and ranks 17th among 20 European countries [1–3].

The problem of water scarcity is further complicated by climate changes, which for Ukraine are characterized by the highest rate of increase in average annual temperature in Europe (over 0.6°C/10 years), as a result of which Ukraine is undergoing a process of progressive dehydration of its territory. Due to a significant increase in total evaporation along with an almost unchanged amount of precipitation, the amount of water withdrawn from the territory of Ukraine today is increasing up to 25–42 cubic km comparing to the period of 1961–1990 [4]. Accordingly, the flow of rivers decreases (from 10–20 % in the north up to 40–50 % in the south) and in low-water rivers of the Kherson, Odesa, Mykolaiv, Dnipropetrovsk, and Zaporizhia regions, its complete cessation is predicted starting from 2041 [4–6]. At the same time, with the growing shortage of water resources, the conditions of natural moisture supply of the territory of Ukraine are deteriorating significantly. In the period from 1991 to 2020, the area of dry and very dry zones increased by 7 %, and the area of arable land with an annual climate balance deficit of more than 300 mm exceeded 10 million ha [1]. The last number can be defined as the one which characterizes Ukraine's general need for irrigation. At the same time, the actual state of the use of irrigation potential (over 2 million ha) and drainage potential (over 3 million ha), which has been available since Soviet times, can be characterized as a crisis because in recent years (until 2022) the area of actual irrigation did not exceed 550 thousand hectares and the area of active water regulation (drained lands) was even smaller (about 300 thousand hectares). The state of on-farm network is especially critical [1; 3; 7].

Currently, there is no reliable and systematic information regarding the technical condition of engineering infrastructure objects and the operation of reclamation systems, allocation by the owners and water users, location, etc. This makes it difficult to make effective management decisions regarding their use, modernization, and restoration [3; 8].

Among the most important reasons for the extremely unsatisfactory state of the use of the existing potential of irrigation and drainage systems are the inefficient structure of water resources and engineering infrastructure management; the detachment of water users from the management of water distribution and water supply processes; insufficient level of funding due to the lack of funds in the state budget. At the same time, the conditions for attracting investments for the implementation of measures for the modernization and reconstruction of the existing engineering infrastructure and the expansion of irrigation and water regulation areas have not been created.

The imperfection of the management system primarily requires legislative regulation of the issues of reforming the organizational structure of water resources management and effective use of reclaimed lands considering the interests of all water users. It also requires carrying out legal and institutional reforms covering all the elements of the structure of supply, transportation, distribution, and consumption of water resources that should be based on the best global experience. Therefore, the measures to reform the systems of water resources and land reclamation management developed with the participation of the experts from the World Bank and FAO and approved by the CM of Ukraine in the "Strategy for Irrigation and Drainage in Ukraine until 2030" (2019) and the Action Plan for its implementation (2021) are classified as priority.

Analysis of the latest studies and publications. Analysis of organization schemes for state governance of water resources in the UK, The Netherlands, Germany, Sweden, Canada, and the United States of America shown that there are different schemes of water resources management ranging from the ones based only on basin principle to the mixed ones. However, for all schemes the participation of state authorities at national and regional (basin) levels is mandatory and the most successful is the basin organization of water management [3; 1; 4]. In the most complete and balanced way such a system was implemented in France and has been in operation since 1964 [11; 12].

Water management in France is entrusted to the Ministry of Ecology, Energy and Sustainable Development (regulation and control). Also, this Ministry is a coordinator of the Inter-Governmental Committee on Water Resources. At the regional and local levels Ministry delegate its responsibilities to the regional authorities of the environmental protection, to the Departments of territories management, and to the prefectures' co-ordinators in each river basin. A separate governmental authority is the National Water Resources and Environment Administration, which is responsible for monitoring and coordinates its actions with the Ministry of Ecology [11].

For the purpose of involvement of society and solving water problems, even at the central national level in France, there is an additional consulting representative organization, which cooperates with the Ministry of Ecology – National Committee of Water Resources. It brought together delegates from water users, regional communities, governmental authorities, as well as representatives and heads of basin committees.

This organization is taking part in the development of state policy; resolving of problems which are common for two or more basins; discussing and agreement of all projects and measures at the level of large regions; the determination of water prices and requirements for the quality of water supply and discharge.

The French case is an example of an effectively functioning system of water resources management, which unites all stockholders in conflict-free water resources management within a hydrographic watershed. Basin organizations perform not only planning and control functions, but also control the performance of functions by other bodies that manage water resources.

In France a unique system for financing all necessary functions of environmental issues has also been created based on the principle of "polluter pays". The above-mentioned aspects of water resources management in France can be used for Ukraine as well [11; 13].

The analysis of international experience regarding the operation and maintenance of reclamation systems' infrastructure and international practices of reforming the land reclamation management showed that economic relations in the field of reclamation of various countries of the world are largely determined by the forms, amount, and conditions of state financial support and regulations of economic processes.

In countries with a developed market economy, investments in hydromelioration measures are carried out by land owners, land users, and the state. National wide objects and objects of inter-economic importance are constructed, as a rule, at the expense of state subsidies and loans, are on the balance sheet of state enterprises, and are maintained at the expense of state funds. On-farm facilities are created at the expense of landowners and land users' own funds as well as soft loans and state funds.

In the global practice of agricultural production, complex land reclamation in combination with the use of scientifically based agricultural technologies and technical means is a crucial condition for sustainable and highly efficient agricultural production. For example, in China the share of reclaimed lands reaches

44.4 %, in India – 35.9 %, in the USA – 39.9 %. In the USA, China, India, and European countries the development of meliorative agriculture is the basis of state policy to ensure food security. Restoring the key role of land reclamation in ensuring the sustainability of agriculture in Ukraine in the face of climate change is one of the priority tasks of Ukraine's agrarian policy.

The purpose of the research is to determine the modern aspects of reforming the systems of water resources and land reclamation management in the context of substantiating the main paths of their enhancement aimed at improving the access of all stakeholders to water resources of good quality and restoring the potential of irrigation and drainage as the ground for increasing the efficiency of the reclamated lands use on the base on international practices and experience.

Materials and methods. The research was carried out based on the methodological approaches that are used in international practice and meet the requirements of international and European standards; legislative acts on the support and regulation of relations in the field of water resources management and land reclamation; current legal documents and generally accepted methods in Ukraine.

The research methodology includes methodical approaches based on system analysis and generalization of knowledge regarding the current state and features of the functioning of the systems of water resources and land reclamation management both in Ukraine and abroad.

Research results. In recent years, Ukraine has already implemented and continues to implement actions aimed at reforming the systems of water resources and land reclamation management. Therefore, all actions are based on the task of harmonizing Ukrainian water legislation with the six EU water directives (Fig. 1).

In accordance with the Action Plan for the Implementation of the Agreement approved by the Decree of the Cabinet of Ministers of Ukraine, obligations regarding harmonization with water directives were assigned to various ministries: the Water Framework Directive and the Marine Environment Directive to the Ministry of Environmental Protection and Natural Resources; Directive on drinking water to the Ministry of Health; Directive on the treatment of urban wastewater to the Ministry of Regional Development, Construction and Housing and Communal Services; Nitrate Directive to the Ministry of Economic Development, Trade and Agriculture; Directive on assessment and management of flooding risks to the State Emergency Service of the Ministry of Internal Affairs.

The main legislative document of Ukraine on the use of water resources is the Water Code, which entered into force on July 20, 1995 with relevant changes and amendments [15]. According to it, the purpose of water legislation is to regulate legal relations in order to ensure the preservation and scientifically based rational use of water for the needs of citizens and branches of the economy of Ukraine. The latest changes to the Water Code and a number of other regulatory acts are related to the signing of the Association Agreement between Ukraine and the European Union in 2014 and, accordingly, the need to harmonize Ukrainian legislation with EU directives. The implementation of the provisions of Directive 2000/60/EC of the European Parliament and the Council "On establishing the framework of the Community's activities in the

Fig. 1. European integration of water policy of Ukraine

field of water policy" dated October 23, 2000 [15] into the practice of water resources management in Ukraine began with the adoption of the Law of Ukraine "On Amendments to Certain Legislative Acts of Ukraine on the implementation of integrated approaches in water resources management according to the basin principle" (adopted by the Verkhovna Rada of Ukraine on October 4, 2016, No. 1641-VIII) [4].

Subsequently, in the development of the provisions of this law, five important documents for the implementation of basin management of water resources were approved: "Names of sub-basins and water management plots within river basin districts"; "Procedure for developing water management balances"; "Model provision on basin councils"; "List of pollutants for determining the chemical state of surface and underground water bodies and the ecological potential of an artificial or significantly modified surface water body"; "On approving the boundaries of river basin districts, sub-basins, and water management plots".

Today, the work on the implementation of the system of integrated management of water resources according to the basin principle [16–20] is focused on the creation of a new monitoring system of surface water and the development of river basin management plans. Unfortunately, due to the lack of funds and financial mechanisms for their involvement, the deployment of these works is far from desired, although, as noted, the plans for nine basins should be ready by 2024.

In general, the process of implementing integrated management while meeting the requirements of European directives formally very often does not meet them in the spirit. First of all, in the already mentioned Law of Ukraine "On Amendments to Certain Legislative Acts of Ukraine Regarding the Implementation of Integrated Approaches in the Management of Water Resources Based on the Basin Principle" the powers of the basin councils were reduced to the role of advisory bodies under the State Agency of Water Resources, which made it impossible for them to perform the functions of monitoring the activities of the basin administrations and, accordingly, water users will never get real opportunities to participate in water resources management. The law also does not foresee the separation of the function of water resources management from the function of reclamation infrastructure management. Moreover, the lack of legislative regulation of this issue made it possible for then leaders of the State Agency of Water Resources to implement a number of destructive decisions aimed at the liquidation of economic entities that managed the reclamation infrastructure with the transfer of their functions to the basin authorities, which significantly complicated the possibility and procedure of transferring the reclamation infrastructure to the State Agency of Land Reclamation and Fisheries of Ukraine, which in 2021 was designated by the Cabinet of Ministers of Ukraine as responsible for the operation of this infrastructure and the implementation of the state policy on land reclamation. Neither this law nor the Water Code foresee the creation of the National Water Council under the Cabinet of Ministers of Ukraine as a body responsible for the development and control of the implementation of the state water policy by a significant number of Ministries and departments responsible for the implementation of its certain parts. The creation of such a body was foreseen by the draft of the "Concept of reforming the system of water resources management" developed and prepared for the consideration by the Cabinet of Ministers of Ukraine in 2019 simultaneously with the "Strategy for Irrigation and Drainage in Ukraine until 2030". Unfortunately, then leaders of the Ministry of Ecology and Natural Resources and the State Agency of Water Resources blocked the submission of the "Concept…" for the consideration by the Cabinet of Ministers of Ukraine and until now Ukraine has neither a systematic vision of approaches for reforming the systems of water resources and land reclamation management nor a full-fledged coordinating body responsible for developing such a vision. Unresolved issues regarding the separation of the function of reclamation infrastructure's operation along with the provision of water supply and water discharge services from the functions of water resources management significantly slow down the process of full implementation of integrated management of water resources according to the basin principle and the implementation of the tasks approved by the Cabinet of Ministers of Ukraine in the "Strategy for Irrigation and Drainage in Ukraine until 2030" [2] and the Action Plan for its implementation [22].

Thus, for almost a year and a half, the Decree of the Cabinet of Ministers of Ukraine dated May 24, 2021 "Some issues of distribution of individual powers of central executive bodies in the field of land reclamation" regarding the transfer of powers to implement state policy on land reclamation and land reclamation infrastructure to the State Agency of Land Reclamation and Fisheries of Ukraine, as a tool for implementation these powers, has not been fully implemented. The State Agency of Water Resources with the support of the Ministry of Ecology and Natural Resources under the completely fabricated pretext of the need to provide water resources to other regions and consumers (except for irrigation) advocates the need to leave a number of national wide canals under its management (Kakhovskyj, Inguletskyj, Dnipro-Donbas, etc.), i. e. retain among its functions the function of providing services using engineering infrastructure, which completely contradicts with the requirements of the European Water Directive and creates prerequisites for a conflict of interests diverting from solving urgent issues of water resources management. Among them are the issues of funding the development of river basin management plans, measures for their implementation, and development of a water monitoring system. The lack of a full-fledged modern monitoring system with equipped observation points and a modern laboratory base does not allow timely diagnostics of the state of one or another basin and, accordingly, reasonably form a list of measures, the implementation of which will allow maintaining the proper state of water resources to meet the needs of all water users. It is also necessary to expand the powers of basin councils to the level of kind of basins' water parliaments fully responsible for the state of water resources within specific basin [21]. Until now, there is also no understanding of what a water resource is: how it is formed, how it accumulates, where it is concentrated, how it is spent according to the water management balance, and how to manage it effectively. When monitoring system will start to work and basin councils will be given real powers, they, together with basin authorities, will receive financial and management tools to implement river basin management plans, will have the opportunity to decide what to do when water conditions deteriorate, how to prevent unauthorized discharges and uncontrolled water withdrawals that disturb ecological balances within watersheds, etc. This synergy will give a better cumulative effect for improving water resources and keeping them in good condition for us and the next generations of Ukrainians, particularly regarding the climate change.

Regarding the reform of the system for the land reclamation management, the first legislative act on this issue was the Law of Ukraine "On Organizations of Water Users and Stimulation of Hydrotechnical Land Reclamation" adopted in 2022. Its adoption introduces a new organizational and legal form for melioration systems management – water user organizations (WUOs). WUOs have the right to acquire free ownership of on-farm reclamation systems as well as part of inter-farm systems – pumping stations, canals and pipelines of a lower level, which are currently in state ownership. In general, positively evaluating the very fact of the adoption of this law, especially in terms of creating conditions for the possibility of attracting funds from water users for measures to modernize existing irrigation areas, at the same time it is necessary to emphasize a number of provisions that are not resolved by the adopted law. First of all, the Law practically makes it impossible to create water user organizations both on lands where there is no irrigation and drainage infrastructure and on lands that are registered as irrigated or drained, but where irrigation or water regulation is not actually carried out. This is due to the fact that the law deprives the current owners of inter-farm and on-farm systems of the right to initiate the creation of WUOs, i. e. it cannot be done by those business entities that have reliable information about the availability of reclamation infrastructure that can be transferred to WUOs, its condition, project capacities, reserves for increasing areas of irrigation and water regulation. The issue of free access to pipeline networks also remains unresolved, which will also significantly complicate the possibility of performing works on their reconstruction and replacement with new ones.

Unfortunately, the draft Law of Ukraine "On Amendments to Certain Legislative Acts Regarding the Improvement of the System of Management of Engineering Infrastructure Objects of State-Owned Reclamation Systems", submitted to the Verkhovna Rada of Ukraine [23] does not create such conditions as well. In general, one gets the impression that the drafters of this Law and the Law "On Organizations of Water Users and Stimulation of Hydrotechnical Land Reclamation", which are mainly representatives of the All-Ukrainian Agrarian Council, see the main goal of adopting these Laws not in the creation of the conditions for the restoration and further expansion of irrigation and drainage areas, but in giving water users the right to actual monopoly management of the irrigation and drainage infrastructure through the transfer the ownership of the lower-level irrigation and drainage infrastructure to the WUOs and the acquisition of the right to manage the state-owned inter-farm irrigation and drainage infrastructure by means of the legal establishment of water users' control over the activities of supervisory boards of operators, which will be created for operating the state reclamation infrastructure in case of the adoption of the above-mentioned Law in its current version. To some extent, this goal is confirmed by the very content of the

Laws and the fact that the development of these laws is conducted without proper justification, although this was provided for by the already mentioned Action Plan for the implementation of the Strategy. Thus, the work provided for in the Action Plan on substantiating the institutional and economic foundations of the creation of a state-owned business entity and the transfer to it the management of state-owned infrastructure objects along with the assessment of the ability to financially support the functioning of the water supply and reclamation complex have not been completed. In the absence of these results, it is impossible to quantitatively assess the impact of these Laws on further development of hydrotechnical reclamation and the ability of water users organizations and operators to carry out their economic activities under self-sufficiency conditions as well as the availability of economic prerequisites for attracting investments for reconstruction and modernization of irrigation and drainage infrastructure both at the international (operators) and at the intra-economic level (WUOs).

This issue will also not be solved by the right of operators to independently form tariffs and services for water supply and discharge in the absence of a national regulator provided by the draft Law "On Amendments and Supplements to Certain Legislative Acts Regarding the Improvement of the Management System of Engineering Infrastructure Objects of State-Owned Reclamation Systems". As evidenced by the results of the studies carried out at the Institute of Water Problems and Land Reclamation [24–25], at the current level of the use of design capacities, almost no irrigation and, especially, drainage system of Ukraine will not be able to work without state funding support, and even more to implement projects for the reconstruction and modernization of engineering infrastructure.

The possibility of transferring operators to self-sufficiency will appear only when the areas of actual irrigation and water regulation reach at least 70% of the design capacity of the systems. Therefore, the presence of a national regulator of tariffs, as well as the mechanisms of state support of both the operators and WUOs for the entire period of the implementation by them of investment projects aimed at increasing irrigation and drainage areas, not only for three years as provided for in the draft Law, should be a mandatory component of state reclamation policy. An approximate list of mechanisms for such support, which not only can but must be supplemented in the process of reforming, is shown in Fig. 2

In general, assessing the results of the reform of the systems of water resources and land reclamation management in Ukraine, it is necessary to state the lack of a systemic vision of this process, which causes the preparation and adoption of laws that, already at the time of adoption as it was in the case of the Law "On Amendments to Certain Legislative Acts of Ukraine on implementation of integrated approaches in the management of water resources

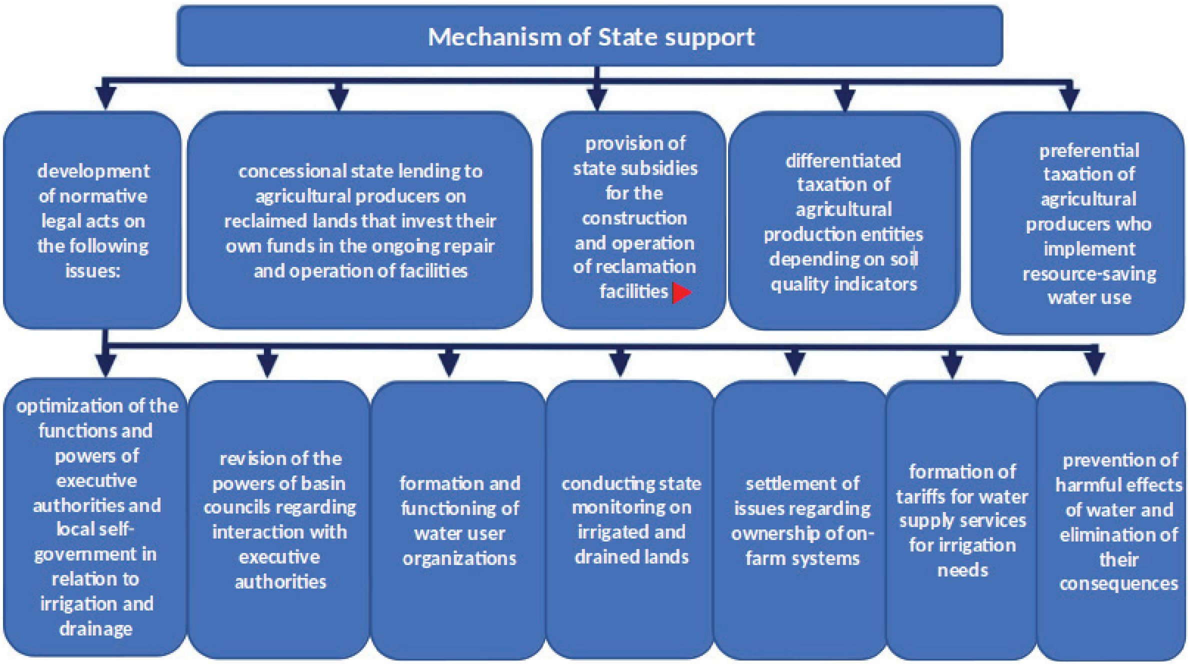

Fig. 2. Mechanisms of state support for reforming the system of land reclamation management

according to the basin principle" and the Law "On organizations of water users and stimulation of hydrotechnical reclamation", need significant changes and amendments.

A certain fetishization of the role of water users and the expectation that they will be the main driving force of the reform process will not contribute to the effectiveness of the reform process. Unfortunately, the analysis of reforming according to a similar scheme in the countries of the former socialist camp shows that the creation of legislative, organizational, and legal conditions for the establishment of water user organizations did not lead to the most important result of the reform – namely, the increase of areas under irrigation and water regulation.

In our opinion, this happened due to insufficient level of state support, both organizational and especially financial. Therefore, we see the possibility of acceleration, mainly the increase in the efficiency of the reform process, in a significant strengthening of the role of the state. This can be realized by firstly completing the process of full transfer of the entire engineering infrastructure with all canals without exception to the sphere of management of the State Agency for Land Reclamation and Fisheries, which will make it possible to start the implementation of investment projects for the modernization and reconstruction of inter-farm network. The first project can and should be an investment project on the reconstruction of the Lower Dniester irrigation system, which is ready to be financed by the European Bank for Reconstruction and Development. The following projects involving foreign investments should be proposed based on the results of the inventory of engineering infrastructure and reclaimed lands, which should also include an assessment of the damage caused by the military aggression of the Russian Federation. The combination of these results will make it possible to determine what share of funds for the implementation of projects should be collected from the aggressor as reparations and what part should be involved in the form of investments. The availability of the inventory results will make it possible to start the process of creating WUOs on lands that are considered as reclaimed but on which neither irrigation nor water regulation has been carried out for a long time although the appropriate engineering network (on-farm systems) still exists. Of course, for this purpose it is also necessary to legislate the right of today's owners of this infrastructure to initiate the creation of WUOs, to whose ownership of this infrastructure can be transferred. Therefore, the presence of WUO should be considered as a prerequisite for the possibility of obtaining financial support for the implementation of irrigation and water regulation restoration projects on lands that are statistically recorded as irrigated or drained. The availability of reliable data on such lands will also provide an opportunity for the full introduction of a two-rate tariff, the first permanent component of which should cover all lands that are statistically recorded as irrigated or drained. In general, it is necessary to emphasize that the process of reforming the systems of water resources and land reclamation management in Ukraine should be returned as soon as possible to the framework outlined by the draft of the mentioned "Concept of reforming the systems of water resources and land reclamation management" by adopting it as soon as possible and resuming the process of unconditional implementation of the "Action Plan on the implementation of the irrigation and drainage strategy". This will return the reforming process to the principles of the EU Water Directive, on the one hand, and will make it possible, on the other hand, to minimize the lobbying influence of the All-Ukrainian Agrarian Council, the main goal of which, as already noted, is an attempt to redirect the reforming process along the path of hidden raiding to take over the working irrigation infrastructure, not to create conditions for expansion of irrigation and drainage areas.

Returning the reform process to the path outlined by the "Concept…" and "Strategy…", in addition to conducting an inventory of infrastructure and land, will require to resolve the issue of creating a national irrigation and drainage operator and a national tariff regulator as soon as possible. The issue of expanding the powers of basin councils to the level of water "parliaments" of the basins and the creation of the National Water Council instead of the established Interdepartmental Coordination Council, whose powers are insufficient to implement the powers of formation and control of the implementation of the national water policy, should also be resolved as soon as possible. It also requires a solution to the issue of the creation and functioning of the Water Fund as the main source of funds for the implementation of river basin management plans. This includes the full legislative implementation of the "polluter pays" principle. All these changes must be reflected in the Water Strategy of Ukraine, which is being developing in accordance with the decision of the National Security and Defense Council of Ukraine, and legislated by introducing changes and amendments to the mentioned Law "On Organizations of Water Users and Stimulation of Hydrotechnical Reclamation", the Law "On Land Reclamation", the Law "On Implementation integrated approaches…", and, certainly, in the Water Code of Ukraine. Of course, the entire set of legislative changes must be based on clear compliance with the provisions of the EU directives mentioned at the beginning of the paper.

Conclusions. The process of reforming the systems of water resources and land reclamation management started in Ukraine is characterized by a lack of systematicity and is focused mainly on the introduction of the institute of water users, which is not always considered as the most important and sufficient condition for the deployment of the process of restoring the existing potential of irrigation and drainage systems.

As a result, for many years there has been no investments in the modernization and reconstruction of the existing irrigation and drainage infrastructure; no prerequisites have been created for attracting investments, including international financial investments, for the implementation of such projects; and the existing systems of water resources and land reclamation management has not yet been reformed in terms of the complete disunion of the functions of water resources management and the management of irrigation and drainage infrastructure.

Until now, the issues of the creation of the National Water Council, the Water Fund, the National Operator of Irrigation and Drainage Infrastructure, the tariff system for irrigation and drainage services, and the national tariff regulator remain unresolved.

Prompt resolution of the outlined problems at the conceptual and legislative level as well as the ensurement of unconditional execution of the tasks already approved by the Cabinet of Ministers of Ukraine in the "Strategy for Irrigation and Drainage in Ukraine until 2030" and "Plan of Measures for its Implementation" taking into account the damage, destruction, and losses caused by the military aggression of the Russian Federation will give an opportunity to start the process of restoring the potential of irrigation and drainage with the aim of transforming reclaimed lands into a guarantor of the sustainability of agriculture in the face of climate change and transforming Ukraine into a guarantor of world food security.

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УДК 332.2 (477): 349.41

ДЕЯКІ АСПЕКТИ РЕФОРМУВАННЯ СИСТЕМИ ВОДНОГО ГОСПОДАРСТВА ТА ЕФЕКТИВНОГО ВИКОРИСТАННЯ МЕЛІОРОВАНИХ ЗЕМЕЛЬ В УКРАЇНІ

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Анотація. *Визначено необхідність та обґрунтовано основні напрямки наукового бачення подальшого реформування системи управління водними ресурсами та ефективного використання меліорованих земель. Необхідність такого реформування диктується тим, що, не дивлячись на прийняття*

04.10.2016 року Верховною Радою України ЗУ «Про внесення змін до деяких законодавчих актів України щодо впровадження інтегрованих підходів в управлінні водними ресурсами за басейновим принципом» та ряду підзаконних актів на його виконання, система управління водними ресурсами та меліорацією земель в Україні до цього часу залишається, практично, не реформованою ще з пострадянських часів, адже і до сьогодні в цій системі залишаються дві взаємовиключні функції: функція управління водними ресурсами і функція управління меліоративною структурою. Більш того, законодавчо визначені підстави для запровадження інтегрованого управління за басейновим принципом були свідомо використані для ліквідації суб'єктів господарювання, які здійснювали управління меліоративною інфраструктурою, що значно ускладнило можливість розділення вищезазначених функцій, як це вимагає Директива 2000/60/ЄС Європейського Парламенту і Ради «Про встановлення рамок діяльності Співтовариства у сфері водної політики» від 23 жовтня 2000 року, імплементація положень якої в українське законодавство є обов'язковим завданням відповідно до Угоди про асоціацію з ЄС. Недавнє прийняття (від 17.02.2022 року) Верховною Радою України ЗУ «Про організації водокористувачів та стимулювання гідротехнічної меліорації земель», підписаний Президентом України 06 травня 2022 року, хоча і є важливим кроком на шляху реформування системи управління водними ресурсами та меліорацією земель, адже цим Законом в Україні вперше запроваджується нова організаційно-правова форма з управління меліоративними системами, а саме організації водокористувачів (ОВК), але також не вирішує головне питання реформування – розділення функцій. Тому успішність подальшого реформування системи управління водними ресурсами та меліорацією земель напряму буде залежати не від швидкості розроблення та прийняття підзаконних актів до ЗУ «Про організації водокористувачів та стимулювання гідротехнічної меліорації земель», а від якнайшвидшого прийняття КМУ «Концепції реформування системи управління водними ресурсами України», проєкт якої був підготовлений і пройшов погодження всіх зацікавлених міністерств і відомств ще у 2019 році, але був свідомо заблокований ще тодішнім керівництвом Міністерства екології і природних ресурсів України. Через це робота з реформування системи управління водними ресурсами та меліорацією земель ведеться безсистемно, а в багатьох випадках практичні кроки, що реалізовуються, особливо в частині удосконалення структури Держводагентства України, в своїй більшості є деструктивними і мінімізація їх негативного впливу буде потребувати значних зусиль та часу. Дана стаття ставить своїм завданням науково обґрунтувати перелік і послідовність заходів, у тому числі і на законодавчому рівні, реалізація яких дасть змогу привести систему управління водними ресурсами та меліорацією земель в Україні у відповідність до вимог Європейського водного законодавства, і тим самим забезпечити в повному обсязі впровадження положень інтегрованого управління за басейновим принципом не лише за формою, але й за змістом.
Ключові слова: *система, реформування, управління, ефективність, водні ресурси, меліоровані землі, зрошення, дренаж, водокористувач*

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FIVE-DIMENSIONAL ASSESSMENT MODEL FOR OPERATION AND MAINTENANCE OF STORMWATER CONTROL MEASURES – TOOL FOR STRATEGIC PLANNING AND CRISIS MANAGEMENT

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Abstract. *Most stormwater infrastructures are aging and deteriorating in the United States. The American Society of Civil Engineers (ASCE) announced in its 2021 Report Card for America's Infrastructure that stormwater infrastructure has received a 'D' grade. The primary study objective is to help decision-makers deal effectively with the control measures of the limited-budgeted, ambiguous and inconsistently applied operation and maintenance of stormwater infrastructures. A five-dimensional assessment model for operation and maintenance of stormwater control measures (5D-SAM) was developed, including location, quality, time/quantity, cost, and environmental aspects. The model is very effective in helping decision-makers identify the current stormwater infrastructure conditions, predict the future state, manage the quantity and improve the quality of stormwater runoff in the most cost-effective manner. It helps determine whether a distressed stormwater system is beneficial to be demolished or it would be cost-effective to either repair, rehabilitate or retrofit. Moreover, the model can be utilized for fast and accurate assessment and better resource allocation for strategic planning of stormwater infrastructures.*

Key words: *assessment model, operation and maintenance, stormwater control measures, stormwater infrastructures*

Introduction and Problem Statement. United States' stormwater infrastructure is rated the lowest grade by the 2021 Report Card for America's Infrastructure (ASCE, 2021). This grade considered different aspects, such as capacity, condition, operations/maintenance, public safety, funding and resilience. The country has over 3.5 million miles of storm sewers with an overall age that exceeded or reached the end of their useful lives. Numerous of these systems have not been maintained to extend their lifespan. The paper also found that the majority of the stormwater lines in the U.S. are currently undersized to control the stormwater flow.

In urban areas, impervious surfaces such as roadways and roofs stop precipitation and melted snow from naturally running into the ground. Rather than water soaking rapidly into storm and sewer systems and drainage ditches, it can cause infrastructure damage, flooding, erosion, turbidity, combined storm and sewage overflow, and contaminated streams (U.S. EPA, 2022).

Flooding is the natural hazard with the most significant social and economic impact in the U.S. These impacts are becoming more critical over time. Catastrophic flooding caused billions of dollars in infrastructure damage, harmfully affected millions of people, and damaged economic welfare. Prominent urban flood cases between 2004 and 2014 cost an average of $9 billion in direct damage and contributed to 71 deaths annually. These figures do not contain the cumulative costs of common small floods, similar to those of infrequent severe floods (NASEM, 2019).

Stormwater infrastructure capacity can impact the hydrologic cycle by detaining or retaining stormwater runoff. Detention reduces peak discharge that increases runoff travel time or rate-controlled storage facilities. Increasing residence time may improve water quality by providing time for other treatment processes, such as sedimentation. The permanent capture of stormwater runoff by infiltration or evapotranspiration reduces the total runoff volume (The WE&RF, 2017).

The Municipal Water Infrastructure Council (MWIC), Green Infrastructure (GI) task committee of the Environmental and Water Resources Institute of the American Society of Civil Engineers (EWRI-ASCE) recognized a necessity for better tracking of operation and maintenance activities for stormwater infrastructures. To meet this requirement, the MWIC GI task committee developed a preliminary suggested list of the operation and maintenance parameters in 2018. These parameters form the foundation of a recommended database to store collected data. The main benefits are to provide recommendations for standardized operation and maintenance activity by local governments and a framework to develop a national cost database (WRF, 2018).

ASCE (2021) recommends specific ways federal funding can help create a stormwater-management network that accommodates changing weather patterns and increased flooding. Among other solutions, the report card authors suggest:

• developing a new federal-level stormwater funding program along with the existing ones,

• establishing a grant program to support training in the stormwater sector,

• extending eligibility for existing water-infrastructure grants to stormwater infrastructure

• promoting new stormwater utilities, and

• updating standards for stormwater infrastructure in response to climate change.

Unfortunately, there is not enough study in the literature on stormwater infrastructure sustainability and improvements considering multi-factors. Semanedi-Davies et al. (2008) studied the potential impacts of climate change and continued urbanization on stormwater flows to a suburban stream. They concluded that city growth and projected increases in heavy rainfalls, both together and alone, are set to raise peak flow volumes and increase flood risk. Conversely, the installation of a sustainable urban drainage system has a positive effect on the urban environment and can largely allay the adverse impacts of changing roads. Cherqui et al. (2013) conducted a survey on performance indicators related to urban drainage systems such as economic aspects, other environmental and sanitary, social aspects, lifespan and long-term effectiveness. Indeed, the performance of sustainable drainage systems should not be limited to pollution and hydrology. Petrucci and Tassin (2011) proposed an empirical approach to quantify the hydrographs' attenuation in sewers to evaluate attenuation's consequences for the scale transfer between the parcel and the catchment in urban settings. A sensitivity analysis on different pipes' and hydrographs' characteristics concluded that the peak attenuation's driving factors differ consistent with the distance from the outlet. The above studies are not comprehensive and do not discuss the multi-dimensions of stormwater assessment.

Research Objectives. A study is thus needed to evaluate the different aspects of stormwater infrastructure conditions. The research objective is to develop a theoretical Five-Dimensional Stormwater Assessment Model (5D-SAM) to analyze and help hydrologic engineers and planners choose the best feasible option with the limited-budgeted, ambiguous and inconsistently applied operation and maintenance of stormwater infrastructures. The paper imparts the rehabilitation of a stormwater system as a feasibility study for applying the proposed 5D-SAM. It presents the outline of the design system for the stormwater system retrofitting based on the performance-based design to satisfy an adequate required level concerning all required performance items, including structural safety and serviceability. The model helps decision-makers identify the current stormwater infrastructure conditions, predict the future state, manage the quantity and raise the quality of stormwater runoff in the most cost-effective manner. It helps determine whether a distressed stormwater system should be demolished or whether it will be cost-effective to either repair, rehabilitate or retrofit it. Moreover, the model can be used in a crisis for fast and accurate assessment and better resource allocation for strategic planning.

Research Scope and Limitations. The research focuses on developing the 5D-SAM model theoretical framework. A model testing and an ArcGIS database of the stormwater infrastructures will be implemented later in several cities in Utah, USA, to validate the proposed model's success.

Methodology. An appropriate rehabilitation method was selected among various alternatives and the performances of the retrofitted stormwater system by the selected method are verified with required performances after retrofitting until the end of service life. The concept is to convert any criteria in measurable values to the same scale. Steps in numerical analysis techniques and the evolution of precise simulation methods are considered. The Five-Dimensional Stormwater Assessment Model (5D-SAM) consists of ten modules to help the operation and maintenance assessment process (Askar, M. et al., 2022).

Stormwater Five-Dimensions:

The stormwater's five dimensions consist of location (X, Y, Z), quality/functionality, time, cost, and environmental/social aspects, as shown in Figure 1.

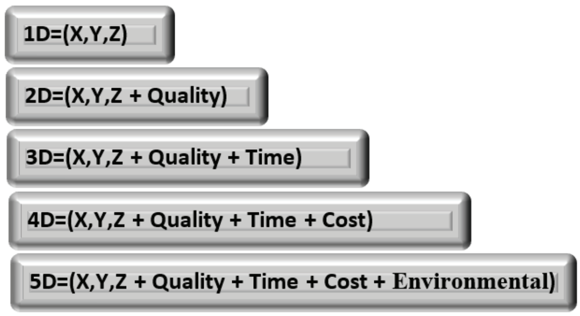

Fig. 1. Stormwater Five Dimension Model

Conceptual Design of the Five-Dimensional Stormwater Assessment Model

Any asset consists of several components with the same conditions at the design stage. However, after years of usage, the conditions of the components change and are not the same anymore. The primary idea of the stormwater assessment model is that the assessment is a result of a combination of different aspects, such as condition, functionality, time, cost, and environment. Furthermore, the stormwater infrastructure's repair cost depends on its components' condition. Two approaches were taken into consideration to achieve the research objectives (Figure 2):

1. The condition approach results from the stormwater's physical condition and structure load/capacity relations, and
2. The cost approach includes the Current Replacement Value (CRV) and Total Repair Cost (TRC).

Model Design and Analysis. Stormwater control measures (SCM) serve various purposes. From maintaining or improving a property's pre-development water quality and quantity conditions to promoting groundwater recharge and reducing downstream flooding and erosion to purely aesthetic considerations, every system is individually engineered to provide optimal performance for the watersheds.

The maintenance review includes the assessment of current maintenance tasks for several infrastructure types and aspects, which include the following:

- Drainage pump station maintenance (pumps and generators),
- Conveyance system cleaning and condition assessment,
- Maintenance hole cleaning, repair, and replacement,
- Drainage inlet and siphon cleaning,
- Channel maintenance,
- Basin and pond maintenance, and
- Access road and grounds maintenance.

Recommended modifications and additions to the current procedures are made to meet best practices and recommended regulatory guidelines. Detailed assessments and recommendations are proposed in the 5D-SAM below for each infrastructure type or aspect. Figure 3 shows the proposed performance-based operation and maintenance management model that considers the required corroboration of the whole stormwater infrastructure. This model consists of 10 modules; as follows:

1. Stormwater Condition Assessment Module,
2. Measurement Module,
3. Comparison Module,
4. Analysis Module,
5. Options Module,
6. Optimization Module,
7. Design Module,
8. Rehabilitation Module,
9. Re-measure Module, and
10. Final Assessment Module.

Module (1): Stormwater Condition Assessment. The condition assessment of an existing stormwater infrastructure determines whether the asset will function safely over a specified residual service life. Guidelines for the assessment of existing assets have been developed in many countries. They are commonly separated into phases, starting with a preliminary evaluation, followed by a detailed investigation, expert investigation, and finally, an advanced assessment, depending on the structural condition of the investigated stormwater facility. Based on the different applications of the selected articles, the relevant techniques are classified into five categories, as shown in Figure 4:

1. Visual Inspection (VI),
2. Testing Response (TR),
3. Finite Element Modeling (FEM),
4. Nondestructive Evaluation (NDE), and
5. Structure Health Monitoring (SHM).

Module (2): Measurement. Both performances of stormwater facilities and requirements should be expressed quantitatively.

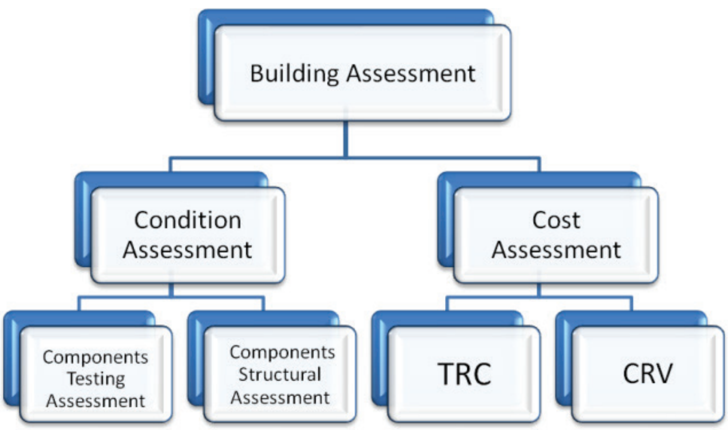

Fig. 2. Main Structure for Stormwater Facility Assessment

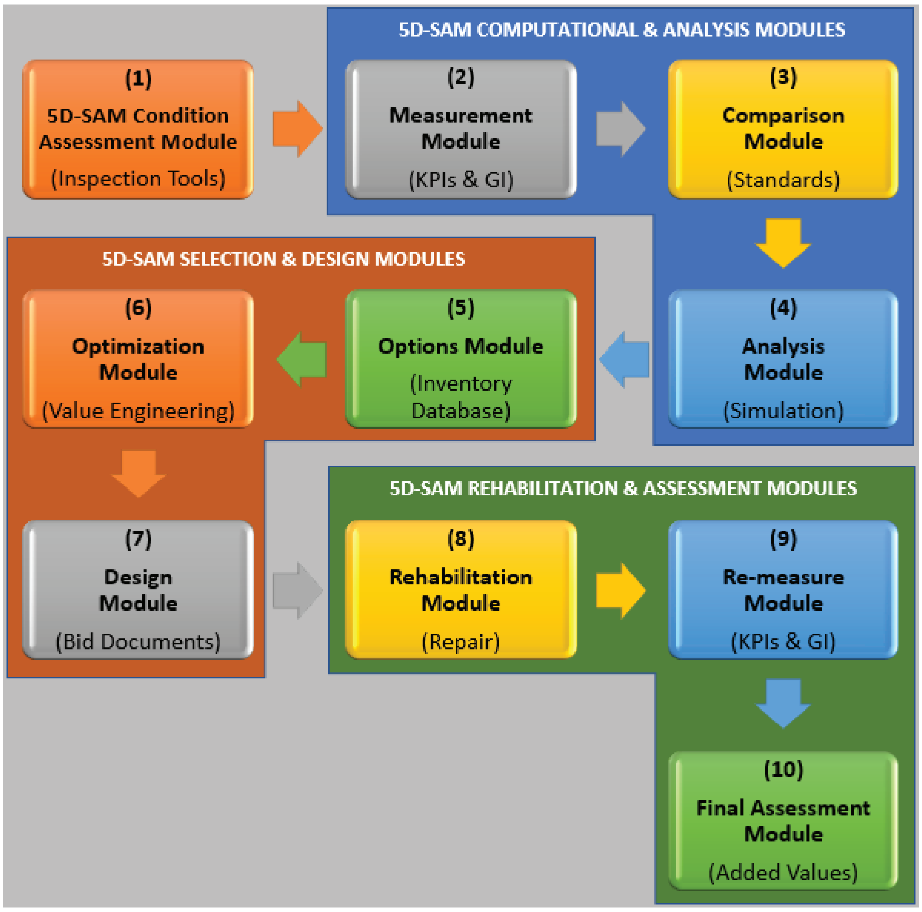

Fig. 3. Proposed stormwater assessment modules

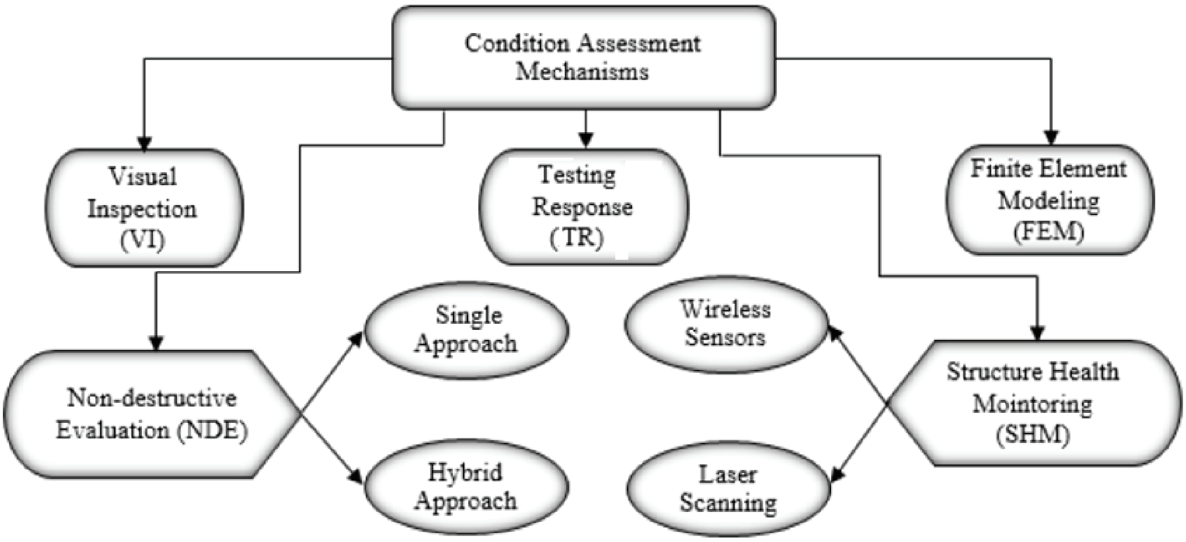

Fig. 4. Condition assessment mechanisms of a stormwater system

Hence, each performance item listed in Table 1 should be symbolized by a corresponding physical variable which can be evaluated through available computational methods. This variable is called a performance index. Table 1 (A-E) shows an example of performance indices for the selected performance items in this proposed operation and maintenance model of the stormwater control measure. The Overall Stormwater Asset Condition (OSAC) equation measures the stormwater infrastructure's general condition ratings (CAS) or performance/health index.

1. A. Performance indices for the Condition of the Stormwater Assets **(1. D = X, Y, Z)**

Category	Item Description	Indicator Designation	Assessment Mechanism	Level	Indicator Formula
1	2	3	4	5	6
Stormwater Hydraulic Asset Condition (SHAC)	Indicating Pipes, Culverts, RCBs Damage Level S = Dia. or Width	Underground pipes to provide hydraulic control of surface flows from collection to treatment (Michael Baker International, 2017)			
	S ≤ 18 in.	Conveyance Asset State (VAS)	Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection every 10 years 4–7 (Fair), if routine inspection bet. 10–12 years 1–4 (Poor), if routine inspection exceeds 12 years
	18 in. < S ≤ 48 in.		Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection every 5 years 4–7 (Fair), if routine inspection bet. 5–7 years 1–4 (Poor), if routine inspection exceeds 7 years
	48 in. < S ≤ 120 in.		Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection every 3 years 4–7 (Fair), if routine inspection bet. 3–5 years 1–4 (Poor), if routine inspection exceeds 5 years
	S > 120 in		Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection every 2 years 4–7 (Fair), if routine inspection bet. 2–3 years 1–4 (Poor), if routine inspection exceeds 3 years
	Indicating Drainage Inlets / Trench Drains Damage Level	Structures that include a drainage inlet and a sediment trap to store surface flows to allow sediment to accumulate			
		Conveyance Asset State (VAS)	Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection annually 4–7 (Fair), if routine inspection bet. 1–5 years 1–4 (Poor), if routine inspection exceeds 5 years
	Indicating Manholes, Junction Boxes Damage Level	Conveyance Asset State (VAS)	Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection every 5 years 4–7 (Fair), if routine inspection bet. 5–7 years 1–4 (Poor), if routine inspection exceeds 7 years
	Indicating Ditches, channels, swales, energy dissipaters Damage Level	Conveyance method used to reduce erosion, promote infiltration of runoff and settling of materials			
		Conveyance Asset State (VAS)	Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection every 5 years 4–7 (Fair), if routine inspection bet. 5–7 years 1–4 (Poor), if routine inspection exceeds 7 years

Continuation of Table 1. A

1	2	3	4	5	6
Stormwater Treatment Asset Condition (STAC)	Indicating Outfalls Damage Level	Locations where a pipe outlet meets criteria contained in the Department's Dry Weather Outfall Inspection Plan. The frequency of inspection of the Outfall of a pipe may differ from the required inspection frequency of the pipe itself			
		Treatment Asset State (TAS)	Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection annually 4–7 (Fair), if routine inspection bet. 1–2 years 1–4 (Poor), if routine inspection exceeds 2 years
	Indicating Bioretention Basin / Bed Filter Damage Level	Basin or filter control structure and underdrain to collect treated water for transport to a discharge point			
		Treatment Asset State (TAS)	Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection annually 4–7 (Fair), if routine inspection bet. 1–2 years 1–4 (Poor), if routine inspection exceeds 2 years
	Indicating Dry Basin / Detention basin Damage Level	Basin with outlet overflow to provide for storage and controlled sedimentation			
		Treatment Asset State (TAS)	Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection annually 4–7 (Fair), if routine inspection bet. 1–2 years 1–4 (Poor), if routine inspection exceeds 2 years
	Indicating Gross Solids Removal Device (GSRD) Damage Level	The flow-through device removes trash, debris and coarse sediment in the water by capturing it in a tubular entrapment			
		Treatment Asset State (TAS)	Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection annually 4–7 (Fair), if routine inspection bet. 1–2 years 1–4 (Poor), if routine inspection exceeds 2 years
	Indicating Infiltration Basin Damage Level	Basin used primarily for infiltration			
		Treatment Asset State (TAS)	Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection annually 4–7 (Fair), if routine inspection bet. 1–2 years 1–4 (Poor), if routine inspection exceeds 2 years
	Indicating Infiltration Trench Damage Level	Infiltration system to temporarily store surface flows and divert underground by infiltration			
		Treatment Asset State (TAS)	Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection annually 4–7 (Fair), if routine inspection bet. 1–2 years 1–4 (Poor), if routine inspection exceeds 2 years
	Indicating Spreading Structure / Level Spreader Damage Level	Structures that redistributes concentrated stormwater flow into sheet flow			
		Treatment Asset State (TAS)	Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection annually 4–7 (Fair), if routine inspection bet. 1–2 years 1–4 (Poor), if routine inspection exceeds 2 years

Continuation of Table 1. A

<table>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th></tr>
<tr><td rowspan="14">Stormwater Treatment Asset Condition (STAC)</td><td rowspan="2">Indicating Permeable Pavement Damage Level</td><td colspan="4">An alternative to conventional asphalt and concrete in highly urbanized settings with low traffic speeds and volumes</td></tr>
<tr><td>Treatment Asset State (TAS)</td><td>Semi-Deterministic (VI) & (TR)</td><td>Component</td><td>7–10 (Good), if routine inspection annually
4–7 (Fair), if routine inspection bet. 1–2 years
1–4 (Poor), if routine inspection exceeds 2 years</td></tr>
<tr><td rowspan="2">Indicating Sand Filter Damage Level</td><td colspan="4">Structures that uses sand to remove sediment and pollutants from stormwater runoff through filtration</td></tr>
<tr><td>Treatment Asset State (TAS)</td><td>Semi-Deterministic (VI) & (TR)</td><td>Component</td><td>7–10 (Good), if routine inspection semi–annually
4–7 (Fair), if routine inspection bet. 1/2–1 year
1–4 (Poor), if routine inspection exceeds 1 year</td></tr>
<tr><td rowspan="2">Indicating Sediment Trap / Traction Sand Trap Damage Level</td><td colspan="4">Particle capture device connected to collection and conveyance system</td></tr>
<tr><td>Treatment Asset State (TAS)</td><td>Semi-Deterministic (VI) & (TR)</td><td>Component</td><td>7–10 (Good), if routine inspection annually
4–7 (Fair), if routine inspection bet. 1–2 years
1–4 (Poor), if routine inspection exceeds 2 years</td></tr>
<tr><td rowspan="2">Indicating Wetland Damage Level</td><td colspan="4">The permanent pond removes sediments and pollutants from stormwater runoff through physical, chemical and biological processes</td></tr>
<tr><td>Treatment Asset State (TAS)</td><td>Semi-Deterministic (VI) & (TR)</td><td>Component</td><td>7–10 (Good), if routine inspection annually
4–7 (Fair), if routine inspection bet. 1–2 years
1–4 (Poor), if routine inspection exceeds 2 years</td></tr>
<tr><td rowspan="2">Indicating Hydrodynamic Separator Damage Level</td><td colspan="4">The vault structure with various configurations to separate sediments from stormwater flows</td></tr>
<tr><td>Treatment Asset State (TAS)</td><td>Semi-Deterministic (VI) & (TR)</td><td>Component</td><td>7–10 (Good), if routine inspection annually
4–7 (Fair), if routine inspection bet. 1–2 years
1–4 (Poor), if routine inspection exceeds 2 years</td></tr>
<tr><td rowspan="2">Indicating Tree Box Filter Damage Level</td><td colspan="4">Designed to mimic natural systems such as Bioretention areas by incorporating plants, soil and microbes</td></tr>
<tr><td>Treatment Asset State (TAS)</td><td>Semi-Deterministic (VI) & (TR)</td><td>Component</td><td>7–10 (Good), if routine inspection annually
4–7 (Fair), if routine inspection bet. 1–2 years
1–4 (Poor), if routine inspection exceeds 2 years</td></tr>
<tr><td rowspan="2">Indicating Vegetated Swale Damage Level</td><td colspan="4">Vegetated channels that convey stormwater runoff as well as remove sediments and pollutants by filtration through grass and infiltration through soil</td></tr>
<tr><td>Treatment Asset State (TAS)</td><td>Semi-Deterministic (VI) & (TR)</td><td>Component</td><td>7–10 (Good), if routine inspection annually
4–7 (Fair), if routine inspection bet. 1–2 years
1–4 (Poor), if routine inspection exceeds 2 years</td></tr>
</table>

End of Table 1. A

1	2	3	4	5	6
Stormwater Treatment Asset Condition (STAC)	Indicating Wet Basin Damage Level	The permanent pond removes sediments and pollutants from stormwater runoff through settling and biological processes			
		Treatment Asset State (TAS)	Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection annually 4–7 (Fair), if routine inspection bet. 1–2 years 1–4 (Poor), if routine inspection exceeds 2 years
Stormwater Asset Structural Condition (SASC)	Indicating the instantaneous probability of failure	Probability of Failure (P_f)	Probabilistic	Section, Component & System	$P_f = P\big(M(t) \le 0\big) = \int_0^\infty F_R(x) f_Q(x) dx$, where R = Random resistance in a certain failure mode. Q = Random load effect in the same failure mode. $F_R(x)$ = Cumulative distribution function of R. $f_Q(x)$ = Probability density function of load effect Q.
	Providing a design margin over theoretical design capacity	Safety Factor in Allowable Stress Design (SF)	Deterministic	Section & Component	$SF = \frac{\sigma_u}{\sigma_{all}}$, where σ_u = Maximum usable stress, σ_{all} = Allowable stress.
	Ratio of the load-carrying capacity of the intact structure to the applied load	Reserve Strength Factor (R1)	Deterministic	Component & System	$R_1 = \frac{C}{Q}$
	The ability of a structure to prevent failure progression	Robustness (RO)	Probabilistic	System	RO, is one of the key measures in the field of progressive collapse and damage-tolerant structures
	Reduce probabilities and consequences of failure and recovery time	Resilience (RE)	Probabilistic	System	RE, can be measured by the infrastructure system functionality after a disaster and by the time it takes to return to pre-disaster levels of performance
Overall Stormwater Asset Condition (OSAC)	Indicating Overall Damage Level	Condition Asset State (CAS)	Deterministic (NDE) & (SHM)	System	$1 \le CAS \le 10$

1. B. Performance indices for the Functionality of the Stormwater System **(2. D = Quality/Functionality)**

Category	Item Description	Indicator Designation	Assessment Mechanism	Level	Indicator Formula
1	2	3	4	5	6
Hydraulic Performance (HP)	Flow Attenuation at the Outlet (Cherqui, 2013)	Multiplicative and Additive Models (MAM)	Deterministic	Section, Component & System	$\frac{Q_{out}}{Q_{in}} = \left(a_0 + \sum_{i=1,3,4} a_i X_i\right)^{b+a_2 X_2}$ [5; 7]
	Volume Reduction at the Outlet (Cherqui, 2013)	Combined Sewer Overflows (CSO), m^3 (Niemczynowicz, 1989)	Probabilistic	Section, Component & System	It is calculated by applying statistical characteristics to several years of rainfall. It is possible to derive a parameterization of the rainfall input and the failure probability and return period of combined sewer overflow to receiving waters can be found
	Pumping Station Overflow (m^3) (Semanedi, 2005)	Dry Weather Flow (DWF)	Deterministic	Section, Component & System	A storage volume of 4 hours at Dry Weather Flow (DWF) shall be provided with DWF being calculated as follows: DWF (m^3/day) = $PG + E + I$, where P = Population in Catchment; G = Domestic Consumption m^3/hd/day); E = Industrial Flows (m^3/d); I = Infiltration (m^3/d)
	Overflow Frequency Indicator (Cherqui, 2013)	Total flow volume (m^3) CSO volume (m^3)	Simulation	Component & System	The overflow frequency of one per year (n = 1) depends on the rain series length, the total flow volume, and the CSO volume used for simulation
	Drainage Duration Frequency (Cherqui, 2013)	Time to peak discharge (time) Volume of peak discharge (m^3)	Deterministic	Component & System	It is calculated from the following formula (Darcy velocity with a hydraulic gradient equal to one)
Hydrological Performance (DP)	Runoff Frequency	Total runoff volume (m^3)	Simulation	Component & System	The runoff and rainfall frequency curves are parallel
	Mean Annual Runoff Volume	Runoff, precipitation, and actual evapotranspiration during year *t*	Deterministic	Component & System	$R_t = P_t - E_t = P_t - P_t F(\phi_t) = P_t[1 - F(\phi_t)]$ [5], where R_t, P_t, and E_t are runoff, precipitation, and actual evapotranspiration during year t, and $F(\phi_t)$ is a functional relationship relating actual annual evapotranspiration to annual precipitation during year t

End of Table 1. B

1	2	3	4	5	6
Hydrological Performance (DP)	Volume of Base Flow and the Stormwater released as Filtered Flows	Pipe flow ratio	Deterministic	Component & System	The pipe flow ratio is defined as $R_q = Q_1/Q_2$, where Q_1 is the flow at the main pipe 1, while Q_2 is the flow at the branch pipe 2.
	Volume of Inflow, Outflow, and Evapotranspired	Inflow to the sewer system (m^3) Inflow to WWTP (m^3)	Deterministic	Component & System	the inflow and outflow/overflow volume are calculated as: $Q_i = \frac{8}{15} utg \frac{\theta}{2} \sqrt{2gh^{2.5}}$ [7], where Q_i is the instantaneous flow of inflow and outflow/overflow, m^3/s
	Catchment-Scale Outcomes	Frequency of flood Duration of the flood (h)	Deterministic	Component & System	The flood frequency can be determined using instantaneous peak discharge data (Log-Pearson Type III distribution).

1. C. Performance indices for the Time-Effectiveness of the Stormwater System **(3. D = Time)**

Category	Item Description	Indicator Designation	Assessment Mechanism	Level	Indicator Formula
Time Condition (TC)	Lifespan and Long-Term Effectiveness	Long-term functionalities	Modeling of Simulation	Component & System	▪ establishment period efficiency = f (vegetation establishment, microbial community assemblage, soil development); ▪ starting efficiency = f (design, installation, local conditions); ▪ efficiency for each storm event = f (storm event features, time of year, watershed conditions, BMP conditions during each storm event); ▪ efficiency between maintenance = f (engineered capability of practices, seasonal changes of vegetation); ▪ efficiency over life cycle = f (maintenance frequency, restored BMP perfomance, failure point); ▪long-term efficiency for each BMP and each environmental concern (runoff/pollutant) = f (establishment period efficiency, starting efficiency, efficiency for each storm event, efficiencybetween maintenance, efficiency over life cycle)
	Lag-Time	Monitoring and maintenance checklist Times	Probabilistic	Component & System	Creating manual outlines procedures and checklists as guidelines for the inspection, monitoring and maintenance.

1. D. Performance indices for the Cost-Effectiveness of the Stormwater System **(4. D=Cost)**

Category	Item Description	Indicator Designation	Assessment Mechanism	Level	Indicator Formula
Environmental and Social Condition (ESC)	Pollutant Concentration Attenuation	Event Mean Concentration (EMC) for predicting water quality	Deterministic	Component & System	$EMC = \frac{\text{total pollutant loading per event}}{\text{total runoff volume per event}} = \frac{\sum_{i=1}^{n} V_i C_i}{V}$, where *EMC* is the event mean concentration, mg/L; *V* is the total runoff volume per event, L; V_i is the runoff volume proportional to the flow rate at the time *i*, L; C_i is the pollutant concentration at time *i*, mg/L; and *n* is number of samples during a single storm event
	Event-Based Pollutant Removal	(%)	Deterministic	Component & System	$Removal\ (\%) = \frac{\sum Inlet\ loading - \sum Outlet\ loading}{\sum Inlet\ loading}$
	Pollution Retention Performance	Pollutant removal rates	Semi-Deterministic	Component & System	$PR_{tot} = (RVR \times PR_{ret}) + ((100 - RVR) \times PR_{over})$, where PR_{tot} is the percent annual pollutant removal rate; *RVR* is the percent annual runoff volume retained; PR_{ret} is the percent annual pollutant removal rate applied to the yearly water volume retained (*RVR*) by the BMP; and PR_{over} is the percent annual pollutant removal rate applied to the yearly water volume routed downstream
	Percentage of Satisfaction	Customer satisfaction	Semi-Deterministic	Component & System	Questionnaire
	Level of Security for the Staff or the Public	Accident frequency rate Accident severity rate Composite Index	Semi-Deterministic	Component & System	Frequency rate = (number of disabling injuries/number of man-hours worked) × 1000,000; Injury severity rate = (number of work-days lost + light-duty days lost) × × 200,000 / total hours worked; Composite index of the frequency rate = the average time loss per case

1. E. Performance indices for the Environmental and Social Impact on the Stormwater Assets **(5. D = Environmental)**

Category	Item Description	Indicator Designation	Assessment Mechanism	Level	Indicator Formula
Cost Condition (CC)	Optimize Preliminary Costs	Value Engineering	Deterministic	Component & System	Implement the systematic approach of VE including all phases: (1) General phase, (2) Information phase, (3) Function phase, (4) Creation phase, (5) Evaluation phase, (6) Investigation phase, and (7) Recommendation phase.
	Optimize Construction Costs	Value Engineering	Deterministic	Component & System	
	Optimize Operational Costs	Value Engineering	Deterministic	Component & System	
	Savings/Return on Investment	Value Engineering	Deterministic	Component & System	

Module (3): Comparison. 5D-SAM calculates the general condition ratings (GCRs) to describe the existing, in-place stormwater infrastructure compared to the as-built condition. The physical, structural condition, functionality/quality, time, cost, and environmental/social aspects are considered. This information is used to determine the GCRs on a numerical scale of 0–9. 0 refers to (failed condition) while 9 is (excellent condition), as described in the Coding Guide (Table 2) and the Equation: $1 \leq GCR \leq 9$

Module (4): Analysis. After almost four decades of use, the general condition ratings are well established in assessing the current condition of the major components of the stormwater infrastructure being inventoried and inspected. The same GCR is true of the appraisal ratings for assessing functional capacities. Changes in these ratings over time reflect the general performance of the stormwater infrastructures. The ratings are used to classify the assets as deficient or not deficient.

Stormwater infrastructures with low GCR condition or appraisal ratings are flagged and classified as follows:

• **SD**: A stormwater asset is classified as structurally deficient if the item Overall Stormwater Asset Condition (OSAC) is rated «poor» condition or worse (coded 4 or lower on the 5D-SAM rating scale).

• **FO**: A stormwater asset classified as functionally obsolete is not SD, but its Hydraulic Performance (HP), Hydrological Performance (DP), and Environmental/Social Aspects are outdated. Classification as FO is triggered by a code of 4 or lower for the three items.

Module (5): Feasible Rehabilitation Strategies. This model establishes existing asset conditions, preservation, rehabilitation, and replacement inventory database guidelines. The determination of the most appropriate intervention for existing stormwater infrastructure is primarily based on the following factors:

- Operation and maintenance conditions
- Stormwater infrastructure conditions
- The extent of corrosion in existing asset
- The extent and widths of cracks
- Functionality conditions
- Strength of materials

The cost analysis of preserving the existing asset should consider the following, as applicable:

• Preserving or replacing the stormwater items

• Effects associated with the elimination of cracks

• Repairing stormwater components

• Impact strengthening on stormwater components with a history

• Mitigating effects of functionality deficient

• Replacing severely corroded or non-functional items

• Adding possible redundancy to system components

• Seismic retrofit, if needed

Module (6): Optimization by Value Engineering. The stormwater asset health index concept is based on a ratio of the current element to the total element values. The health index formulated ranges between 0 % and 100 %. The 5D-SAM rating of 6.9 may be comparable to a health index of 77 %.

2. Common Actions Based on the General Condition Ratings

Code	Description	Common actions
9	EXCELLENT CONDITION	Preservation / Cyclic maintenance
8	VERY GOOD CONDITION – No problems noted	
7	GOOD CONDITION – Some minor problems	
6	SATISFACTORY CONDITION – Structural elements show some minor deterioration	Preservation / Condition-based maintenance
5	FAIR CONDITION – All primary structural elements are sound but may have some minor section loss, cracking, spalling, or scour	
4	POOR CONDITION – Advanced section loss, deterioration, spalling, or scour	Rehabilitation or Replacement
3	SERIOUS CONDITION – Loss of section, deterioratuion, spalling or scour have seriously affected primary structural components. Local failures are possible	
2	CRITIAL CONDITION – Advanced deterioration or section loss present in critical structural components	
1	IMMINENT FAILURE CONDITION – Major deterioration or section loss present in critical components	
0	FAILED CONDITION – Out of service, but beyond corrective action	

Module (7): Design. A new structural and/or hydraulic design of the stormwater infrastructures should be considered for cases of health indices less than 40 %.

Module (08): Stormwater Asset Rehabilitation. Rehabilitation involves major work required to repair the structural integrity of a stormwater asset and work necessary to correct major safety and functionality defects. Stormwater asset rehabilitation projects provide complete or nearly complete restoration of elements or components. Rehabilitation work can be done on multiple elements and components of a structure. Agencies may choose to combine preservation activities on several elements while rehabilitating a component. These projects require significant engineering resources for design, a lengthy completion schedule, and considerable costs. Total replacement of an existing stormwater system with a new facility constructed in the same system requirements must meet the facility's current design aspects and needs over its design life.

Module (09): Re-measure. Inventory items pertain to stormwater infrastructure's characteristics. These items are permanent characteristics for the most part, which only change when the asset is altered in some way, such as rehabilitation. So, inventory items should be replaced after rehabilitation and include the following items:

• Identification – Identifies the structure using location codes and descriptions.

• Structure Type and Material – Categorizes the structure based on the material, design and construction, and wearing surface.

• Age and Service – Information showing when the structure was constructed or reconstructed features the structure information.

• Geometric Data – Includes pertinent structural dimensions.

• Design Aspects – Includes the structural and hydraulic design.

• Navigation Data – Identifies the existence of navigation control, protection, and waterway clearance measurements.

• Classification – Identifies the classification of the structure.

• Required Inspections – Includes designated inspection frequency and critical features requiring special inspections or special emphasis during the inspection.

Module (10): Final Assessment and Solutions to Green Stormwater Infrastructure. The final rehabilitation assessment will be completed and recommendations for green stormwater infrastructure will be proposed involving media filtration, infiltration, ponds, facility design requirements, detention structures, distribution pipes, pumps, basins, and permeable pavements. These items tend to be widely implemented and often unsatisfactorily maintained (Erickson et al., 2013). Guidelines and examples for green stormwater infrastructure solutions will be based on recent scientific research and practitioner experience. Inspection and maintenance examples will be provided in the next research and drawn from practical examples and maintenance suggestions depending on regional characteristics.

Conclusion. The maintenance of stormwater control measures is essential for efficient water management. Very often, some parameters are missing or are expensive to measure. Because of many influential factors, it is challenging to precisely predict the operation and maintenance. Some of which can be changed easily and quickly, but also because of the consequences due to incorrect predictions. The 5D-SAM is beneficial for this purpose to support the final decision that can be made based on a probability distribution. Further, in the 5D-SAM model, the parameters are conditionally independent; thus, it is easy to manipulate the data (add, delete, change) within the ten modules. Finally, the model in this work accurately predicts the optimal solutions and gives correct results when some data are missing.

Recommendations. As a recommendation for future studies, a more rigorous analysis with more variable parameters for minute-level accuracy could be performed. Real-world validation is another scope.

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П'ЯТИВИМІРНА МОДЕЛЬ ОЦІНКИ ЕКСПЛУАТАЦІЇ ТА ТЕХНІЧНОГО ОБСЛУГОВУВАННЯ ЗАХОДІВ ПО БОРОТЬБІ ЗІ ЗЛИВОВИМИ ВОДАМИ – ІНСТРУМЕНТ СТРАТЕГІЧНОГО ПЛАНУВАННЯ І КРИЗОВОГО УПРАВЛІННЯ

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Анотація. *У Сполучених Штатах більшість систем зливової каналізації старіють і руйнуються. Американське товариство інженерів-будівельників (ASCE) у своєму звіті про американську інфраструктуру за 2021 рік оголосило, що дощова інфраструктура отримала оцінку «D». Основна мета дослідження полягає в тому, щоб допомогти особам, які приймають рішення, ефективно впоратися із заходами контролю обмеженого бюджету, неоднозначного та непослідовного застосування експлуатації та обслуговування дощової інфраструктури. Було розроблено п'ятивимірну модель оцінки експлуатації та обслуговування засобів контролю зливових стоків (5D-SAM), включаючи аспекти розташування, якості, часу/кількості, вартості та екологічних аспектів. Модель дуже ефективно допомагає особам, які приймають рішення, визначити поточний стан зливової інфраструктури, спрогнозувати майбутній стан, керувати кількістю та покращити якість зливових стоків у найбільш економічно ефективний спосіб. Це допомагає визначити, чи доцільно знести пошкоджену дощову систему чи її ремонт, реконструкція чи модернізація буде економічно ефективним. Крім того, модель може бути використана для швидкої та точної оцінки та кращого розподілу ресурсів для стратегічного планування інфраструктур зливової каналізації.*

Ключові слова: *модель оцінки, експлуатація та технічне обслуговування, заходи з контролю зливових стоків, зливові інфраструктури*

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THERMODYNAMIC ASPECTS OF THE GEOSYSTEM FUNCTION OF THE PEDOSPHERE

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Abstract. *Modern unceasing processes of dehumification and degradation of arable soils require the search for new non-traditional approaches to solving this global environmental problem, which determines the relevance of the research. After all, plowing significantly disrupts the thermodynamic interaction of the soil with environmental factors. The purpose of the publication is to consider the regularities of the evolution of the properties of the pedosphere from a geosystem perspective, to define the concept of geomembrane properties, and to reveal the mechanism of regulating the thermodynamic interaction of the soil with the environment based on the concept of its homeostasis, which will allow a more reasonable explanation and forecast of modern evolutionary changes in the properties of soils and soil cover from a higher perspective organizational level of the geosystem. The main tasks are defined as: the development of a methodology for studies of the thermodynamic interaction of soil with climatic factors, the creation of tools for monitoring the course of thermodynamically unbalanced processes in the soil environment, and their approbation in the Forest-Steppe zone of Ukraine. It is proposed to consider the soil as a dissipative thermodynamic non-equilibrium system that is constantly in the process of self-stabilization and self-organization due to interaction with climatic factors of the environment. Therefore, soil homeostasis means the presence of subordinate energy-consuming processes of a certain intensity, which form the structure of the thermodynamic system of the soil, as the structure of its pore space. It was determined that the general direction of the development of the pedosphere, as an element of the Earth's lithospheric shell, is the densification of the parent rock with the formation of structural macroporosity of the soil and the development of heterogeneity. It is shown in the example of Ukraine, that the geomembrane properties of soils have a zonal nature and aimed at limiting the power of the zone of active energy-mass exchange. The concept of the dynamics of geomembrane properties of the pedosphere, as a manifestation of a higher hierarchical level of geosystem organization, is proposed to be used to solve purely applied issues, such as assessing the impact of climate change, humus formation, and modern dynamics of soil fertility, increasing the sustainability and ecological safety of soil use.*

Keywords*: pedosphere, soil, thermodynamic system, dissipation, pore space structure, energy efficiency of interaction, soil homeostasis*

Topicality. The pedosphere is the part of the Earth's lithospheric shell bordering the atmosphere, which experiences the strongest influence of external factors that determine the most intensive processes of soil reconstruction and self-organization. According to the Le Chatelier-Braun principle, a system capable of self-stabilization and self-organization changes its properties in a direction that limits the penetration of external disturbances into the system [1]. In fact, the pedosphere regulates the exchange flows of the Earth's lithosphere with the atmosphere and space. However, the most important aspect is the regulation of the thermodynamic interaction of the pedosphere with the external environment, which determines the direction of its self-organization processes and biosphere properties and gives grounds for considering the soil as a thermodynamic system, the functioning of which is determined by the thermodynamic interaction with the environment.

Analysis of recent research and publications. Although the concept of soil moisture potential was formulated by E. Buckingham at the beginning of the last century [2], and in the practice of reclamation agriculture, the potential characteristic of soil moisture has been used to control the water regime for decades, but until now the soil has not been considered as a complete thermodynamic system. After all, the postulates of classical equilibrium thermodynamics are unsuitable for displaying processes in a permanently thermodynamically unbalanced system of the soil environment. Attempts to establish the relationship between soil properties and classical thermodynamic functions – Gibbs potential and entropy – were very time-consuming and not sufficiently effective [3]. And only after the formulation in the period the 70s to 90s of the provisions of synergetics, which deals with the theory of self-organization of complex thermodynamically unbalanced systems [4; 5], at the Institute of Water Problems and Land Reclamation of the National Academy of Agrarian Sciences of Ukraine (IWPLR NAAS), an attempt was made to consider the soil as an integral thermodynamic system.

The purpose of the publication is to consider the regularities of the evolution of the properties of the pedosphere from a geosystem perspective, to define the concept of geomembrane properties, and to reveal the mechanism of regulating the thermodynamic interaction of the soil with the environment based on the concept of its homeostasis, which will allow a more reasonable explanation and forecast of modern evolutionary changes in the properties of soils and soil cover from a higher perspective organizational level of the geosystem.

Research methods. From the point of view of synergy, the soil is identified as a dissipative active kinetic environment in which flows of matter, energy, and information are transformed [6]. Therefore, it is proposed to characterize the soil as a microgradient dissipative structure, in which a special role belongs to macropores with air trapped by liquid membranes, which actively reacts to changes in external thermodynamic parameters of temperature (T, °C), atmospheric pressure (R_{atm}) and moisture saturation (θ_{vol}) by changing its volume and gas pressure. As a consequence of this, macropores become centers of thermodynamic imbalance (CTI), acid centers (AC), and centers of formation of ecotones of soil biota, around which periodically centrifugal gradients of moisture potential and gradients of solution acidity are observed, which causing reciprocating movements of substances with phase transitions. Such energy-consuming subordinate (internal) processes are actually processes of soil formation. This allows to state that soil formation processes occur in the pedosphere everywhere and all the time, and the soil, which genetic soil science defines as a natural-historical body that has constant properties on a real-time scale, actually is a dynamic thermodynamically unbalanced system that is constantly in the process of self-stabilization within the tolerance plateau of external factors, and self-organization when external factors go beyond the tolerance plateau, for example, global climate change. This approach allows substantiates the concept of soil homeostasis, which is determined by the level of consumption (dissipation) of external flows of energy and matter due to energy-consuming subordinate processes of a certain intensity [7]. An eloquent example of the impact of a change in the level of soil homeostasis is the formation of the so-called compacted “plow sole” in the subsoil horizon of soils which used in agriculture. This negative ecological phenomenon of agriculture is actually a systemic reaction of the soil environment to the reduction of soil homeostasis in the subsoil horizon due to damping of the amplitude of temperature and soil moisture fluctuations in the loosened arable layer. This plow sole is formed during the first decades after plowing. And although in agrophysics it is believed that this phenomenon is the result of an increase in the weight of tillage aggregates, in fact, the formation of a plow sole is a reaction to plowing, and an increase in the weight of aggregates can only be a tool for transitioning to a new level of dynamic balance. Failure to use a plow destroys this plow sole over time [8].

Soil homeostasis determines the energy efficiency of soil interaction with the external environment and depends on three components which are the design of the thermodynamic system; the available moisture in it, as a working element, due to which subordinate processes are implemented; the intensity of variability of external thermodynamic factors [7]. To characterize the design of the thermodynamic system, in contrast to the traditional determination of soil structure in agrophysics through the ratio of soil fragments based on granulometric, aggregate, and microaggregate analysis, it is proposed to use its pore space structure (PSS), which reflects the heterogeneity of the environment. With using of a physical model of the capillary porosity of the soil in the form of a corrugated equivalent capillary, the “Method of determining the structure of the pore space of soils (dispersed media)” was developed in IWPLR NAAS [9]. This method is based on the study of the capillary hysteresis loop of the water-holding capacity of the soil. Using it as a research tool made it possible to establish the regularities of spatio-temporal variability of PSS in soils of different genesis, which is characterized by the so-called structural characteristic, which is essentially a differential curve of the distribution of the volume of pore space by porosity radii (Fig. 1) [7]. The PSS is a sensitive tool for monitoring epigenetic changes of pore space in different types of soils, both for irrigation and drainage conditions. If for most soil types the structural characteristic has an extremum, which indicates the presence of pores of a predominant size in them, then for the most fertile chernozem soils this structural characteristic has the form of a monotonically increasing curve. This indicates the development in chernozems of the volumetric structure of the three-dimensional soil matrix, in which the largest volume belongs to the largest macroporosity. This PSS curve is proposed as a benchmark for the development of soil formation, according to which it can be argued that the general progressive development of soil formation is the densification of the parent rock with the formation of macroporosity resistant to external factors. Degradation processes of these soils begin with a decrease in the volume of this very largest porosity, which was recorded, for example, on irrigated chernozems due to non-compliance with scientifically based irrigation regimes.

A system of complex laboratory diagnostics of water-physical properties of soils has been developed and successfully tested at the IWPLR

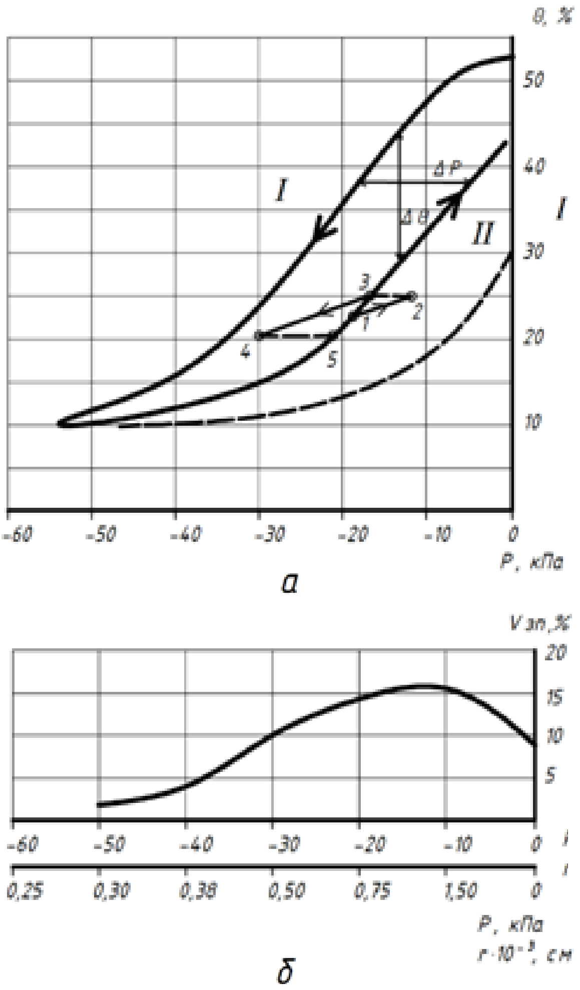

Fig. 1. Hysteresis diagram of soil water-holding capacity (a); structural characteristic of the pore space $V_{зп} = f(r)$; I – bifurcation area, II – tolerance area [7]

NAAS [10]. In particular, the regularities of PSS in the soil profile approaching the ground surface were established. The result of soil formation is a natural decrease in the volume of elementary pores of the predominant size, but an increase in the size (radii) of this predominant porosity [11]. For hydromorphic conditions of soil formation, it was found that the volume of a certain group of pores decreases in the capillary border, until it completely disappears, due to the lack of their self-development due to capillary filling with water. According to the depression of the structural characteristic, it is even possible to identify the weighted average position of the groundwater level, relative to the depth of sample selection, with an accuracy of up to 10 cm [12]. However, the structure of the soil pore space is derived from the diagram of the thermodynamic state, which combines the capacitive properties with the power of stabilizing moisture in the soil (Fig. 1), and the most informative is the capillary hysteresis loop obtained in a special mode. Therefore, from the geosystemic point of view, the thermodynamic interaction of the soil with the environment is regulated by the construction of the three-dimensional soil matrix, which combines such fundamental properties as heterogeneity and hysteresis. Using the example of chernozem, it can be concluded that the implementation of geomembrane properties to limit the penetration of external disturbances deep into the soil profile is ensured by the growth of water-holding capacity and hysteresis, which generally reduces the conductivity parameters of the soil environment, primarily for moisture flow, but increases its dissipativeness in relation to energy flows. Enrichment of chernozem with free types of surface energy ensures its high fertility.

Research results and their discussion. Characterized for chernozem soils PSS, as a design of a thermodynamic system, ensures a high intensity of subordinate processes by dissipating external flows in the soil, which creates increased availability of nutrients from the soil to plants, i. e. is a determining factor of soil fertility. In fact, the energy efficiency of soil interaction with climate factors has a direct correlation with soil fertility, and the production process is considered as the utilization of external energy by plants according to their own genetic program. An important role in these processes is played by the symbiosis of the mineral component of the soil with organic matter, in particular, the accumulation of humus, which should primarily be considered not as a chemical formation, but as a thermodynamic process of qualitative ordering (assembly) of high-molecular organic compounds in conditions of cyclic washing of low-molecular compounds by subordinate processes. However, it is no less important that the accumulation of humus in the soil transforms it from a purely capillary body into a colloid-capillary body, in which the mobility of moisture is significantly limited. After all, moisture is removed from the colloidal body mainly through evaporation. This is seen as one of the mechanisms for the formation of geomembrane properties of soils and the pedosphere in general – limiting the penetration of external thermodynamic disturbances, in particular moisture flows, deep into the Earth in the radial direction. The process of densification of the parent rock with the formation of stable structural macroporosity also limits the thermal conductivity parameters and the depth of active energy-mass exchange in the soil environment.

Experimental monitoring studies of soil regimes up to a depth of 5.0 m using thermodynamic hydrophysical methods in the soil-geochemical chain from the watershed to the floodplain of a small river were conducted in the Obukhiv district of Kyiv region (Forest-Steppe zone) in the period of 1989–2005 [13]. These studies made it possible to establish a regular spatial variability of the geomembrane properties of the soil cover, which is characterized by a set of indicators such as the infiltration nutrition and seasonal dynamics of moisture reserves, the chemistry of pore solutions, the structure of the pore space of soils and the level of their fertility, etc. The highest development of the geomembrane properties of soils is established in the plakor part of the watershed which is characterized by the zone of active energy mass exchange did not exceed 3–4 m, because at this depth the mineralization of pore solutions of chloride-sulfate composition increased to 3–5 g/dm^3, infiltration nutrition is virtually absent, the automorphic mode of soil formation, the growth of the soil profile occurs due to atmospheric dust deposition, so here is the most complete section of the holocene with the presence of humus buried soils. The realization of geomembrane properties occurs due to the loosening and growth of soil heterogeneity and its humus content. On the slopes which are characterized by the zone of active energy-mass exchange exceeding 5 m, there is a periodically washing water regime, and the development of PSS is relatively lower due to water erosion and planar washing of fine soil, the processes of epigenetic restructuring of PSS is activated in the entire soil profile, in particular, at its lower border in the parent rock, soil fertility is reduced, the chemistry of pore solutions is hydrocarbonate-calcium with mineralization up to 1 g/dm^3. In the floodplain of a small river which is characterized by the effluent water regime with fluctuations of soil water levels from 0.0 to 2.0 m, which determines the zone of active energy-mass exchange, and the realization of geomembrane properties, in particular, from limiting the depth of active water exchange, is ensured by magnesium-sodium salinization, PSS is characteristic of hydromorphic soils.

In addition to the variation of geomembrane properties within the Forest-Steppe and the formation of different types of soils (the principle of divergence), it was established that within Ukraine, the formation of geomembrane properties is determined by the degree of balance of moisture and heat flows, and specified the latitudinal zonation of these properties. In particular, in the energy-limited zone of Polissia, the limitation of the zone of active energy-mass exchange ensures the formation of a weakly permeable, unstructured, compacted illuvial (podzolic, glee, etc.) horizon within the first meter of the soil section. This horizon, serving as a pre-surface screen for moisture flows, ensures the discharge of excess atmospheric precipitation by surface runoff. In the conditions of modern climatic changes, which increase the energy supply of the Polissia zone, this illuvial horizon serves as a screen for the reproduction of underground water resources, which leads to their progressive depletion. A radical means of combating such a negative ecological phenomenon for the new climatic conditions in Polissia is the destruction of this illuvial horizon by means of deep meliorative loosening or plantation plowing [14]. Such measures have been practiced in drainage reclamation to accelerate the cultivation of drained soils, which require periodic repetition to maintain a high level of homeostasis (fertility) of these soils. After all, in the drained soils of reclamation systems, which are mainly in the capillary border of groundwater, the disappearance of a certain group of pores due to intense fluctuations of soil water levels, which leads to the compaction of these soils, was found.

For the Steppe zone of Ukraine, the limiting factor of the self-development of the soil and its energy efficiency is the lack of moisture. That is why, in this water-limited zone, irrigation melioration is the most effective for increasing soil homeostasis and fertility.

Therefore, in the Forest-Steppe of Ukraine, with a balanced amount of precipitation and heat, the highest development of the geomembrane properties of the pedosphere is recorded. Accordingly, this zone is the most bioproductive [15]. In the direction of the energy-limited zone of Polissia, the geomembrane properties of the pedosphere are aimed at limiting the depth of active water exchange, and when moving from the Forest-Steppe to the south to the water-limited zone of the Steppe, the geomembrane properties of the pedosphere decrease due to the insufficient level of soil self-organization, which is limited by the lack of moisture. Such regularities should be taken into account when predicting evolutionary changes in soil properties under the conditions of global climate changes and shifts in the balance of the amount of heat and moisture.

Conclusions. Considering the soil as a complete thermodynamically unbalanced system in interaction with the thermodynamic factors of the environment according to the formulated concept of homeostasis makes it possible to unambiguously evaluate and predict changes in soil properties under global climate changes at any point of the soil environment according to the level of consumption in the subordinate processes of the soil of the kinetic energy of external flows, as a manifestation geomembrane function. A conservative criterion for changing such soil properties is epigenetic changes in the structure of its pore space, as a design of a thermodynamic system, which is characterized by a laboratory-determined loop of capillary hysteresis of water-holding capacity in a special mode.

Constant processes of self-organization and self-stabilization provide a change in the geomembrane properties of the pedosphere, which have a latitudinal zonation and depend on the degree of balance of heat and moisture flows. The highest development of geomembrane properties of the pedosphere, caused by the balance of heat and moisture flows, is observed in the Forest-Steppe zone. Within the energy-limited zone of Polissia, the limiting geomembrane function of the pedosphere is aimed at reducing the penetration depth of water flows. Within the soil-climatic zones, the spatial differentiation of the soil cover according to geomembrane properties is determined by the relief, lateral flows of matter, and other natural and anthropogenic factors that limit the level of soil self-organization.

The level of homeostasis, as the top manifestation of the geomembrane properties of the soil, which has an energetic nature, can be studied by remote methods and can have a direct correlation with fertility parameters.

The application of the concept of geomembrane properties of the soil cover will make it possible to move away from purely stochastic models of spatial distribution and dynamics of soil properties and to increasingly use parametric dynamic deterministic models for modeling geomechanics. In particular, their use in soil rheology is promising. The latitudinal zonality of the development of geomembrane properties determines the latitudinal zonality of the ecological resistance of the pedosphere to pollutants and pollution: the most resistant is the Forest-Steppe zone, which must be taken into account when placing environmentally hazardous enterprises and justifying the zonal coefficient of ecological stability of the soil cover.

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ТЕРМОДИНАМІЧНІ АСПЕКТИ ГЕОСИСТЕМНОЇ ФУНКЦІЇ ПЕДОСФЕРИ

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Анотація. *Сучасні невпинні процеси дегуміфікації та деградації орних ґрунтів вимагають пошуку нових нетрадиційних підходів до вирішення цієї глобальної екологічної проблеми, що й визначає актуальність дослідження. Адже оранка суттєво порушує термодинамічну взаємодію ґрунту з чинниками довкілля. Метою публікації є розгляд закономірностей еволюції властивостей педосфери з геосистемних позицій, визначення поняття геомембранних властивостей та розкриття механізму регулювання термодинамічної взаємодії ґрунту з довкіллям на основі поняття його гомеостазу, що дозволить більш обґрунтовано пояснювати і прогнозувати сучасні еволюційні зміни властивостей ґрунтів і ґрунтового покриву з позицій більш високого організаційного рівня геосистеми. Основними завданнями визначено: розроблення методології досліджень термодинамічної взаємодії ґрунту з кліматичними чинниками, створення інструментарію для контролю перебігу термодинамічно нерівноважних процесів у ґрунтовому середовищі та їхня апробація у зоні Лісостепу України. Запропоновано розглядати ґрунт як дисипативну термодинамічну нерівноважну систему, що постійно перебуває у процесі самостабілізації і самоорганізації за рахунок взаємодії з кліматичними чинниками довкілля. За цього під гомеостазом ґрунту розуміється наявність субординаційних енерговитратних процесів певної інтенсивності, що формують конструкцію термодинамічної системи ґрунту, в якості якої прийнята структура його порового простору. Визначено, що загальним спрямуванням розвитку педосфери, як елементу літосферної оболонки Землі, є розущільнення материнської породи з формуванням структурної макропористості ґрунту та розвитком гетерогенності. На прикладі України показано, що геомембранні властивості ґрунтів мають зональну природу і спрямовані на обмеження потужності зони активного енергомасообміну. Концепцію динаміки геомембранних властивостей педосфери, як прояв більш високого ієрархічного рівня геосистемної організації, пропонується використовувати для вирішення суто прикладних питань, таких як оцінювання впливу змін клімату, гумусоутворення і сучасна динаміка родючості ґрунтів, підвищення стійкості і екологічної безпеки використання ґрунтів.*

Ключові слова: *педосфера, ґрунт, термодинамічна система, дисипація, структура порового простору, енергоефективність взаємодії, гомеостаз ґрунту*

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PROSPECTS OF SOYBEAN GROWING IN THE WESTERN POLISSIA ZONE

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Abstract. *Modern climatic changes, namely significant warming in the northern Forest-Steppe and Polissia zones of Ukraine, provide opportunities for growing a number of grain and leguminous crops (maize for grain, soybeans, sunflower, and others), previously unusual for this region. Among the above-mentioned crops, soybean is a crop that can significantly improve the nitrogen balance of the soil without the use of mineral fertilizers; its cultivation to some extent can be an alternative to expensive nitrogen fertilizers because, under the condition of inoculation, soybean can leave up to 80 kg/ha of biological nitrogen, which equivalent to 300 kg of ammonium nitrate, which is enough for forming decent harvest of winter wheat or corn. The analysis of meteorological data shows that when having the current amount of heat supply during the growing season in the Western Polissia zone, it is possible to grow ultra-early and early-ripening soybean varieties with a duration of the growing season of up to 90–100 days and a required number of heat units – up to 2400–2500 CHU. It was established that the main factor limiting the cultivation of soybeans on the peat soils of the Western Polissia zone is a significantly shorter frost-free period (compared to the adjacent sod-podzolic soils on dry land). Therefore, for growing on peat soils, it is necessary to choose ultra-early varieties of soybeans with a growing season of up to 85 days and the required number of heat units – up to 2400–2500 CHU. That will allow obtaining physiologically ripe seeds before the onset of the first autumn frosts, which in some years can already occur in the first decade of September. On peat soils, the yield of the Yunka soybean variety by the variants of the experiment ranged from 15,1–24,8 t/ha, while on the adjacent sod-podzolic light loamy soils it was 30,3–46,8 t/ha. The reason for the significantly lower soybean yield on peat soils is a short frost-free period compared to sod-podzolic soils, which did not allow the studied varieties to fully realize their potential for 2 years in a row. The research has established that on sod-podzolic light loamy soils of the Western Polissia zone, under favorable conditions, the yield of such ultra-early and early-ripening soybean varieties as Yunka and Astor of the Sevita genetics selection (Canada) can be up to 45,0–46,8 t/ha. The use of Rizofix inoculant in a combination with Rice Pi phosphorus-mobilizing product allows increasing the productivity of soybeans to 6,7–7,0 t/ha. Additional profit from their use is about 8–8,3 thousand hryvnias from 1 ha.*

Keywords**:** *soybean, soil, Polissia zone, climate change, biological preparations, fertilizers*

Relevance of research. Soybean is one of the most widespread leguminous crops in world agriculture. This is a potentially highly productive crop, as confirmed by American farmers, where a grain yield of 7–8 t/ha is normal. The world record for soybean yield belongs to the US farmer Randy Dowdy (Missouri) – 12,78 t/ha. Record high yields (more than 10 t/ha) in production conditions were obtained by the farmer from the USA, Kip Cullers (California). In Ukraine, in production conditions, no more than 4–5 t/ha of soybean grain is usually obtained [1; 2].

In the USA, crop rotation with alternating soybean and corn is widely used. Soybean monoculture is common here, but genetically modified varieties resistant to Glyphosate are mainly grown in unchanged plantings. The importance of soybeans is evidenced by the fact that the United States annually exports more of its grains than the Russian Federation of oil, gas, and metal. For comparison, corn in the USA occupies 32% of the cultivated area, and soybeans – 29% [2; 3].

The total area of grain and leguminous crops in Ukraine has remained almost unchanged for more than 30 years, but the share of their production by natural and climatic zones has changed. Thanks to the increase in yield, 65 % of grain is grown in Polissia and the Forest Steppe zones, although the share of their plantings in these regions is only 53 % [1; 3; 4].

As for the sown areas of soybeans in Ukraine, in 2021 they amounted to about 1.28 million hectares. In general, since 1990, soybean acreage has increased more than 20 times. A comparison of the data for the last 10 growing seasons showed an increase in the area of soybean crops in 16 regions of Ukraine. Thus, for the period from 2010 to 2019, the largest increase was recorded in the farms of the Forest-Steppe zone: Khmelnytsky region – 100.64 thousand hectares; Sumy region – 53,3 thousand hectares, Ternopil region – 64,2 thousand hectares. In the humid zone, the largest increase in cultivated area under soybeans was recorded in the Zhytomyrska region – 99,34 thousand hectares; Chernihiv region – 62,06 thousand hectares, Lviv region – 53,66 thousand hectares. In the Rivne region, the sown area under soybeans increased from 23,000 hectares to 86,000 hectares, and in the Volyn region from 9,000 hectares to 37,000 hectares [4].

Soy occupies a leading position due to the high profitability of cultivation and stable demand of domestic and global agricultural markets. In addition, soybean is a unique fodder, food, technical, and medicinal crop and an excellent previous crop for any crop, including winter wheat, corn, winter rapeseed, and sugar beet [5].

Analysis of recent research and publications. In modern economic conditions, producers are rapidly moving to the cultivation of several export-oriented crops, the vast majority of which are corn for grain, sunflower, winter rapeseed, winter wheat, and soybeans [6]. Among the above-mentioned crops, soy is the crop that can significantly improve the nitrogen balance of the soil without the use of mineral fertilizers [7]. The rest of the crops are characterized by very high rates of removal of nutrients per unit of the crop. Therefore, their cultivation technologies are based on the application of increased rates of mineral fertilizers, without which it is almost impossible to achieve a high yield. In addition, soybean is a crop that is very sensitive to the content of certain trace elements in the soil, such as sulfur and magnesium [1; 2]. In the conditions of a significant increase in the cost of mineral fertilizers and especially nitrogen fertilizers, which are limiting in the technology of growing corn, sunflower, and winter wheat, soybean plants get up to 65–80 % of the total need for nitrogen from the atmosphere [8].

Soybean is, without exaggeration, a new crop for the Western Polissia zone, because 15–20 years ago, its cultivation here was considered very risky [1; 2; 9]. The main limiting factor for growing soybeans for grain in the Western Polissia region is the low natural fertility of most soil types, high acidity and light mechanical composition of the soil, limited heat resources, etc. [9; 10]. At the same time, because of climate warming, a real opportunity has appeared to grow soybeans in this zone, and it has every prospect of occupying its niche among other crops [1; 3; 11].

The possibility of successful soybean cultivation in this soil-climatic zone is indicated by the fact that as the results of the experiments in the territory of the neighboring Republic of Belarus (which is located much north of the Western Polissia zone of Ukraine), 19–29 t/ha of physiologically ripe soybean grain of the ultra-early Yaselda variety was obtained [12].

Under certain conditions, soybean almost does not need nitrogen fertilizers. Therefore, in the conditions of a significant rise in the cost of nitrogen fertilizers, there is every reason to claim that its acreage will increase significantly in the coming years in Ukraine because the application of nitrogen fertilizers is minimal when cultivating soybeans. If inoculants are used for growing soybeans, the need for nitrogen fertilizers is eliminated. Soy leaves up to 60–80 kg of nitrogen per 1 hectare in the soil, so it is an excellent previous crop for subsequent crops in a crop rotation [7; 13; 14]. In modern agriculture, winter wheat or corn is widely cultivated after soybeans. Soy replenishes up to 70 % of the total nitrogen consumption due to its biological fixation from the air with the help of symbiosis with nodule bacteria [1; 7; 10].

Since the soils of the Polissia zone do not contain symbiotic nodule bacteria Rhizobiumjaponicum, the introduction of bacterial preparations is mandatory [2; 7]. World practice has proven that inoculation is a relatively inexpensive and effective measure to increase soybean productivity, since the cost of using most preparations per 1 ha is on average 5–6 US dollars, and the yield increase, by the averaged data from scientific institutions, is 2–6 c/ha [8; 13].

Soy is a monsoon climate crop, and when planning its cultivation in the Polissya zone, scientists recommend choosing the most early-ripening varieties, which are guaranteed to ensure the production of physiologically ripe seeds under the condition of limited heat resources [1; 2; 7].

In previous years' research conducted by the Sarny Research Station on test plots located on drained peat soils, ultra-early soybean varieties with a growing season of 75–85 days had enough time to form physiologically ripe grain before the onset of persistent frosts. Even later ripening varieties with a growing season of 100–105 days ripened on the adjacent sod-podzolic soils.

The soil cover of the Polissia zone consists of 2 large groups of soils – mineral and organic. Mineral soils are mainly represented by various types of sod-podzolic soils, among which the light loam and loam types are the most suitable for growing soybeans [9; 10; 11].

Organogenic soils of the Polissya zone are mainly represented by lowland peat soils of various thicknesses, which, unlike sod-podzolic soils, are well supplied with nitrogen and moisture. One of the advantages of peat soils over sod-podzolic soils is the presence of significant moisture reserves [15]. The analysis of long-term data of the Sarny Research Station shows that in the one-meter layer of peat, the total moisture reserves, even in the driest years, amount to more than 4600–5000 m^3 per 1 ha; that is more than enough for the normal growth and development of all crops.

So, until recently, the issue of growing soybeans in the Western Polissia zone has been poorly studied, as well as the selection of varieties by the ripeness groups, the effectiveness of fertilization, inoculation, and the use of plant growth regulators, etc.

The goal of the research is to specify the possibility and expediency of growing new high-yielding varieties of soybeans of different ripeness groups and the effectiveness of using phosphorus-mobilizing and nitrogen-fixing preparations of biological origin on the drained land of the Western Polissia zone.

Research materials and methods. In 2021, a study on the possibility of growing soybeans on drained sod-podzolic and peat soils under the condition of limited heat resources was started at the Sarny Research Station of the Institute of Water Problems and Land Reclamation of the National Academy of Agrarian Sciences of Ukraine. For research, 5 varieties of soybeans of different ripeness groups (from ultra-early to medium-late) were chosen to establish the possibility of obtaining physiologically ripe seeds in the climatic conditions of the Western Polissia zone. In the experiment, 4 (non-GMO) soybean varieties of Canadian selection (Sevita genetics) and 1 of American selection were studied:

– Yunka, vegetation period is 85 days; the required number of heat units is 2350 CHU;

– Astor, vegetation period is 105 days; the required number of heat units is 2500 CHU;

– Niagara, the vegetation period is 108 days; the required number of heat units is 2600 CHU.

– Neptune, vegetation period is 120 days; the required number of heat units is 2700 CHU.

– SB142 – a variety of American selections, vegetation period is 125 days; the required number of heat units – 2750 CHU.

The above soybean varieties were studied in 2 blocks of field experiments (on drained peat and sod-podzolic light loam soils), which are the most common in the Western Polissia zone; that makes the obtained data representative for the entire region.

In the first block of field research, in 2 identical experiments, the yield potential of new soybean varieties of different ripeness groups and the effectiveness of nitrogen-fixing and phosphorus-mobilizing preparations were studied on drained peat and sod-podzolic light loamy soils. In the experiments, the effectiveness of Rise P and RhizoFix Soy preparations of a well-known Canadian brand Lallemand, the official distributor in Ukraine – the company «Agritema» was studied.

RhizoFix Soy is a high-quality dry inoculant for soybeans that contains at least 4x109/g (4 billion CFU/g) of live cells of Bradyrhizobium elkanii bacteria. The preparation initiates the mass formation of productive nitrogen-fixing nodules already at the initial stages of plant development. That is a dry sterile peat-based preparation of highly effective strains U1301 and U1302 of the bacterium Bradyrhizobium elkanii. **Rise P** is a phosphorus-mobilizing preparation (Bacillius anyloliquefacies bacterium) strain IT 45. Agritema company is the official representative and distributor of these preparations in Ukraine.

Research results and their discussion. When choosing soybean varieties by ripeness, it is necessary to pay attention to the heat supply indicators during the growing season, which include the average monthly air temperatures and their anomalies, the dates of the beginning and end of different temperature periods, in particular the growing season (warm) and the period of the active growing season, the sum of the active and effective temperatures and others [13; 14; 16]. The dates of stable transition of the average daily air temperature over 0, 5, 10, and 15 °C and the duration of the periods with the temperatures above these limits are used to determine the duration of the vegetation of cold-resistant (period with a temperature above 5 °C) and heat-loving (above 10 °C) crops, the period of their intensive growth (over 15 °C), when planning the dates of the start of fieldwork in the spring (dates of transition over 5 °C) and their termination (transition over 0 °C) in autumn, etc. (Table 1).

1. Dates of stable transition of temperature over 0, 5, 10, 15 °C and the duration of the corresponding periods in the drained peat bog massif Chemerne (Rivne region), average for 2007–2021

Value	Dates of temperature transition over certain limits and the duration of the corresponding periods											
	> 0°	< 0°	days	> 5°	< 5°	days	> 10°	< 10°	days	> 15°	< 15°	days
$D_{average}$	24.02	5.12	284	25.03	30.10	217	22.04	3.10	163	12.05	7.09	116
D_{min}	26.01	9.11	254	14.03	6.10	186	4.04	24.09	128	27.04	24.08	100
D_{max}	30.03	31.11	331	11.04	25.11	248	30.04	23.10	188	7.06	18.09	141

The analysis of the dates of the stable temperature transition confirms the trend of the last decades towards an earlier start of the growing season (on average 10 days earlier than usual) and a later ending, which ultimately results in an increase in the length of the growing season by an average of 11 days. Over the years of research, its duration varied from 186 to 248 days with an average value of 217 days. The duration of the period of active vegetation (with temperatures > 10 °C) exceeded the norm by an average of 5 days, and the period of intensive vegetation (> 15 °C) by 10 days. In most cases, the growing season began in the third decade of March, and the period of active vegetation began in the third decade of April.

It should be noted that by the data of Belarusian scientists (Republican Center of Hydrometeorology) in the territory of Belarusian Polissia, since 1989, an abnormally early steady transition of the air temperature over 0 °C in spring has also been registered. On average, for 1989–2018, the transition of air temperature over 0 °C in spring occurs 8–13 days earlier compared to the multi-year dates. The transition of air temperature over 5 and 10 °C in spring also occurs earlier than multi-year dates by 7–10 and 2–7 days, respectively [17, 18]. These data are fully consistent with the data of our meteorological station for almost all key indicators.

The sum of active temperatures above 10 °C, at which ultra-early soybean varieties ripen having a duration of the vegetation period (VP) up to 91 days, amounts to 2100–2200 °C; for early ripening varieties with a duration of VP of 91–100 days, the sum of active temperatures is 2200–2600 °C, while for medium-early ripening ones with a duration of VP of 101–110 days, the sum of active temperatures is 2600–2800 °C, and for medium-ripening ones with a duration of VP of 111–120 days, the sum of active temperatures is 2800–3000 °C. There are more late-ripening varieties of soybeans; however, it is impractical to consider them for growing in the Polissia zone [1; 2]. The hydrothermal conditions of active vegetation period on the drained peat bog massif Chemerne of the Sarny research station are given in the table. 2.

Based on the data given in Table 2, it can be stated that having the current heat supply during the growing season in the Western Polissia zone, it is possible to grow ultra-early and early-ripening soybean varieties with a growing season of up to 100 days. However, it should be kept in mind that during the vegetation period heat-loving crops use less active heat than the amount entering the regions of the Western Polissia zone. This is due to the fact that the vegetation period is limited by spring and autumn frosts, which can occur even after the average daily air temperature is higher than 10 °C.

One of the dangerous meteorological phenomena complicating the cultivation of soybeans in the Western Polissia zone is a short frost-free period. Frosts on peat soils are especially dangerous. The duration of the frost-free period on the drained peat bog massif Chemerne of the Sarny research station is given in the table 3.

Based on the data of the weather station of the Sarny research station (the only one in the

2. Hydrothermal conditions during active vegetation period on the drained peat bog massif of the Sarny research station

Years	Active vegetation period							
	Dates		days	Σt > 10 °C	Σp, mm	HTC	T aver, °C	Σd, mb
	beginning	end						
2018	04.04	19.10	198	3186	248	0,78	16,9	1231
2019	23.04	28.04	188	2864	323	1,13	16,2	1121
2020	28.04	16.10	171	2760	342	1,24	16,7	968
2021	30.04	18.09	141	2477	228	0,92	18,0	968
2022	24.04	20.09	149	2412	201	0,83	16,8	982
Average	**25.04**	**30.09**	**158**	**2498**	**302**	**1,23**	**16,3**	**822**

3. Duration of the frost-free period on the drained peat bog massif of the Sarny experimental station

Year	Date of the last spring frost in the air	Date of the first autumn frost in the air	Duration of the frost-free period
2018	28.04	26.09	150
2019	09.05	19.09	132
2020	21.05	20.09	121
2021	09.05	05.09	118
2022	24.05	01.09	99
Average	08.05	23.09	137

system of hydrometeorological observations of Ukraine, which is located directly on the peat bog massif), in some years the last spring frosts in the Western Polissia zone can be observed even in the 2nd decade of May, while the first autumn frosts can be already observed in the beginning of September, as was the case in 2021–2022. The average long-term duration of the frost-free period for the Chemerne peat bog massif is 137 days. However, there are years with an abnormally short frost-free period. So, for example, in 2022, the frost-free period on the Chemerne peat bog massif was only 99 days.

In order to establish the yield potential of the studied soybean varieties on sod-podzolic soils, mineral fertilizers were applied at the rate of $N_{60}P_{60}K_{60}$ and $N_{35}P_{60}K_{90}$ on peat soils. The previous crop in both cases was corn for grain (Table 4).

As the research carried out during 2021–2022 showed, in general, high yields of soybean grain were obtained for all studied varieties that were sown on drained sod-podzolic light loamy soils. The highest yields were obtained for the varieties of the early ripeness group, namely Yunka and Astor varieties – 45,1 and 45,0 t/ha, respectively.

The varieties of the later ripeness group – Niagara and Neptune – lower yields were obtained – 34,3 and 37,6 t/ha, respectively. The American selection variety Sb_{142} (the most late-ripening variety of the studied ones) provided a lower yield compared to the Canadian selection varieties – 27,5 t/ha)

It should also be noted that in the experiments on sod-podzolic soils, it was necessary to desiccate crops of such varieties as Astor, Niagara, Neptune and Sb_{142} for 2 years. Among the studied varieties, only the Yunka variety provided grain with a moisture content of 14,2–14,6% without desiccation for 2 years.

Regarding the studied biological preparations, on sod-podzolic soils, higher efficiency was obtained with the use of RhizoFix Soy inoculant, the increase in yield from its use in the studied varieties was 3,5–4,0 t/ha. The use of the phosphorus-mobilizing preparation Rise P was somewhat less effective, the increase in yield from its use in the studied varieties was 2,8–3,4 t/ha.

When combining RhizoFix Soy inoculant and the phosphorus-mobilizing preparation Rise P the yield increase in the studied varieties was 5,2–7,0 t/ha. The rather low efficiency of inoculation on peat soils is explained by their high nitrogen content.

Results of the research on organogenic soils**.** Soil and climatic conditions on drained peatlands are fundamentally different from soils of mineral origin on dry land located in their immediate vicinity [15; 17]. The study on the possibility of growing soybeans on peat soils in the very first year revealed a number of limiting factors and risks, without taking into account of which a partial or complete loss of the yield is possible. The yield of studied soybean varieties on drained peat soils is given in the Table 5.

4. Effect of nitrogen-fixing and phosphorus-mobilizing preparations on soybean productivity on drained mineral soils, average for 2021–2022

Variety	Duration of the vegetation period, days	Number of heat units,CHU	Soybean yield by the variants of using preparations, tons/ha			
			Without preparations	RhizoFix Soy	Rise P	RhizoFix Soy + Rise P
Yunka	85	2350	38.5	42.5	41.6	45.1
Astor	105	2575	38.0	41.8	41.4	45.0
Niagara	108	2600	28.7	32.3	31.9	34.3
Neptune	120	2700	31.2	34.7	34.0	37.6
Sb_{142}	124	2750	22.3	26.0	25.1	27.5
$Hip_{0.5}$ c/ha			1.75	1.44	1.56	1.72

5. Effect of nitrogen-fixing and phosphorus-mobilizing preparations on soybean productivity on drained peat soils, average for 2021–2022

Variety	Duration of the vegetation period, days	Number of heat units,CHU	Soybean yield by the variants of using preparations, tons/ha			
			Without preparations	RhizoFix Soy	Rise P	RhizoFix Soy + Rise P
Yunka	85	2350	21.0	22.0	25.6	26.2
Astor	105	2575	19.7	20.2	22.8	23.7
Niagara	108	2600	19.2	19.9	22.4	23.2
Neptune	120	2700	15.9	16.4	19.1	19.6
Sb_{142}	124	2750	13.7	14.3	18.3	18.8
Hip $_{0.5}$ c/ha			1.19	1.27	1.17	1.25

In contrast to sod-podzolic light loamy soils, relatively low yields of soybeans were obtained on peat soils for 2 years for all studied varieties. Especially low yields, compared to sod-podzolic soils, were recorded for late-ripening varieties, namely Neptune and Sb_{142}.

The reason for this is that already in the first decade of September, for 2 years in a row, abnormally early first autumn frosts were observed on drained peat soils, which actually ceased the vegetation of all studied soybean varieties. During the period of the first decade of September, only the most early-ripening variety from the studied ones, namely the Yunka variety, managed to form the largest number of physiologically ripe seeds. Its productivity by the variants was 21,0–26,2 t/ha. However, even for the Yunka variety, there was a significant shortfall in the yield, since the vegetation was ceased at the time of intensive grain filling. Thus, the weight of 1000 seeds of the Yunka variety on sod-podzolic soils was 185–190 grams, while on peat soils it was only 140–145 grams. For the rest of the late-ripening varieties (Astor, Niagara, Neptune and Sb_{142}), the plants did not have enough time to form physiologically ripe seeds in the beans of the upper tier.

Regarding the studied biological preparations, higher efficiency on peat soils, compared to the treatment of seeds with RhizoFix Soy inoculant, was provided by the use of the phosphorus-mobilizing preparation Rise P. The rather low efficiency of inoculation on peat soils is due to the high nitrogen content. While the higher efficiency of the phosphorus-mobilizing preparation Rise P is due to the presence of phosphorus in the peat soil in difficult-to-access forms (vivanite), which, due to the action of bacteria contained in this preparation, is transformed into forms more accessible to plants. In the second block of field research, the productivity of short crop rotation with such an alternation of crops as winter wheat, soybean, corn, sunflower, and sugar sorghum was studied. In the second block of research, the Yunka variety was studied – the earliest ripening one of Sevita genetics selection varieties.

The yield of the Yunka soybean variety depending on the fertilization system and the variants of using biological preparations is shown in Table 6.

As a result of study on sod-podzolic soils it has been established that the use of the inoculant RhizoFix Soy and the phosphorus-mobilizing preparation Rise P against along with the application of mineral fertilizers at the rate of $N_{30}P_{30}K_{30}$ provided an increase in the yield of soybeans by 6,7 c/ha, while the application of mineral fertilizers at the rate of $N_{60}P_{60}K_{60}$ provided an increase in the yield of soybeans by 10,5 c/ha. When increasing the rate of application of mineral fertilizers, the effectiveness of the use of the RhizoFix Soy inoculant and the phosphorus-mobilizing preparation Rise P significantly decreased.

By the results of 2-year study, it was found that in general, the effectiveness of using the RhizoFix Soy inoculant and the phosphorus-mobilizing preparation Rise P on peat soils is lower compared to sod-podzolic soils. This is primarily due to lower soybean inoculation efficiency, as peat soils are naturally rich in nitrogen.

In general, the economic expediency of using the above preparations on sod-podzolic soils in soybean crops is more than obvious. Thus, the cost of using both preparations (RhizoFix Soy + Rise P) per 1 ha of sowing area is about UAH 850–900, while the additional profit from their use is approximately UAH 8000–8300.

Conclusions. Based on the meteorological data of the Sarny Research Station, it can be stated that having the current heat supply during the growing season in the area of the Western Polissia on sod-podzolic soils, it is possible to grow ultra-early and early-ripening soybean varieties with a vegetation period of up to 90–100 days and the required number of heat units – up to 2400–2500 CHU.

On sod-podzolic light loamy soils of the Western Polissia zone, under favorable conditions, the yield of ultra-early and early-ripening soybean varieties can be 35–45 t/ha. The use of

6. Effect of fertilization systems on the yield of the Yunka soybean variety on drained land, Sarny Research Station of IWPLR of NAAS, average for 2021–2022

Fertilization systems	Fertilization variants and biological preparations	Yield, c/ha	± to reference		± to standard	
			c/ha	%	c/ha	%
sod-podzolic soil						
Reference	$N_{30}P_{30}K_{30}$	30.8	–	–	–	–
Organic fertilization system	Agrobiotech (Biosyl + Stimpo + Regoplant)	34.1	3.3	10.7	–	–
	Agritema (RhizoFix Soy+Rise P)	37.5	6.7	21.8	–	–
Mineral fertilization system (standard)	$N_{60}P_{60}K_{60}$	41.3	10.5	34.1	–	–
Organo-mineral fertilization system	$N_{60}P_{60}K_{60}$ + Agrobiotech (Biosyl + Stimpo + Regoplant)	43.1	12.3	39.9	1.8	4.4
	$N_{60}P_{60}K_{60}$ + Agritema (RhizoFix Soy+Rise P)	46.8	16.0	51.9	5.5	13.3
Hip $_{0,5}$ c/ha		1.01				
peat soil						
Reference	Without fertilizers	15.1	–	–	–	–
Organic fertilization system	Agrobiotech (Biosyl + Stimpo + Regoplant)	16.4	1.3	8.6	–	–
	Agritema (RhizoFix Soy+Rise P)	20.3	5.2	34.4	–	–
Mineral fertilization system (standard)	$N_{35}P_{60}K_{90}$	21.4	6.3	41.7	–	–
Organo-mineral fertilization system	$N_{35}P_{60}K_{90}$	23.4	8.3	55.0	2.0	9.3
	$N_{35}P_{60}K_{90}$ + (RhizoFix Soy+Rise P)	24.8	9.7	64.2	3.4	15.9
Hip $_{0,5}$ c/ha		0.78				

the RhizoFix Soy inoculant and the phosphorus mobilizing preparation Rise P allows to increase the productivity of soybeans up to 6.7 t/ha.

The results of the study conducted in 2021–2022 show that the main limiting factor of the cultivation of soybeans on the peat soils of the Western Polissia zone is a significantly shorter (compared to the adjacent sod-podzolic soils on dry land) frost-free period. Therefore, for growing soybeans on peat soils, it is advisable to choose ultra-early varieties of soybeans with a vegetation period of up to 85 days and the required number of heat units – up to 2400–2500 CHU, which will allow obtaining physiologically ripe seeds before the onset of first autumn frosts, which in some years may be observed in the first decade of September.

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ПЕРСПЕКТИВИ ВИРОЩУВАННЯ СОЇ В ЗОНІ ЗАХІДНОГО ПОЛІССЯ

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Анотація. *Сучасні кліматичні зміни, а саме суттєве потепління в зонах північного Лісостепу та Полісся України, дають можливості для вирощування низки зернових та зернобобових культур (кукурудзи на зерно, сої, соняшнику та інших), раніше непритаманних для цього регіону. Серед вищевказаних культур саме соя є культурою, яка здатна істотно покращити азотний баланс ґрунту без застосування мінеральних добрив, саме вирощування її деякою мірою може стати альтернативою дороговартісним азотним добривам, адже за умови інокуляції після себе соя може лишати до 80 кг/га біологічного азоту, що еквівалентно 300 кг аміачної селітри, чого достатньо для формування пристойного урожаю озимої пшениці чи кукурудзи. Аналіз метеоданих показує, що при нинішніх показниках теплозабезпеченості вегетаційного періоду в зоні Західного Полісся на дерново-підзолистих ґрунтах можливе достигання ультраранніх та ранньостиглих сортів сої з тривалістю вегетаційного періоду до 90-100 днів і необхідною кількістю теплових одиниць – до 2400-2500 CHU. Встановлено, що основним лімітуючим чинником, що обмежує вирощування сої на торфових ґрунтах зони Західного Полісся, є значно коротший, (порівняно з прилеглими дерново-підзолистим ґрунтами на суходолі) безморозний період. Тому для вирощування на торфових ґрунтах слід обирати ультраранні сорти сої з тривалістю вегетаційного періоду до 85 днів і необхідною кількістю теплових одиниць – до 2400-2500 CHU, що дозволить одержати фізіологічно-стигле насіння до настання перших осінніх заморозків, які в окремі роки можуть бути відмічені уже в першій декаді вересня. На торфових ґрунтах урожайність сої сорту Юнка по варіантах досліду становила – 15,1-24,8 ц/га, в той час як на прилеглих дерново-підзолистих легкосуглинкових ґрунтах – 30,3-46,8 ц/га. Причиною значно нижчого врожаю сої на торфових ґрунтах є короткий безморозний період порівняно з дерново-підзолистими ґрунтами, який протягом 2-х років поспіль не дав змоги повною мірою реалізувати потенціал досліджуваних сортів. Дослідженнями встановлено, що на дерново-підзолистих легкосуглинкових ґрунтах зони Західного Полісся за сприятливих умов урожайність таких ультраранніх та ранньостиглих сортів сої як Юнка та Астор селекції Sevita genetics (Канада) може становити до 45,0-46,8 ц/га. Застосування інокулянту Різофікс у поєднанні з фосформобілізуючим препаратом Райс Пі дозволяє підвищити урожайність сої до 6,7-7,0 ц/га. Додатковий прибуток від їхнього застосування становить близько 8-8,3 тис.грн з 1 га.*
Ключові слова: *соя, ґрунт, зона Полісся, зміни клімату, біопрепарати, удобрення*

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OPTIMIZATION OF THE PARAMETERS OF DRIP IRRIGATION REGIMES FOR CROPS IN THE STEPPE OF UKRAINE

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Abstract. *The purpose of the research was to improve and substantiate the parameters of the drip irrigation regimes for crops in the Steppe of Ukraine. Field studies were carried out at the Kamyansko-Dniprovska experimental station (47°46' N 34°42' E), the Brylivska experimental station (46°40' N 33°12' E) and the Southern research station (46°33' N 33°59' E) from 2004 to 2021 on 11 crops. The research scheme assumed the implementation of a one-factor experiments' series with different levels of soil humidification, the control was the variant without irrigation. At the first stage, the mathematical dependencies "Soil moisture level (SML) –Number of vegetation irrigations" and "SML–Irrigation rate" were obtained for all crops. The establishment of correlations between the evapotranspiration of crops and their productivity is the result of the work. Based on this, were built the dependencies (statistical models) "Evapotranspiration – Productivity" and the most optimal options for using water were determined in terms of its costs for the formation of products for the drip irrigation of the Steppe of Ukraine. The given dependencies are reaction curves for a one-factor experiment, they consist of three areas: limiting, stationary and excessive. Correlation coefficients r=0,92–0,98 indicate a close relationship between these parameters. Established relationships "Evapotranspiration – Yield" from an agro biological point of view are not stable since there are potential opportunities for increasing yields with the same evapotranspiration. It has been established that the optimal moisture range for drip irrigation of most crops is a narrow range of soil moisture suction pressure of –9 to –15 kPa. This involves irrigation with small rates (50–75 m³/ha) while reducing the inter-irrigation periods. Under such conditions, the ratio of actual transpiration (Tc) to potential (T_0) approaches 1 (≈ 0,83–0,87), which characterizes the water supply of plants as close to optimal.*

Keywords: *drip irrigation, soil moisture level, evapotranspiration, yield crops, mathematical dependencies*

Relevance of research The unfavorable water regime of the soil is a limiting factor in the realization of agricultural resource potential in the Steppe zone of Ukraine. Today, there are many measures aimed at minimizing the negative impact of droughts, however, as practice shows, irrigation is the most effective. During the most active development of land reclamation (1966–1990), the area of irrigated land in Ukraine was brought to 2,62 million hectares [8]. In 1990–2000 during the economic crisis in Ukraine, the actual irrigated area decreased sharply – to 0,58–0,69 million ha, which corresponds to the indicators of 1966–1968, and in 2014 – to 0,49 million ha (excluding Crimea). However, we note that this reduction refers to the so-called "large irrigation" – sprinkling. On the other hand, the area under drip irrigation increased from 4,5 thousand ha (2000) to 75,5 thousand ha (2014), of which 46,5 thousand ha were under field crops [12].

Analysis of recent research and publications. The advantages of drip irrigation over other irrigation methods (sprinkling, surface irrigation) are known. In this aspect, it should be noted that due to the compliance of drip irrigation technologies with two interrelated conditions – high economic efficiency and environmental safety, it has become widely used for irrigating vegetables, fruit crops, and vineyards [1]. In recent years, the interest of Ukrainian farmers in the introduction of drip irrigation on crops such as corn, soybeans, sugar beet, sunflower, and others has increased. [3; 5]. At the same time, we state that farmers, using intensive technologies for growing field crops on drip irrigation, do not always get the desired effect. After all, drip irrigation involves changing the main components of agricultural technology: irrigation regimes, fertilization, plant protection, sowing patterns, sowing and harvesting techniques and technologies. At present, these elements have not yet been fully developed and scientifically substantiated specifically for the soil and climatic conditions of the Steppe of Ukraine.

Research materials and methods. Field studies were carried out at the Kamyansko-Dniprovska experimental station (47°46' N 34°42' E), the Brylivska experimental station (46°40' N 33°12' E) and the Southern research station (46°33' N 33°59' E) from 2004 to 2021 on 10 crops. The research scheme assumed the implementation of a one-factor experiments' series with different levels of soil humidification, the control was the variant without irrigation.

The placement of experimental sites is systematic, and replication is fourfold [14]. Tensiometric sensors installed at different depths of the soil profile and distance from the water supply point were used to determine the timing of irrigation and study evapotranspiration [10; 12]. For accounting and observations, they were used as generally accepted [2; 14], as well as improved methods [9; 11; 12].

Research results and their discussion. It has been experimentally established that, among the other factors, the level of pre-irrigation soil moisture has the greatest influence on the formation of the irrigation regime. It was recorded that with an increase in SML from -20 kPa to -15 kPa, the number of watering's and the irrigation rate, respectively, increase by 45 % or 25 pcs. and by 42 % or 900 m^3/ha (Fig. 1).

1. Objects (geography of research) and types of crops

№	The name of the scientific station	Location / soil-climatic zone	Crops / years of research
1	Kamyansko-Dniprovska experimental station	vill. Kamyanka-Dniprovska, Zaporizhzhia region, South-Central Steppe subzone, 47046' N 34042' E	carrots (2004–2006), potatoes (2006–2010), pepper, eggplant (2010–2013), sugar beet (2010–2014), corn (2012–2020), soybeans (2010–2020)
2	Brylivska experimental station	vill. Pryvitne, Oleshkivs′ky district, Kherson region, Dry Steppe, 46040' N 33012'	tomato (2009–2011), onion (2011–2013), corn (2012–2020), sugar beet (2012–2014), chickpeas (2018–2021)
3	Southern research station	vill. Velykyy Klyn, Holoprystanskyi district, Kherson region, Dry steppe 46033', N 33059' E	watermelon (2006–2008)

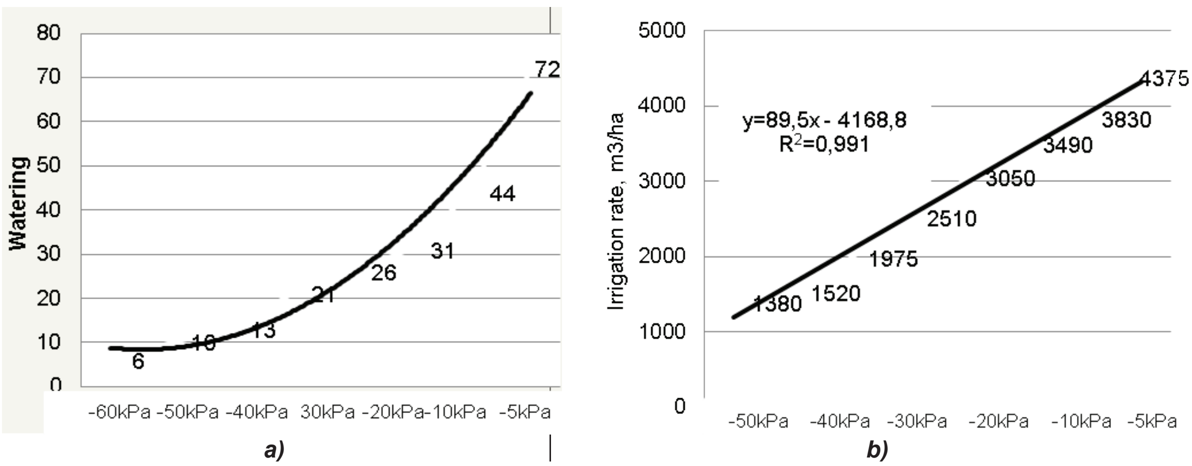

Fig. 1. Dependencies of the number of watering's (a) and irrigation rate (b) from the soil moisture level

It is known, that the irrigation regime is closely related to the meteorological parameters that directly affect physical evaporation and transpiration: the amount of precipitation, temperature and relative humidity of the air, and wind strength. The closest correlation dependence "Irrigation regime – Meteorological parameters" is established only by the "Amount of precipitation" factor.

In particular, the records state that the influence of the amount of precipitation is greater, the lower the level of moisture supply of plants: when maintaining the pre-irrigation threshold of 60% of the minimum moisture-holding soil capacity (MMHSC), the difference in the irrigation rate (or the number of watering's) between years with 50% and 75% precipitation 42%, for 70% MMHSC – 36%, 80% MMHSC – 25%, 85% MMHSC – 22%, 90% MMHSC – 17% and MMHSC – 7% (Fig. 2).

The inter-irrigation period also shortens with an increase in the temperature regime. However, such regularity can be observed only in periods of abnormal heat. For example: in August, the duration of the inter-irrigation period, while maintaining a soil moisture level of -20 kPa, is 3,5–5,5 days, depending on the crop, and in periods with abnormally high average daily air temperatures of +29–30 °C (maximum – +39,0–40,5 °C), the inter-irrigation period is shortened to 1–2 days.

As a result of research, correlations between evapotranspiration and crop yield have been established. Based on this, "Evapotranspiration-Yield" dependencies were built for drip irrigation conditions, and optimal options for water use by plants were determined from the point of view of its costs for the formation of a unit of production (Fig. 3).

These dependencies are response curves for a one-factor experiment, they consist of three

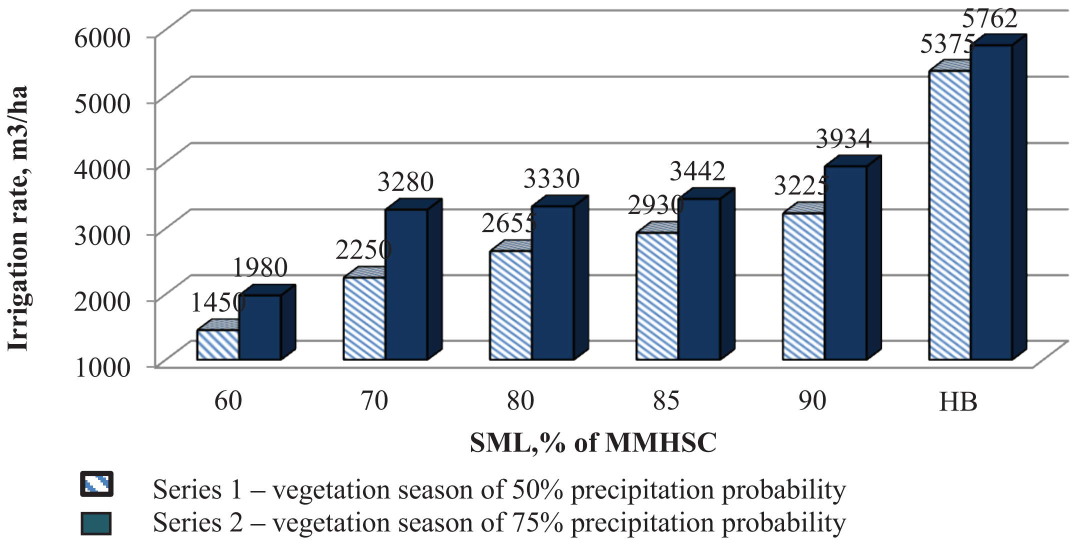

Fig. 2. Dependence of the irrigation rate on the availability of precipitation

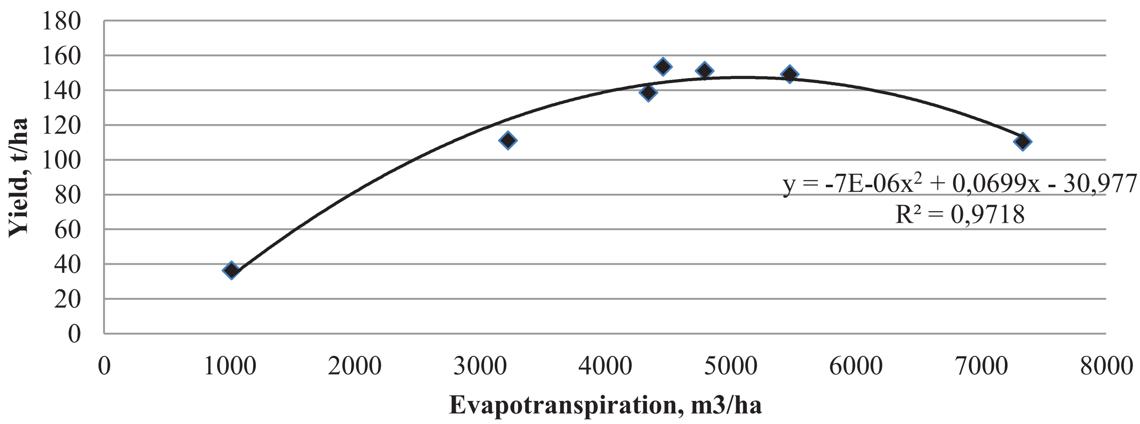

Fig. 3. Dependence of "Evapotranspiration-Yield" under drip irrigation (on the example of tomatoes)

areas: limiting, optimal, and inhibitory (excessive). The coefficient of determination R^2 = 0,81–0,98 indicates a close relationship between these values. It has been established that the limiting area of the curve corresponds to the experimental options for RPWG from -50 to -35 kPa and the variant without irrigation (control), the optimal area – from –35 to –10 kPa and the inhibitory area (excess area) – from –10 to 0 kPa. Established dependencies "Evapotranspiration-Yield", from an agro biological point of view, are not stable, since there are opportunities to increase yields with the same plant's evapotranspiration. Therefore, the task of future research on the study of plant's evapotranspiration processes is to reduce unproductive water consumption (for physical evaporation, runoff into the lower soil horizons) while simultaneously increasing crop yields.

Generalized experimental data on irrigation regimes prove that for most crops the lowest critical limit of soil moisture is -25… -30 kPa (Table 2).

The optimal moisture range for light and medium loams for tilled crops is a fairly narrow interval from -15 to -9 kPa, which provides for irrigation with relatively small rates while reducing the inter-irrigation periods. According to analytical calculations, with such a narrow range, the ratio of actual transpiration (T) to potential (T_0) approaches 1 (≈0,83–0,87), which characterizes the moisture supply of plants as close to optimal [6]. The results obtained are a refinement of the previously stated conclusions [7], that noted that the optimal lower limit of moistening of hard loamy soil is 75–80 % of MMHSC, medium and light loam – 65–70 % of MMHSC and sandy loam – 65 % from MMHSC and data confirmation [4].

It is natural that the maintenance of high humidity conditions the growth of both physical evaporation and transpiration. This, in turn, increases irrigation rates (Table 3), which are 3,3–4,1 thousand m^3/ha for vegetables, and 3,8–5,4 thousand m^3/ha for other field crops. Based on these data, the thesis about the "economy of irrigation water with drip irrigation" was clarified: with practically the same irrigation rates, with drip irrigation, a 1,5–3,5 times higher yield is formed, which gives reason to talk exclusively about the saving of specific water consumption for the formation of a crop unit.

Differentiation of the moisture level by development stages of plants confirmed the existence of critical periods in the life of plants, during which even a slight decrease in soil moisture beyond the optimal range leads to significant yield losses. It has been established that plants experience the highest sensitivity to a decrease in available moisture in the soil during the period of formation of fruiting organs or the period preceding it (Table 3).

The result is the hypothesis's confirmation [13] that states that biennial plants (onion, carrots, sugar beet) in the first year of life do not have a clearly defined critical period regarding moisture availability. At the same time, even in the first year of life, when we grow these crops to obtain productive organs, we note their unequal resistance to the reduction of soil moisture in different phases of development. For example, for carrots and sugar beets, such a "sensitive", but not critical period – Is the intensive growth of root crops.

Studies have confirmed the patterns of evapotranspiration formation: the minimum amount of moisture consumed by plants at the beginning of the growing season gradually increases with the development of their above-ground mass and decreases again by the end of the growing season. Peak parameters of plant evapotranspiration were recorded in the hottest periods; calendar-wise, they usually

2. Generalized parameters of drip irrigation regimes for field crops (heavy/medium loam soil)

Crop	Preirrigation soil humidity, -kPa	Waterings	Irrigation rate, m^3/ha	Evapo-transpiration, m^3/ha	Evapo-transpiration coefficient, m^3/t	Yield, t/ha
Tomato	25–20–30	40	3450	4950	32.7	151.9
Pepper	25–20	42	3655	5020	74.9	67.0
Eggplant	20	53	4085	5330	112.7	47.3
Watermelon	27	15	1200	2600	48.4	45.4
Carrots	25–30	22	3280	5075	72.6	69.8
Onion	15	42	3340	4280	74.7	57.3
Potato	25	17	1250	2300	84.9	27.1
Corn	20	29	4400	6500	357.1	18.2
Soy	20	31	5400	6900	1112.9	6.22
Sugar beet	23	23	3840	5400	44.5	121.4
Chickpeas	25	26	4800	6860	1410	4.90

3. Critical periods for moisture supply of field crops with drip irrigation

Crop	A critical phase or growth stages of plants
Tomato	budding – flowering
Pepper	flowering – development of fruits
Eggplant	flowering – development of fruits
Watermelon	flowering – development of fruits
Potato	budding – flowering
Corn	10 days before throwing out the panicle – flowering – 10 days after flowering
Soy	budding – flowering

corresponded to the 2nd-3rd decade of July – the 1st – 2nd decade of August. The maximum indicators of daily evapotranspiration are fixed at the level of 9–12 mm in the conditions of the Steppe of Dry Ukraine and 8–11 mm in the conditions of the Steppe of Southern Ukraine. Design institutions should be guided by such parameters when designing drip irrigation systems in these soil-climatic zones.

Conclusions. The obtained dependencies "Evapotranspiration-Yield" for drip irrigation are response curves for a single-factor experiment, which have the form of an asymmetric parabola, described by a quadratic equation. The coefficient of determination R^2 = 0,81–0,98 indicates a close relationship between evapotranspiration and productivity parameters. It has been established that the optimal range of moistening of light and medium loams for field crops is a narrow interval from -9 kPa to -15 kPa, which provides for irrigation with lower rates while simultaneously shortening the periods between watering. Therefore, the ratio of actual transpiration (T) to potential transpiration (T_0) is close to 1 (≈0,83–0,87), which characterizes the moisture supply of plants as close to optimal. The existence of critical periods in the life of plants regarding moisture supply was confirmed, at the same time, it was established that in the first year of life, two-year plants (onion, carrots, sugar beet) do not have a clearly defined critical period regarding moisture supply. It was established that the maximum daily evapotranspiration rates of field crops under drip irrigation in the conditions of the Steppe of Dry Ukraine are 9–12 mm, and the Steppe of Southern Ukraine is 8–11 mm.

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УДК 631.674.6

ОПТИМІЗАЦІЯ ПАРАМЕТРІВ РЕЖИМІВ КРАПЛИННОГО ЗРОШЕННЯ СІЛЬСЬКОГОСПОДАРСЬКИХ КУЛЬТУР В СТЕПУ УКРАЇНИ

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Анотація. *Метою досліджень було удосконалення та обґрунтування параметрів режими краплинного зрошення сільськогосподарських культур в Степу України. Польові дослідження проводили на Кам'янсько-Дніпровської дослідній станції ІВПіМ (47046' пн.ш. 34042' сх.д.), Брилівському опорного пункту ІВПіМ (46°40΄ пн.ш. 33°12΄ сх.д.) та Південній дослідній станції ІВПіМ (46°33΄ пн.ш. 33°59΄ сх.д.) у період з 2004 по 2020 роки на 10 сільськогосподарських культурах. Схема досліджень передбачала реалізацію серії однофакторних дослідів з різними рівнями зволоження ґрунту, контрольним був варіант без зрошення. На першому етапі нами отримали математичні залежності «Рівень зволоження ґрунту – Кількість вегетаційних поливів» та «Рівень зволоження ґрунту – Зрошувальна норма» для всіх культур. Режим краплинного зрошення також знаходився у зв'язку з метеорологічними параметрами, які безпосередньо впливали на фізичне випаровування та інтенсивність транспірації. Найбільш тісну кореляційну залежність «Режим краплинного зрошення – Метеорологічні параметри» було встановлено за фактором «Кількість опадів». Результатом роботи є встановлення кореляційних зв'язків між евапотранспірацією сільськогосподарських культур та їх урожайністю. На основі цього для краплинного зрошення Степу України побудовано залежності (статистичні моделі) «Евапотранспірація – Урожайність» та визначено найбільш оптимальні варіанти використання води з точки зору її витрат на формування продукції. Наведені залежності є кривими реакції на однофакторний дослід, вони складаються із трьох областей: лімітуючої, стаціонарної та інгібуючої. Коефіцієнти кореляції r = 0,92 – 0,98 свідчать про тісний зв'язок між цими параметрами. Встановлені залежності «Евапотранспірація – Урожайність» з агробіологічної точки зору не є стійкими, тому що існують потенційні можливості підвищення врожайності за однакової евапотранспірації. Встановлено, що оптимальним діапазоном зволоження за краплинного зрошення більшості сільськогосподарських культур є вузький інтервал всмоктуючого тиску ґрунтової вологи -15 до -9 kPa. Це передбачає проведення поливів невеликими нормами (50-75 м³/га) за одночасного скорочення міжполивних періодів. За таких умов співвідношення фактичної транспірації (Тс) до потенційно можливої (T_0) наближається до 1 (≈ 0,83–0,87), що характеризує вологозабезпечення рослин як близьке до оптимального.*

Ключові слова: *краплинне зрошення, рівень вологості ґрунту, випаровування, урожайність сільськогосподарських культур, математичні залежності*

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EVALUATION OF THE ECONOMIC EFFICIENCY OF RESTORATION OF DRAINAGE SYSTEMS IN THE HUMID ZONE OF UKRAINE: MAKING INVESTMENT DECISIONS

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Abstract. *Approaches to assessment of the economic effectiveness of restoring drainage systems in the humid zone of Ukraine are substantiated. A conceptual scheme has been developed that determines the stages of evaluation, sources of the input array of information, strategic orientation, and invariance of restoration projects, provides for considering a number of risks and limitations of a systemic and non-systemic nature when evaluating the project effectiveness of strategic alternatives. The basis of the evaluation is the results of the analysis of materials regarding the technical condition of drainage systems, the restoration of which in the drainage area is carried out according to two options: modernization of working (on an area of 1311.2 thousand ha) and restoration of non-working (on an area of 1962.9 thousand ha) drainage systems. In the calculations of restoration (modernization) costs, the results of a preliminary assessment of the cost of restoration work for various types of drainage systems (drainage, drainage-humidification, polder, and water circulation systems) were used based on the reduced costs for restoration of the intra-farm and inter-farm network, which were adopted in the "Strategy of Irrigation and Drainage ..." [27]. The economic indicators of the production of agricultural crops economically attractive to farming producers (grain corn, sunflower, rapeseed, soybean) were calculated under the conditions of their production before and after the implementation of the project of restoration (modernization) of drainage systems. The application of the traditional scheme for projected indicators calculating, at which the discount rate was defined as the weighted average cost of capital (WACC), is substantiated. Taking into account the specifics of drainage system restoration (modernization) projects and their duration, the weighted average rates for long-term loans and deposits (risk-free) for legal entities, taking into account the inflation component and the value of equity capital of agro-industrial complex enterprises, were chosen as the discount rate for the preliminary pre-investment analysis. Based on the calculation of the project effectiveness of the restoration (modernization) of drainage systems using the scenario approach according to the consolidated option for determining the payback of investment costs, it is proved that the options at the discount rates r1 (for 2021) and r2 (for the beginning of 2022), as well as the discount rate for the equity scheme, they give positive indicators of the investment project, which indicates the expediency of its implementation and economic efficiency. The internal rate of return for the three options shows a sufficient margin of safety (24–26%). The most economically expedient is the option with a source of financing from the equity capital of agro-industrial complex enterprises, for which the non-discounted (RR) and discounted (DPP) payback terms are 3.4 and 4.7 years, respectively.*

Keywords: *drainage system, restoration of drainage systems, economic efficiency, scenario approach, investment project*

Relevance of research. The global long-term practice of agricultural production on drained lands shows that the effective use of drainage systems and regulation of the water regime of the soil allows to ensure the stability of cultivation and growth of crop yields, strengthening of the economy of farms and positive socio-economic changes [1–5].

In the humid zone of Ukraine, there is powerful water management and reclamation (drainage) infrastructure, which is located on a total area of about 3.3 million hectares and includes 1.671 reclamation systems, in particular: 835 drainage systems of one-way action on an area of 1,6 million hectares (51%), 585 two-way drainage-irrigation systems on an area of 1.1 million hectares (34%) and 251 polder and water circulation systems on an area of 0.51 million hectares (15%) [6].

Reclamation measures were carried out on most of the lands of the amelioration fund of the humid zone (60.5%). Thus, in the Zakarpattia region almost 99% of the reclamation fund has been drained, 76% – in the Chernivetskyu region, and 84% in the Rivnenskyu region [2]. According to the indicator of land reclamation, the drainage zone corresponds to the level of such countries as the USA (60%), Germany (66%), the Netherlands (81%) [3; 6].

At the same time, modern climate changes create new conditions for growing crops, including on drained lands, which, accordingly, transforms the role of drainage systems, the economic, ecological, and social stability of the region depends on the efficiency of their use.

At the same time, 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, the 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 established that the technical condition of drainage systems is characterized by general depreciation of engineering infrastructure elements due to their long-term operation by an average of 60% (inter-farm network – 55% and intra-farm network – 65%) [6]. Consequently, the effectiveness of the use of drained lands and their role in the food and resource provision of the state has significantly decreased. Therefore, the current stage of the development of the water management industry of the humid zone is characterized by a complex of unresolved tasks, which are related to the peculiarities of the functioning of drainage systems in the complex and changing conditions of the humid zone.

Along with this, the determining condition for the possibility of implementing not only modern intensive technologies for growing agricultural crops, but also the formation and preservation of water resources, the creation of favourable living conditions, and the protection of the rural population and rural areas from harmful effects is the restoration of the effective functioning of the drainage systems of the drainage area [6; 7].

Analysis of the latest research and publications on the world experience of restoring drainage systems shows that in many countries (England, Belgium, the Netherlands, Germany, France, Denmark, etc.) permanent reconstruction is carried out [5; 8–10]. And the development of agricultural production on reclaimed land is proof that the greatest success was achieved by countries that implemented large-scale national programs for the development and restoration of both drainage and irrigation systems [11].

Abroad, much more attention is paid to evaluating the economic efficiency of land reclamation investments than in Ukraine [12]. The scientists' developments are aimed at creating economically profitable projects for the reconstruction of drainage systems, which consider the directions of their use and possible investment options [13].

The following Ukrainian scientists were involved in the assessment of economic efficiency in the field of water management and land reclamation: A.S. Gordiychuk, V. Ya. Humenyuk, E.A. Zin, N.E. Kovshun, L.F. L.F. Kozhushko, R.M. Kostyukevich, A.H. Kulibabyn, A.A. Stakhiv, V.M. Trehobchuk, M.A. Khvesyk, et al. [14–19]. Literary sources indicate the existence of a number of studies in the direction of a comprehensive assessment of the economic effectiveness of reclamation measures, taking into account the peculiarities of their implementation in modern market conditions. In the global practice of economic calculations, there are two main approaches to the economic assessment of project effectiveness of investments: static and dynamic [20–22].

In domestic practice, the "production" approach, based on the calculations of static indicators, prevailed. This approach focuses mainly on production efficiency (reducing costs and increasing labor productivity) and is poorly focused on investors and other stakeholders. Financial, economic, and other types of efficiency fade into the background [20; 23].

In modern conditions, a feature of approaches to the justification of investment projects, including in the field of restoration of drainage systems, is the calculation based on dynamic models. They have become widespread since the late 1980s. Almost 88% of enterprises in Europe (Germany, Austria, Switzerland, etc.) and the USA use dynamic models to evaluate the effectiveness of investments [24].

According to the above, to assess and analyze the economic efficiency of long-term capital-intensive investment projects, incl. such in scale as the restoration of the drainage systems of the humid zone of Ukraine, it is advisable to use primarily dynamic methods and indicators. This will allow you to make informed management decisions. [25; 26].

The purpose of the research is to evaluate the economic efficiency of the restoration of drainage systems as a comprehensive long-term project, which is based on the algorithm for calculating basic dynamic design indicators and a scenario approach to assessing the effectiveness of investment decisions.

Research materials and methods. Research methods are based on the use of a system approach, a monographic method (summarization of scientific studies on the assessment of economic efficiency in the field of water management and land reclamation), dynamic methods, and indicators of pre-investment analysis of drainage system restoration projects, and a scenario approach to the assessment of the effectiveness of investment decisions.

Research methodology. The methodology for determining the economic efficiency of the restoration of drainage systems includes the calculation of economic indicators for the production of crops that are economically attractive for agricultural producers for two conditions: production without restoration and production during the implementation of the project for the restoration of drainage systems; using a scenario approach and an enlarged version of determining the payback of investment (capital) costs for the restoration of drainage systems (with an analysis of possible financing options, discount rates, volumes and rates of cost recovery and other factors of systemic and non-systemic impact, alternative cost). The assessment of the effectiveness of the restoration of drainage systems is carried out according to the developed general conceptual scheme by the tasks set in the "Irrigation and drainage strategy in Ukraine for the period up to 2030" (approved by the order of the Cabinet of Ministers of Ukraine dated August 14, 2019, No. 688-r.), Plan measures for its implementation (approved by the order of the Cabinet of Ministers of Ukraine dated October 21, 2020, No. 1567-r.), which notes the need to expand the functionality of drainage systems in the current conditions of their operation and provides for priority measures for restoration (modernization) (Fig. 1) [27; 28].

In the framework of this study, the focus is on the justification of the approach to assessing the financial and economic efficiency of the restoration (modernization) of drainage systems.

The main indicators for evaluating the project efficiency of restoration (modernization) of drainage systems, the use of which is justified by the concept of changing the value of money over time and which are key in making investment decisions, regardless of the type of investment project and sources of obtaining financial resources, are: net present value of the project (NPV), internal rate of return/return (IRR), return on investment (PI), payback period (PP) and discounted payback period (DPR) [24].

The calculation and forecasting of the profitability of the implementation of the project of restoration (modernization) of drainage systems is carried out according to the standardized approach of pre-project analysis, which consists in comparing the income during the implementation of the project with all incurred costs (including the costs of raw materials and materials, wages of employees, fuel and energy, depreciation, administrative costs, taxation, etc.) and taking into account the factor of change in the value of money over time.

The cash flow accumulated over the entire period of future project activity (the difference between the present value of the net cash flow for the period of project operation and the reduced amount of investment costs for its implementation) is determined by the net present value indicator according to the formula:

$$NPV = CF_0 + \frac{CF_1}{(1+r)^1} + \frac{CF_2}{(1+r)^2} + \ldots \\ \ldots + \frac{CF_n}{(1+r)^n} = \sum_{k=0}^{n} \frac{CF_k}{(1+r)^k}, \quad (1)$$

where, CF_i – the project's net cash flow (the difference between the project's income and expenditure in monetary units) in the i-th year; n – number of years; $CF_к$ – net cash flow of the project; CF_0 – the amount of initial investment in the project; r – the discount rate in the i-th year.

An investment decision is made if the net present value (NPV) indicator for an individual project is greater than or equal to zero; among several alternative projects, the one with a higher NPV is accepted [24].

When calculating project efficiency, both the traditional scheme for evaluating the effectiveness of an investment project and the equity capital scheme can be used. The difference between them is determined by the calculation of the discount rate and the construction of the project's cash flow. All things being equal, the equity scheme is more visible, flexible, and reliable for investors, and reflects the financial stability and ability of the enterprise. When applying the equity scheme, the discount rate is the cost of equity, and when forecasting cash flows, both interest payments and repayment of the body of credit funds are considered.

The justification of the discount rate is one of the most difficult tasks in the process of making an investment decision. In the scientific literature and business practice, several methods are used to justify the discount rate: WACC, CAMP, cumulative construction method, normative, market extraction, expert evaluation, etc. [25].

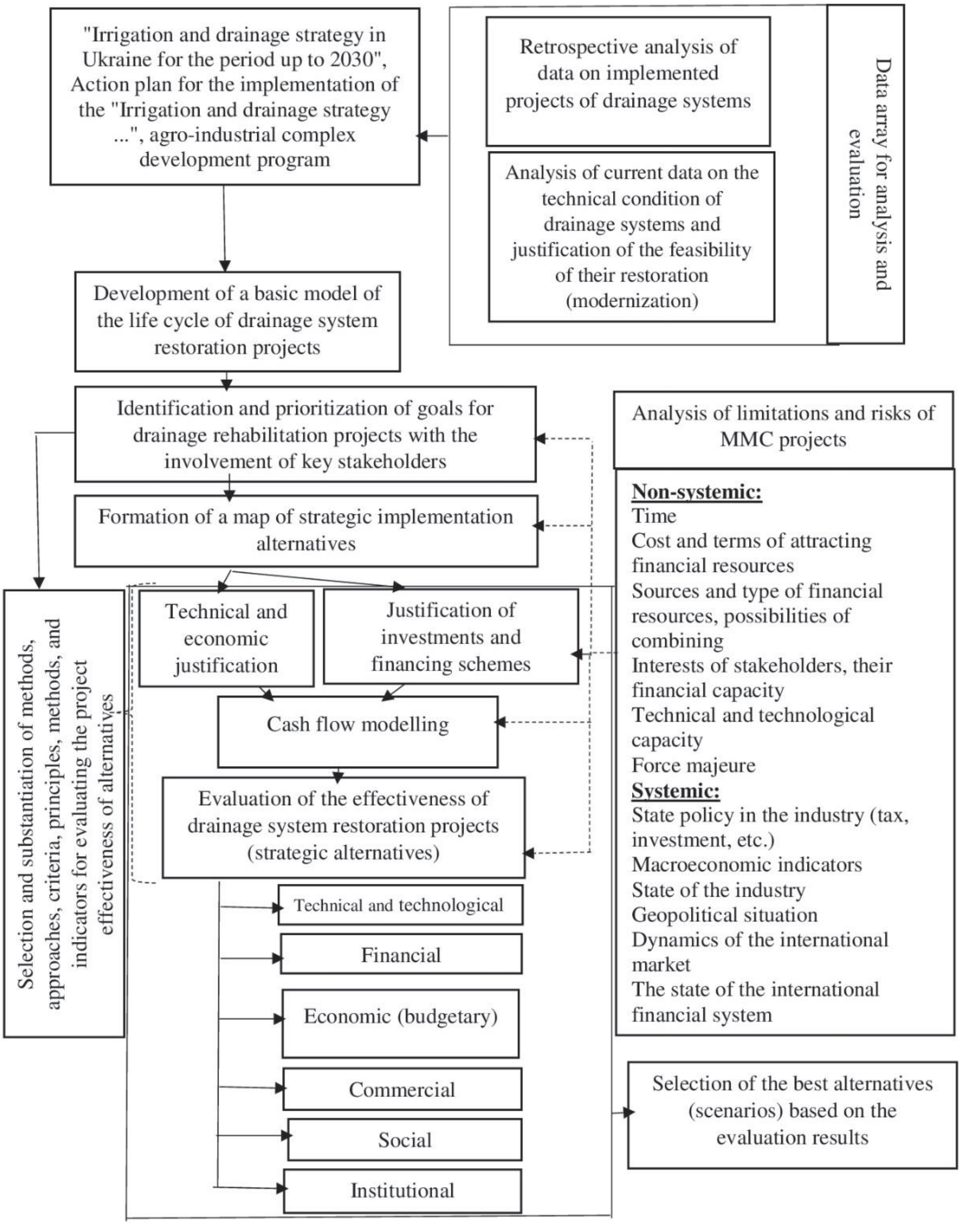

Fig. 1. Conceptual scheme for evaluating the effectiveness of restoration (modernization) of drainage systems

In the traditional scheme for evaluating the effectiveness of an investment project, the discount rate when financing a project from various sources (own, borrowed, borrowed) is taken as the weighted average cost of capital WACC (Weighted Average Cost of Capital).

The calculation of the discount rate using the WACC method is carried out according to the formula [25]:

$$WACC = k_e w_e + k_d \left(1 - t\right) w_t , \qquad (2)$$

where k_e is the cost of equity; w_e – the share of equity capital in the capital structure; k_d – the cost of loan capital; t – the tax rate; w_t – the share of loan capital in the capital structure.

The cost of capital for companies whose securities are not quoted on the stock market can be determined through the ratio of the company's annual profit to the number of its funds accumulated up to the period under consideration, that is, through the return on equity (ROE).

In the capital asset pricing model (CAMP), the discount rate consists of the rate of return on a risk-free investment and an additional rate that compensates for the uncertainty associated with investing in a particular asset. Therefore, the discount rate is calculated by the formula [25]:

$$r^* = r_j + \beta\left(r_m - r_j\right), \quad (3)$$

where r_j – risk-free investment rate of return; r_m – average market return; β – risk factor.

Attention also deserves the approach to calculating the discount rate, which is based on considering such main components: risk-free income, inflation premium, and risk premium (provides additional compensation for project risks associated with an investment decision). The use of such an approach to determining the discount rate is expedient when inflation is "homogeneous". [25].

$$r_i = (1 + r)(1 + i) - 1, \quad (4)$$

де r_i – discount rate (coefficient) adjusted for inflation; r – discount rate (ratio) excluding inflation (risk-free); i – average annual inflation index (coefficient).

As a risk-free rate, deposits for legal entities in the national currency of the most reliable banks are most often accepted (contains a risk-free component and a risk associated with investments in Ukraine) or in currency [29].

If the project is financed by borrowed funds, the discount rate is taken to be the bank's credit rate chosen to attract investment funds. The base of choice is also the rates of official statistics, in particular, the National Bank of Ukraine, taking into account the terms, region, currency, types and sizes of enterprises. These data characterize the weighted average market rates for secured loans, including country risk.

According to the recommendations of the Ministry of Finance of Ukraine, the discount rate when attracting credit funds can be calculated according to the following components: interest rate on borrowed funds; interest rate of credit risk; expected inflation rate [30].

When financing projects by raising funds in European markets, it is recommended to use the LIBOR (London Interbank Offered Rate) method, according to which the discount rate is calculated using the formula [31]:

$$r^* = LIBOR + \beta_k\left(1\ldots2\%\right), \quad (5)$$

where $LIBOR$ – the weighted average interest rate on interbank loans provided by banks to each other in different currencies or the so-called benchmark rate or cost of selling money in European currency markets; β_k – country risk level.

The internal rate of return/return (IRR) is one of the key indicators for making investment decisions. This is, in its way, an indicator of the "margin of safety" or, in other words, the "margin of return" of the project. This is the value of the discount rate at which the present value of the investment is equal to the present value of the cash flow from the investment, which provides a "0" value of NPV.:

$$\sum_{j=1}^{n} \frac{CF_j}{(1 + IRR)^j} = INV\ , \quad (5)$$

where CF_j – incoming cash flow in the j-th period, INV – the amount of investment.

If the internal rate of return is equal to the cost of capital, then the project should be accepted. If it is smaller, the project should be rejected. In the first case, we have a margin of safety for the return of invested investments and the return of funds, in the second case, the volume of funds is insufficient.

The investment profitability index (PI) is a relative indicator that reflects the level of profitability (profitability) of the project or the return on funds invested in the project, which allows you to compare investment projects that are different in scale, complexity, and conditions and is calculated by the formula:

$$PI = NPV / CF_0, \quad (6)$$

where NPV – the net present value of the project; CF_0 – the amount of initial investment in the project.

If $PI > 1$, the project is profitable and should be considered for investment; in the case of $PI = 1$, the project must be evaluated based on a set of performance indicators to make a rational investment decision, and if $PI < 1$, the project is unprofitable and it is not advisable to invest in it. If investment funds are distributed over time, the calculation of RI takes the form:

$$DRI = \sum_{t=1}^{n} \frac{CF_t^n}{\left(1+r\right)^t} / \sum_{t=0}^{n} \frac{CF_t^n}{\left(1+r\right)^t}\ , \quad (7)$$

where DPI – discounted project's profitability.

Another way to calculate the return on investment is to determine the payback period (PR) or the time required for the revenues from the project to ensure reimbursement of costs (investments) for its implementation. Calculation of the payback period with uniform project revenues for the corresponding period is carried out by dividing the number of initial investments (expenses) by the average annual cash receipts.

With uneven cash flows, it is more appropriate to calculate the cumulative discounted or non-discounted payback period. The first takes into account the change in the value of money over time (DPP).

It is calculated from the initial (investment) costs of the project (CF_0), successively subtracting the discounted cash receipts until the payback point (obtaining a positive cumulative cash flow). Similarly, however, without discounting, the second indicator considers the uneven cash flows of the project.

The methodology for determining the economic efficiency of the restoration of drainage systems also includes the rationale for budgetary efficiency, taking into account forecasting changes in yield, volumes and profitability of sales from the standpoint of the "Irrigation and drainage strategy in Ukraine for the period up to 2030", and the Action Plan for its implementation [27; 28], programs for the development of agricultural production in the regions, additional revenues of the budgets of the corresponding levels. When determining budget efficiency, specific forms of participation of budgetary funds in project financing are taken into account, including the provision of budgetary resources in the form of an investment loan or on a gratuitous basis; provision of budget subsidies related to the implementation of a certain price, structural, sectoral policy; development programs and enforcement of established social and environmental priorities; provision of state (regional) guarantees of investment risks for certain types of activities.

Research results. To carry out calculations of the economic efficiency of the restoration of drainage systems, the generalization results regarding their technical condition obtained based on the analysis of patent research materials on constructive solutions of drainage systems, many years of experience in their operation, and inventory data of the State Water Agency of Ukraine (2011), were used. The conducted analysis shows that the technical condition of the drainage systems of the humid zone of Ukraine is characterized by satisfactory (the systems are in working (operable) condition and can perform their functions in the design mode) and unsatisfactory (the functionality of the drainage systems is possible only thanks to the implementation of measures to restore them) [6; 7]. Therefore, the restoration of drainage systems in the drainage area is carried out according to two options:

– modernization of working drainage systems;

– restoration of non-working drainage systems [27].

Taking into account climate changes, the priority measures for the modernization of drainage systems include work on expanding their functional capabilities with the ability to regulate the water regime of the soil during the growing season of crops [7; 27; 37].

The conducted studies and the scientific and practical results obtained on their basis made it possible to substantiate the directions and scope of modernization of working and restoration of non-working drainage systems. Calculations of costs for the restoration (modernization) of drainage systems were carried out based on the results of a preliminary assessment of the cost of restoration works for various types of drainage systems based on the reduced costs for restoration of the intra-farm and inter-farm network, which are adopted in the "Irrigation and Drainage Strategy…", (Table 1) [7; 27].

Modernization of working drainage systems is carried out taking into account their division into draining, drying-moistening, polder and water circulation systems [6]. The set of modernization measures is determined on the basis of inventory data and will include various types of work on different types of drainage systems.

1. Volumes and cost of restoration works for different types of drainage systems

System type	Total area, thousand ha	The need for repair and restoration works		The cost of restoration of 1 ha (up to the project level), c.u.		
		thousand ha	%	Inter-farm network	On-farm network	Total 1 ha
Drainage	1649.4	1072.1	65	160	800	960
Drainage-irrigation	1113.1	679.0	61	190	1300	1490
Polder	306.6	113.4	37	300	2000	2300
Water-circulation	205.0	98.4	48	350	2300	2650
Total	3274.1	1962.9	60	250	1600	1850

On drainage systems of one-way action, the basis of modernization measures is the installation of irrigation systems on them; drainage-irrigation ones – to ensure the possibility of implementing a guaranteed two-way regulation of the water regime of the soil. Modernization of polder and water circulation systems to the level of drainage and irrigation is carried out by building irrigation systems (drip irrigation or sprinkler systems) on them. The total area of such systems is 1311.2 thousand hectares. According to the "Strategy of Irrigation and Drainage…" the total area of drainage systems of various types, on which measures to modernize and expand their functional capabilities should be carried out as a priority, is 350 thousand hectares (Table 2).

For non-working drainage systems, restoration of their performance to the design level is carried out mainly by carrying out repair and restoration works on intra-farm and inter-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; the arrangement of wells-filters for removal of surface water; an arrangement of existing dams, strengthening of mouths of drainage collectors, etc [7; 27].

The total area of such systems is 1962.9 thousand hectares. First of all, the restoration of these systems is proposed to be carried out on an area of 632.0 thousand hectares (Table 3). Along with restoring the functionality of non-working drainage systems, the possibilities of these systems performing the function of protecting territories and settlements from inundation and flooding are taken into account. The calculation of the economic efficiency of the restoration (modernization) of drainage systems includes the calculation of the economic indicators of the production of economically attractive crops for agricultural producers under the conditions of production before the restoration (modernization) and production during the implementation of the project of restoration (modernization) of drainage systems.

The selection of economically attractive crops is carried out based on research on the current state of use of drained lands. It was established that the modern structure of cultivated areas is subject to both climatic changes and the market situation, which dictates the cultivation of economically attractive crops. Since 1990, the cultivated area of sunflower has increased by 4.1; corn per grain – 4.5; rapeseed – 14.6; soybeans – 11.4 times, and their products today serve as the basis of exports. At the same time, 42 to 83 % of these crops are in the Forest Steppe and Polissia. Therefore, in agricultural production in the zone of drainage reclamations, grain corn, sunflower, rapeseed, and soybeans are grown. [32; 33].

The estimated yield levels of the specified crops during their pre-project cultivation and

2. Available areas, volumes and costs for modernization of working drainage systems

Type and area of reclamation systems, thousand ha	Type of system after modernization	Recommended area, thousand ha	Cost of modernization, c.u./ha	Modernization costs, million c.u.
1. Drainage – 577.3	drainage-irrigation	200.0	2000.0	400.0
2. Drainage-irrigation – 434.1	drainage-humidification-irrigation	100.0	2000.0	200.0
3. Polder – 193.2	drainage-irrigation	30.0	2000.0	60.0
4. Water-circulation – 106.6	drainage-irrigation	20.0	1700.0	34.0
Total 1311.2		350.0		694.0

3. Available areas, volumes and costs for restoration of operational efficiency of non-working drainage systems

Type and area of reclamation systems, thousand ha	Type of system after modernization	Recommended area of modernization, thousand ha	Cost of modernization, c.u./ha	Modernization costs, million c.u.
1. Drainage – 1072.1	drainage	200.0	960.0	192.0
2. drainage-irrigation – 679.0	drainage-irrigation	300.0	1490.0	447.0
3. Polder – 113.4	polder	112	2300.0	257.6
4. Water-circulation – 98.4	water-circulation	20.0	2650.0	53.0
Total: 1962.9		632.0		949.6

the implementation of the project of restoration (modernization) of drainage systems on drained lands were adopted based on the results of the analysis of statistical data and research by scientists of the IWP&LR of NAAS of Ukraine (Table 4) [33; 34].

We consider in detail options for determining the payback of investment (capital) costs for the restoration (modernization) of drainage systems. To do this, first of all, we calculate the economic indicators of the pre-project and after the implementation of the project production of the main crops (Tables 5, 6).

A comparative analysis of the production of the main crops before and after the implementation of the drainage system restoration (modernization) project was carried out, the results of which are presented in Table 7.

When determining the discount rate and calculating project indicators directly for the restoration (modernization) of drainage systems, we determine possible financing options:

– budgetary on the inter-farm network (agreed programmatically from the state, regional, municipal budgets and donor in the ratio agreed by the government and donors) and private or mixed on the intra-farm network (land users of different forms of ownership: owner funds, credit, donor funds, etc.);

– private financing by land users or mixed (donor and land users).

The option of full state financing is not considered taking into account the changes in the legislation and the "Irrigation and Drainage Strategy…", which states that the financing of investment projects will be carried out in stages, taking into account priority and economic indicators of cost effectiveness and a wide range of potential investors [27]. In addition, this option is difficult to implement due to a significant budget deficit.

4. Yield levels of pre-project cultivation of crops and during the implementation of the project of restoration (modernization) of drainage systems on drained lands

Type of crop	Pre-project yield, t/ha	Yield under the implementation of the restoration (modernization) project, t/ha
Corn for grain	7.0	12.0
Soybean	2.0	4.0
Winter wheat	5.0	8.0
Sunflower	2.5	4.0

5. Economic indicators of pre-project production of major crops on drained lands

Crops	Share in the structure of crops, %	Productivity, t/ha	Total production costs, thousand UAH/ha	Sales price (without VAT), thousand UAH/ha	Cost of gross production, thousand UAH/ha	Gross profit, thousand UAH/ha	Profitability of production, %
Winter wheat	20	5.0	16.0	4.1	20.5	4.5	28.13
Corn	35	7.0	18.3	3.7	25.9	7.6	41.53
Sunflower	10	2.5	14.0	8.0	20.0	6.0	42.86
Soybean	35	2.0	10.4	8.0	16.0	5.6	53.85
	100	-	14.6	5.7	20.6	6.12	41.79

6. Economic indicators of the production of the main agricultural crops on drained lands during the implementation of the project of restoration (modernization) of drainage systems

Crops	Share in the structure of crops, %	Productivity, t/ha	Total production costs, thousand UAH/ha	Sales price (without VAT), thousand UAH/ha	Cost of gross production, thousand UAH/ha	Gross profit, thousand UAH/ha	Profitability of production, %
Winter wheat	20	8.0	19.2	4.1	32.8	13.6	70.83
Corn	35	12.0	22.0	3.7	44.4	22.4	101.82
Sunflower	10	4.0	16.8	8.0	32.0	15.2	90.48
Soybean	35	4.0	12.5	8.0	32.0	19.5	156.00
–	100	–	17.6	5.7	36.5	18.9	107.45

7. Project indicators of the production of the main agricultural crops on drained lands during the implementation of the drainage system modernization project

Crop	Increase in yield, t/ha	Sale price (without VAT), thousand UAH/ha	Total production costs, thousand UAH/ha (20%)	Cost of gross production, thousand UAH/ha	Gross profit, thousand UAH/ha	Net profit, thousand UAH/ha	Share in the crop structure, %
Winter wheat	3	4,1	3,84	12,3	8,46	6,94	0,2
Corn	5	3,7	4,4	18,5	14,1	11,56	0,35
Sunflower	1,5	8	3,36	12	8,64	7,08	0,1
Soybean	2	8	2,5	16	13,5	11,07	0,35
–	–	–	3,52	15,74	12,22	10,02	1

The option of full private financing is possible for implementation in the presence of significant state benefits and guarantees, effective credit policy in the field of agro-industrial complex (APC) for land users, including water user associations.

That is, for the project of restoration (modernization) of drainage systems, the sources of investment can be the funds of landowners, donors, creditors, budget funds, etc. Accordingly, it is possible to use the traditional scheme for calculating project indicators, where the discount rate is calculated as the weighted average cost of capital (WACC).

Under certain conditions, namely: significant variability and uncertainty of the current sources of financial resources and investment conditions; gradual introduction of changes in legislation; continuation of evaluation works on reclaimed territories; the crisis state of Ukraine's economy; specifics of the project of restoration (modernization) of drainage systems and its duration, for the discount rate for the preliminary pre-investment analysis we choose:

– weighted average interest rate for long-term loans for legal entities, taking into account the inflation component;

– weighted average interest rate on deposits (risk-free) for legal entities, taking into account the inflation component;

– the value of equity capital of enterprises of the agro-industrial complex.

We compare the results at different rates in 2021 and at the beginning of 2022.

The average weighted rate on loans in the national currency for non-financial corporations as of December 31, 2021 amounted to 9.1%, and as of February 2022, 10.6%. The weighted average rate in Ukraine on long-term deposits for non-financial corporations in the national currency as of December 31, 2021 was 5.8%; as of February 23, 2022 – 8.0% [35].

The National Bank of Ukraine expected inflation at the level of 5.5% at the end of 2021, and the average annual forecasted rate at the level of 5.8% [36]. In fact, the inflation index in 2021 was 110.0% [37]. The inflation index as of March 2022 was 104.5% [37], and for the year it was forecast at the level of 107.6%. For calculations for 2022, we use the forecasted annual indicator.

Discount rate for restoration (modernization) projects of drainage systems for calculating the effectiveness of an investment project in national currency with a credit source of funds for a period of more than 5 years ($r_{1к}$ та $r_{2к}$) is:

$$r_{1к,\,2021} = (1 + 0{,}0901)(1 + 0{,}1) - 1 \approx 20\%;$$

$$r_{2к,\,2022} = (1 + 0{,}106)(1 + 0{,}076) - 1 \approx 19\%.$$

The discount rate for the project of restoration (modernization) of drainage systems according to the data of 2021 and the beginning of 2022($r_{1д}$ та $r_{2д}$) based on the average rate for long-term deposits for legal entities:

$$r_{1д,\,2021} = (1 + 0{,}058)(1 + 0{,}10) - 1 \approx 16\%;$$

$$r_{2д,\,2022} = (1 + 0{,}080)(1 + 0{,}076) - 1 \approx 16\%.$$

Taking into account the relatively stable projected rates of inflation recently, this calculation approach is justified, and the discount rates (r_1, r_2) take into account the main risks for investors.

Investment costs for the project of restoration (modernization) of drainage systems (for drainage and moisturizing) in national currency are: 56.54 thousand UAH/ha (2020); 54.79 thousand UAH/ha (2021); 58.52 thousand UAH/ha (beginning of 2022).

We build the cash flow taking into account the design yield when implementing the restoration (modernization) of drainage systems, the dynamics of prices for priority agricultural crops grown on drained lands, at discount rates at levels r_1 and r_2. To determine the net profit in the calculations, we accept the rate of taxation of the profit of enterprises according to the general taxation system. The cash flow includes depreciation deductions during the 8 years of project implementation (the term corresponds to the late payback period calculated according to the "Irrigation and Drainage Strategy…"). The liquidation value at the stage of project completion is assumed equal to 0.

According to the conditions adopted in this study and the analytical data obtained, we have the design efficiency indicators given in Table. 8.

The results indicate that all calculation options give positive indicators of the financial efficiency of the investment project for the restoration (modernization) of drainage systems, which indicates the feasibility of its implementation. In addition, the internal rate of return shows a sufficient margin of safety (24–26 %). The return on investment is sufficient and corresponds to market indicators and its dynamics. This indicator is the highest for options with sources of funds from long-term deposits (34 and 25 %, respectively, for 2021 and at the beginning of 2022) and the equity capital of agribusiness enterprises (43 %). At the same time, the calculated non-discounted (PP) and discounted (DPP) payback periods of the option with sources of funds from long-term deposits are 3.2 and 4.9 (for 2021) and 3.5 and 5.5 years (at the beginning of 2022), which is more profitable compared to the option with long-term loans. The most economically expedient, of course, is the option with a source of equity capital of agribusiness enterprises, for which the non-discounted (PP) and discounted (DPP) payback terms are 3.4 and 4.7 years.

Profit can be reinvested by land users to ensure further economic development by introducing innovations, including the acquisition of modern equipment, and the development of new varieties of crops and technologies for their cultivation. Part of the funds can be reinvested in research and development in the field of agro-industrial complex, which will speed up the introduction of innovations into production practice.

When calculating project efficiency, land users, donors, and representatives of state or regional authorities need to operate at a decisive rate precisely taking into account the specifics of investment, interests of stakeholders, state policy in the field of agriculture, and regional and municipal development investment programs. The rate of taxation of the profit of agricultural producers may also vary depending on the taxation system and the availability of tax benefits. The norms and peculiarities of taxation of agrarians are being revised, including reimbursement of value-added tax (VAT), the amount of which is in the range from 20 to 14 %; reduction of personal

8. Indicators of the effectiveness of the project for the restoration (modernization) of drainage systems using different discount rates

The discount rate is the weighted average rate for long-term loans for legal entities, considering the inflation component		
Project efficiency indicator	**At discount rate $r_{1к,\ 2021}$ = 20 %**	**At discount rate $r_{2к,\ 2022}$ = 19 %**
NPV, thousand UAH	9.94	8.91
IRR, %	26	24
PI, %	18	14
PP, years	3.2	3.5
DPP, years	5.8	6.2
The discount rate is the weighted average rate for long-term deposits for legal entities, considering the inflation component		
Project efficiency indicator	**At discount rate $r_{1д,\ 2021}$ = 16 %**	**At discount rate $r_{2д,\ 2022}$ = 16 %**
NPV, thousand UAH	18.49	14.45
IRR, %	26	24
PI, %	34	25
PP, years	3.2	3.5
DPP, years	4.9	5.5
Discount rate – the cost of equity of agribusiness enterprises (data for 2021 and 2022 are not available)		
Project efficiency indicator	**At discount rate $r_{1вк,2020}$ = 13 %**	
NPV, thousand UAH	24.42	
IRR, %	25	
PI, %	43	
PP, years	3.4	
DPP, years	4.7	

income tax (PIT); taxation of the income of agricultural producers, land, etc.

Municipal and regional authorities receive direct and indirect effects from the implementation restoration (modernization) of drainage systems projects, particularly, in terms of ensuring the growth of budget efficiency, and indicators of social and environmental efficiency. The state ensures the preservation and increase of the export potential of the agricultural industry.

An important role in accelerating the implementation of the projects under study is also played by the introduction of the Law "On water user organizations and stimulation of hydro technical land reclamation" (dated February 17, 2022 No. 2079-IX), incl. from the standpoint of stimulating the inflow of investments, regulatory harmonization of land reclamation issues [38].

These and other regulatory, technical, technological, and organizational measures will speed up the process of involving the World Bank and other interested foreign financial institutions in the investment process. Accordingly, we can predict that soon, hydro-technical reclamation in Ukraine will acquire a programmatic and systemic character, which will allow combining the efforts of both national and foreign stakeholders, creating conditions for long-term growth in the agricultural sector.

According to analytical data, the government continues to work on programs for the agricultural sector development, where reclamation occupies a prominent place. In general, in 2021-early 2022, the government continued work on the following development programs: support for insurance of agricultural products; compensation for losses from damage to crops as a result of man-made and natural emergencies; support for agricultural producers who use reclaimed land; support for producers of organic products; support of potato producers; support of agricultural producers by allocating budget subsidies per unit of cultivated land (buckwheat) [39].

Conclusions. The assessment of the economic efficiency of the restoration of the drainage systems of the humid zone of Ukraine is proposed to be carried out according to a conceptual scheme that determines the stages of the assessment, the sources of the input array of information, the strategic orientation and invariance of restoration projects, involves considering risks and limitations of a systemic and non-systemic nature when assessing the design effectiveness of strategic ones.

It is determined that the basis of the assessment should be:

– the results of studies on establishing the technical condition of drainage systems, the restoration of which in the drainage area is carried out according to two options: modernization of working and restoration of non-working systems;

– data on the preliminary assessment of the cost of restoration works for different types of drainage systems (drainage, drainage-irrigation, polder, and water circulation systems) based on the reduced costs for the restoration of intra-farm and inter-farm networks;

– economic indicators of the production of agricultural crops that are economically attractive for agricultural producers (grain corn, sunflower, rapeseed, soybeans) under the conditions of their production before and after the implementation of the project of restoration (modernization) of drainage systems.

Indicators of the project effectiveness of restoration (modernization) of drainage systems were established using the scenario approach based on the consolidated version of determining the payback of investment costs. It is proven that the options at the discount rates r_1 (for 2021) and r_2 (for the beginning of 2022), as well as the discount rate for the equity scheme, give positive indicators of the investment project, which indicates the feasibility of its implementation and economic efficiency. The internal rate of return for the three options shows a sufficient margin of safety (24–26 %). The most economically expedient is the option with a source of financing from the equity capital of agro-industrial complex enterprises, for which the non-discounted (PP) and discounted (DPP) payback terms are 3.4 and 4.7 years, respectively.

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ОЦІНЮВАННЯ ЕКОНОМІЧНОЇ ЕФЕКТИВНОСТІ ВІДНОВЛЕННЯ ДРЕНАЖНИХ СИСТЕМ ГУМІДНОЇ ЗОНИ УКРАЇНИ: ПРИЙНЯТТЯ ІНВЕСТИЦІЙНИХ РІШЕНЬ

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Анотація. *Обґрунтовано підходи до оцінювання економічної ефективності відновлення дренажних систем гумідної зони України. Розроблено концептуальну схему, яка визначає етапність оцінювання, джерела вхідного масиву інформації, стратегічну орієнтацію та інваріантність проєктів відновлення, передбачає врахування низки ризиків та обмежень системного й несистемного характеру при оцінюванні проєктної ефективності стратегічних альтернатив. Основою оцінювання є результати аналізу матеріалів щодо технічного стану дренажних систем, відновлення яких у зоні осушення виконується за двома варіантами: модернізація працюючих (на площі 1311,2 тис. га) та відновлення непрацюючих (на площі 1962,9 тис. га) дренажних систем. Враховуючи кліматичні зміни, до першочергових заходів із модернізації дренажних систем віднесені роботи з розширення їх функціональних можливостей здатністю регулювати водний режим ґрунту протягом періоду вегетації вирощування сільськогосподарських культур. У розрахунках витрат на відновлення (модернізацію) використано результати попередньої оцінки вартості відновлювальних робіт для різних типів дренажних систем (осушувальні, осушувально-зволожувальні, польдерні та водооборотні) на основі приведених витрат на відновлення внутрішньогосподарської та міжгосподарської мережі, які прийняті у «Стратегії зрошення та дренажу…». Розраховано економічні показники виробництва економічно привабливих для агровиробників сільськогосподарських культур (зернової кукурудзи, соняшника, ріпаку, сої) за умов їх виробництва до та за реалізації проєкту відновлення (модернізації) дренажних систем. Обґрунтовано застосування традиційної схеми розрахунку проєктних показників, за якої ставку дисконтування визначали як середньозважену вартість капіталу (WACC). Враховуючи специфіку проєктів відновлення (модернізації) дренажних систем та їх тривалості, за ставку дисконтування для здійснення попереднього передінвестиційного аналізу обрано середньозважені ставки за довгостроковими кредитами і депозитами (безризикова) для юридичних осіб з урахуванням інфляційної складової та вартістю власного капіталу підприємств АПК. На основі розрахунку проєктної ефективності відновлення (модернізації) дренажних систем з використанням сценарного підходу за укрупненим варіантом визначення окупності інвестиційних витрат доведено, що варіанти при ставках дисконтування* r_1 *(за 2021 р.) та* r_2 *(на початок 2022 р.), а також ставці дисконтування для схеми власного капіталу дають позитивні показники інвестиційного проєкту, що свідчить про доцільність його реалізації та економічну ефективність. Внутрішня норма рентабельності для трьох варіантів показує достатній запас міцності (24–26%). Найбільш економічно доцільним є варіант з джерелом фінансування за рахунок власного капіталу підприємств АПК, для якого недисконтований (PP) та дисконтований (DPP) терміни окупності становлять, відповідно, 3,4 і 4,7 роки.*

Ключові слова: *дренажна система, відновлення дренажних систем, економічна ефективність, сценарний підхід, інвестиційний проєкт*

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PROTECTION OF TERRITORIES FROM WATERLOGGING IN THE ZONE OF THE NORTH CRIMEAN CANAL OF KHERSON REGION AND WAYS TO IMPROVE IT

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Abstract. *he system of protecting territories from the harmful effects of water using vertical drainage in the zone of the North Crimean Canal of the Kherson region was considered and the proposals for its improvement by creating additional horizontal drainage systems with gravity drainage were substantiated. Field drainage studies were carried out at 8 research and production sites with a total area of 4763 hectares and a term of operation of 48–55 years and more. The conducted studies included surveying the drainage in the areas, measuring the drainage flow and the depth of groundwater levels, and determining work efficiency. The research covered the settlements: Chornyanka, Nova Mayachka, Stara Mayachka, Podo-Kalynivka, Tarasivka, Velyki Kopani, Kalanchak, and Skadovsk, for the protection of which 119 water intake wells with a depth of 26–70 m were installed. It is shown that vertical drainage is effective during the whole operation and periods of selective work when the groundwater levels were at depths of 2–3 m and 1–2 m, respectively. To ensure reliable protection of territories from waterlogging and flooding in current conditions due to the impossibility and economic impracticability of restoring the operation of all existing vertical drainage wells, it is proposed to supplement the existing protection systems based on it with systems of closed horizontal drainage of the gravity type with low-sloping and non-sloping drainage. The area of additional horizontal drainage is about 40 thousand hectares, the estimated length of the collector and drainage network is 456 km, and the depth of laying drains and collectors is 2.5–11.0 m.*

Keywords**:** *vertical drainage, efficiency of horizontal drainage, gravity drainage*

Formulation of the question. Vertical drainage is a relatively new and rather complex type of reclamation system that is used to protect territories from waterlogging, built in a relatively short time, and required forced drainage based on electrification and automation [2; 8; 10; 15; 16; 25; 28]. Therefore, the territory belongs to the flooded area if the depth of the groundwater level exceeds the critical limit, which is defined as 1.5–2.0 m [10; 22].

Vertical drainage is used to protect territories from waterlogging in the area of irrigation, drainage, and Dnieper reservoirs [1; 10; 15; 16; 19; 20; 25–27]. In the irrigation zone, the total area of territories covered by vertical drainage systems, is 250.000 hectares, on which about 2.000 wells have been built [8; 10; 17; 26; 30–32]. This drainage is widespread in the Kherson region (110.000 hectares), and the number of water-lowering wells is 924, of which 96.000 hectares (557 wells) are on irrigated and adjacent lands, and 14.000 hectares (367 wells) are in 81 settlements [4–7; 10; 26; 39].

The long period of operation, obsolescence, and high energy consumption of vertical drainage systems, as well as the military aggression of the Russian Federation, complicate the effectiveness of its work and lead to the aggravation of the problem of waterlogging of territories on a significant scale, especially in wet and abnormally wet periods, which requires an increase in the overall drainage of territories. Ensuring the efficient operation of drainage in these conditions requires the development and application of additional measures, first of all, the addition of horizontal drainage systems with gravity drainage.

The purpose of the work is to justify the reliable protection of territories from waterlogging in the zone of the North Crimean Canal based on increasing the drainage capacity of vertical drainage systems by installing horizontal drainage with gravity drainage.

Research methodology. Field studies of the work of vertical drainage were carried out at objects located in the zone of the North Crimean Canal (NCC) within the Kherson region [3; 11; 12; 21; 29; 30; 32; 34; 36–38]. The research covered systems in the settlements of Chornyanka, Nova Mayachka, Stara Mayachka, Podo-Kalynivka, Tarasivka, Velyki Kopani, Kalanchak, and Skadovsk (Fig. 1).

Field studies of the work of vertical drainage included examination of drainage systems, measurement of drainage flow, and depths of groundwater levels through observation and specially drilled wells. The survey was conducted using the materials of design, construction, and operating organizations and the results of published manuscripts.

Measurements of drainage flow and groundwater levels were carried out by traditional methods [10; 22]. According to the survey results, drainage operation conditions, drainage runoff flow rates, depth of groundwater levels in various conditions, data on drainage efficiency, and operating conditions were determined.

The area of vertical drainage covered by research is 4.763 hectares, with 3.455 hectares in the Lower Dnieper basin and 1.308 hectares in the Black Sea. The water receivers of the drainage runoff are the North Crimean Canal and the Black Sea.

The characteristic of the studied drainage systems. The research was carried out on the drainage system in Chernyanka village, which contains 32 wells, and the vertical drainage system in Nova Mayachka town, which consists of 20 water-lowering wells, mostly 23 m deep,

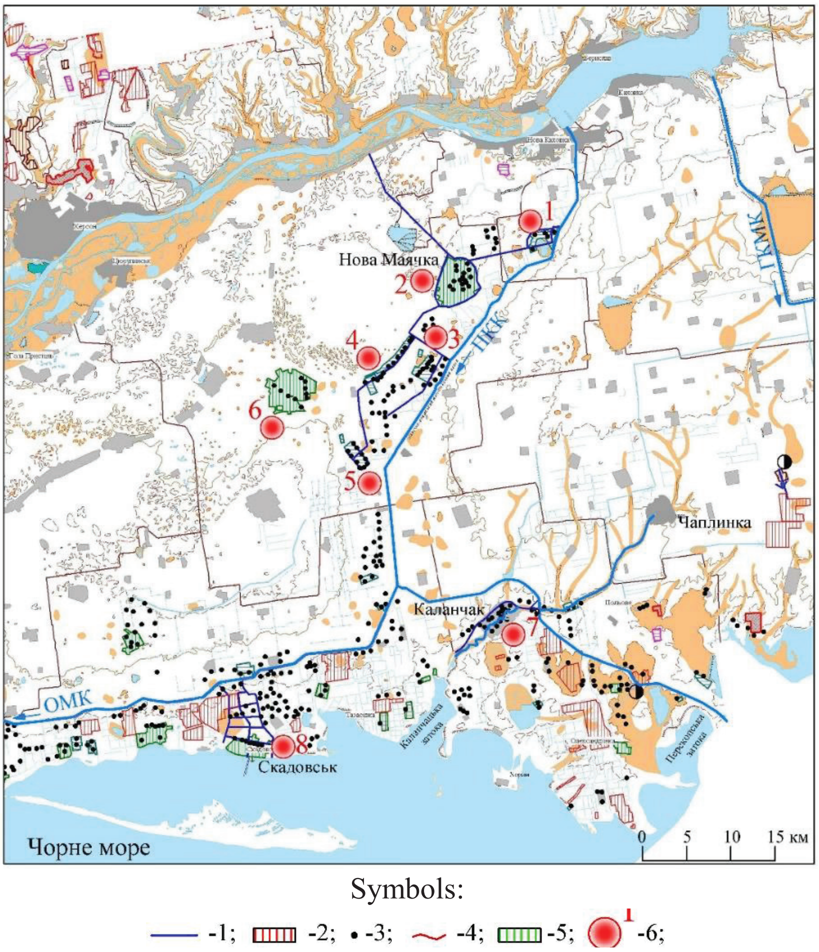

Fig. 1. Scheme of the vertical drainage in the zone of NCC:
1 – irrigation canal; 2 – horizontal drainage systems; 3 – vertical drainage well;
4 – horizontals of the area; 5 – vertical drainage systems; 6 – areas of drainage studies № 1–8

550 mm in diameter, and 500–1000 m apart. The total flow rate is 910 l/s. Drainage water is pumped into the North Crimean Canal or used for irrigation. The system has been operating for over 55 years.

The system in Stara Mayachka village and the surrounding areas contains 16 wells that situated in two lines. In the first line, which is located at a distance of 550–800 m from the NCC, there are 6 wells, the distance between which is 600–1100 m. In the second line, at a distance of 2100–2400 m from the NCC, there are 8 wells, the distance between which is 300–500 m. The distance between the two line is about 1.500 m. The depth of the wells is 70 m.

The system of vertical drainage in Podo-Kalynivka village contains 11 wells located linearly at a distance of 500–1000 m. The length of the well is 7200 m. The depth of the wells is 65 m. The wellhead is located at a distance of 5400 m from NCC.

The vertical drainage system in Tarasivka village, which is located on a gentle slope within the terrace, is 2–3 km from the highway of NCC. The absolute level of the water in the canal is 14.3 m, and the surface of the land in the village is 11.0 m. The canal bed during the inter-irrigation season provides drainage of the adjacent territories. Vertical drainage in Tarasivka village has an area of 365 hectares. The 10 wells were laid, which are located linearly along the contour of the village, with the exception of the northwestern territory on the rise. The distance between the drains is 500–750 m, and between the drainage lines is 1350 m. The wells work according to the circular cut-off drainage scheme. The depth of the drains is 70 m.

The vertical drainage in Velyki Kopani village is located on the lowest territory of the village in two lines of 5 wells. The distance between the drains is 500–900 m, and between the rows of drains is 1000–1500 m. The depth of the wells is 70 m. In Velyki Kopani village wells are located within the settlement, and in Tarasivka village are outside its borders, along the contour.

There are 19 vertical drainage wells located in Kalanchak town, which are located mostly linearly along both banks of the Kalanchak River. The distance between the drains is 400–1000 m, and between the drain lines is 800–1500 m. The length of the drainage is 5400 m, and the width is 2500 m. The depth of the wells is 42–62 m.

The vertical drainage system in Skadovsk city belongs to the linear type. The drainage is located on the northern outskirts of the city. The distance of the drainage to the sea to the south is about 3000 m, and to the north to the Oleksandrivskyi (Krasnoznamyanskyi) canal is 7000 m. The drainage contains 7 wells, the distance between which is 350–700 m. The total length of the drainage line is 3100 m. The depth of the wells is 48–51 m.

Research results. The results of field studies [3; 9; 11; 12; 21; 28–30; 32–38] show that with practically continuous operation of all existing wells, which was characteristic until 1995, vertical drainage ensured the maintenance of the groundwater level at depths of 2–3 m and there was almost no waterlogging of protected areas. After 1995, in connection with a sharp increase in the price of electricity, a large part of the wells was disconnected, but, as the results of the research showed, with the constant operation of only part of the wells (about 30 %), there was a gradual rise in the level of groundwater to a depth of 1–2 m. Moreover, during this mode of operation in wet periods (1997–1998, 2004–2005), temporary flooding of drainless depressions and long-term waterlogging of lands were observed [3; 11–14; 18; 21; 23; 24; 28–30; 32–38]. Including an additional number of wells in operation helped eliminate flooding, but in general, did not ensure a decrease in groundwater levels to the required depth of 2–3 m (Table 1).

1. Main characteristics and performance indicators of vertical drainage

Name of the settlement	Area, ha	Drainage area, ha	Number of wells, pcs.	Depth of wells, m	Operation of wells, years	Number of wells, pcs.	Depth of groundwater levels, m
Chornyanka	463	180	32	–	50	3	1–2
Nova Mayachka	1984	1248	20	26	55	12	1–2
Stara Mayachka	314	267	10	65	51	4	1–2
Podo-Kalynivka	519	420	11	65	51	3	1,4–3,0
Tarasivka	441	365	10	70	52	2	1–3
Velyki Kopani	1821	975	10	65	51	2	1,5–3,0
Kalanchak	1292	683	19	42–62	48	5	1–2
Skadovsk	1500	625	7	48–51	53	3	1–3
	8334	4763	119	26–70	48–55	34	1–3

Long-term studies have established that with the constant operation of only a part of the existing vertical drainage wells (no more than 30 %), a sharp increase in water inflow and rise in groundwater levels are observed, which in wet periods causes the development of flooding and waterlogging process, which cannot be quickly eliminated by including additional wells. In these conditions, in order to ensure effective protection of territories, it is proposed to additionally strengthen the effect of vertical drainage by installing closed horizontal drainage systems with self-flowing, low-sloping, and non-sloping drainage of runoff in the Dnipro River and the Black Sea in the area of the settlements of Korsunka, Oleshky, and Darivka (Fig. 2–5).

In addition, during the period of extreme waterlogging, it is recommended to include

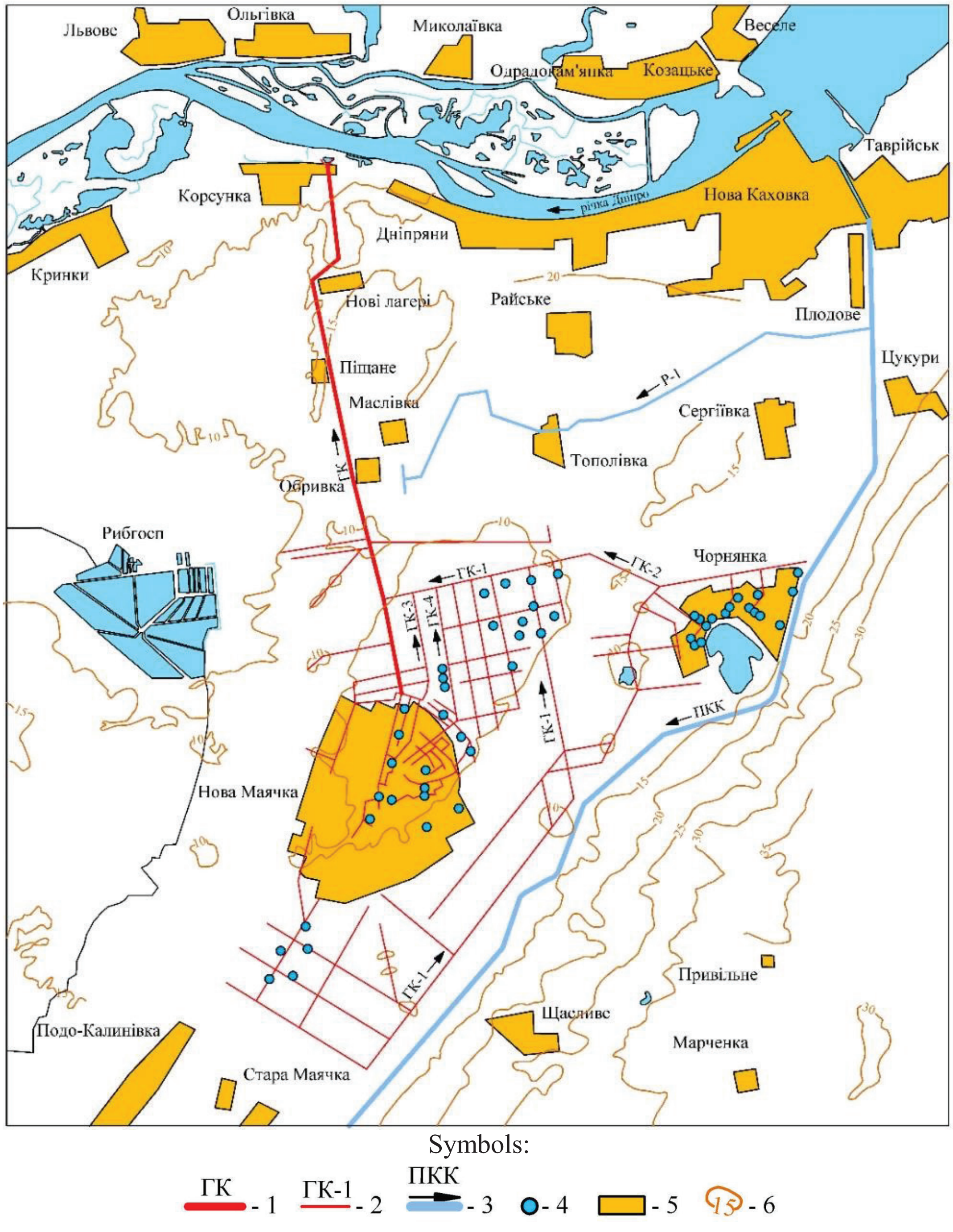

Fig. 2. Scheme of the collector and drainage network in the area of Nova Mayachka village:
1 – main collector; 2 – closed drains; 3 – main canals; 4 –vertical drainage wells; 5 – settlements;
6 – horizontals of the area

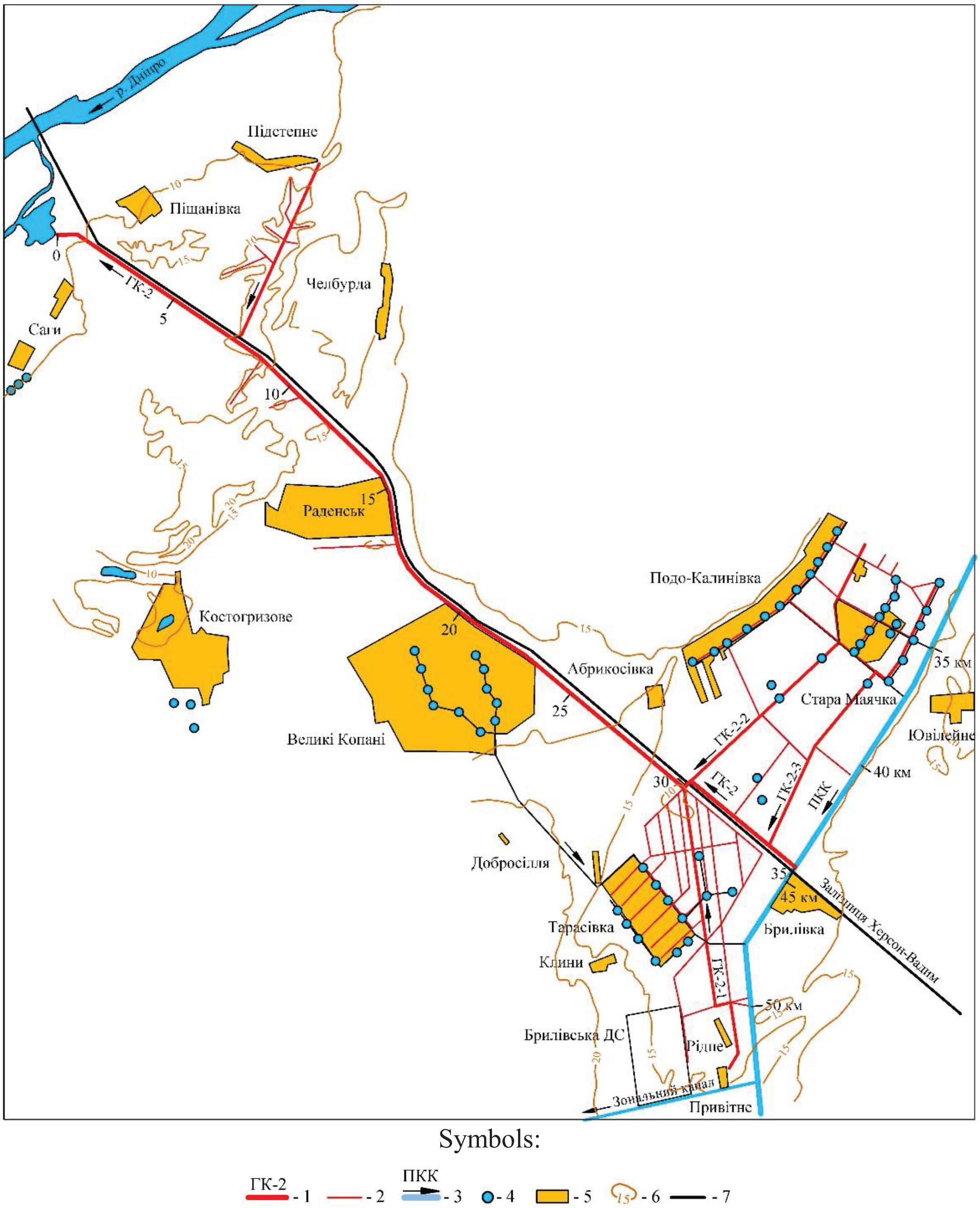

Fig. 3. Scheme of Tarasivka main collector MC-2:
1 – main collector; 2 – closed drains; 3 – main canals (NCC, Zonal); 4 – vertical drainage wells;
5 – settlements; 6 – horizontals of the area; 7 – railway lines

in that operation part of the existing vertical drainage wells that are not constantly in use. The area of land on which horizontal drainage with gravity drainage should be arranged is about 40.000 hectares, and the depth of laying the drains should be 2.5–3.5 m. Drainage water is proposed to be carried out by gravity collectors with a depth of 2.5 to 11.0 m.

The total approximate length of the collector and drainage network reaches 456 km (Table 2).

The closed horizontal drainage is laid from plastic drainage pipes with a diameter of 200 mm, wrapped with fiberglass in two layers. Under laying pipes in one line are formed drains, for two or more lines are formed drains and draining collectors. Drains are connected to the collector using inspection reinforced concrete wells. Wells are also arranged at the bends of drainage lines, before and after highway crossings, after 2.0–2.5 km, etc.

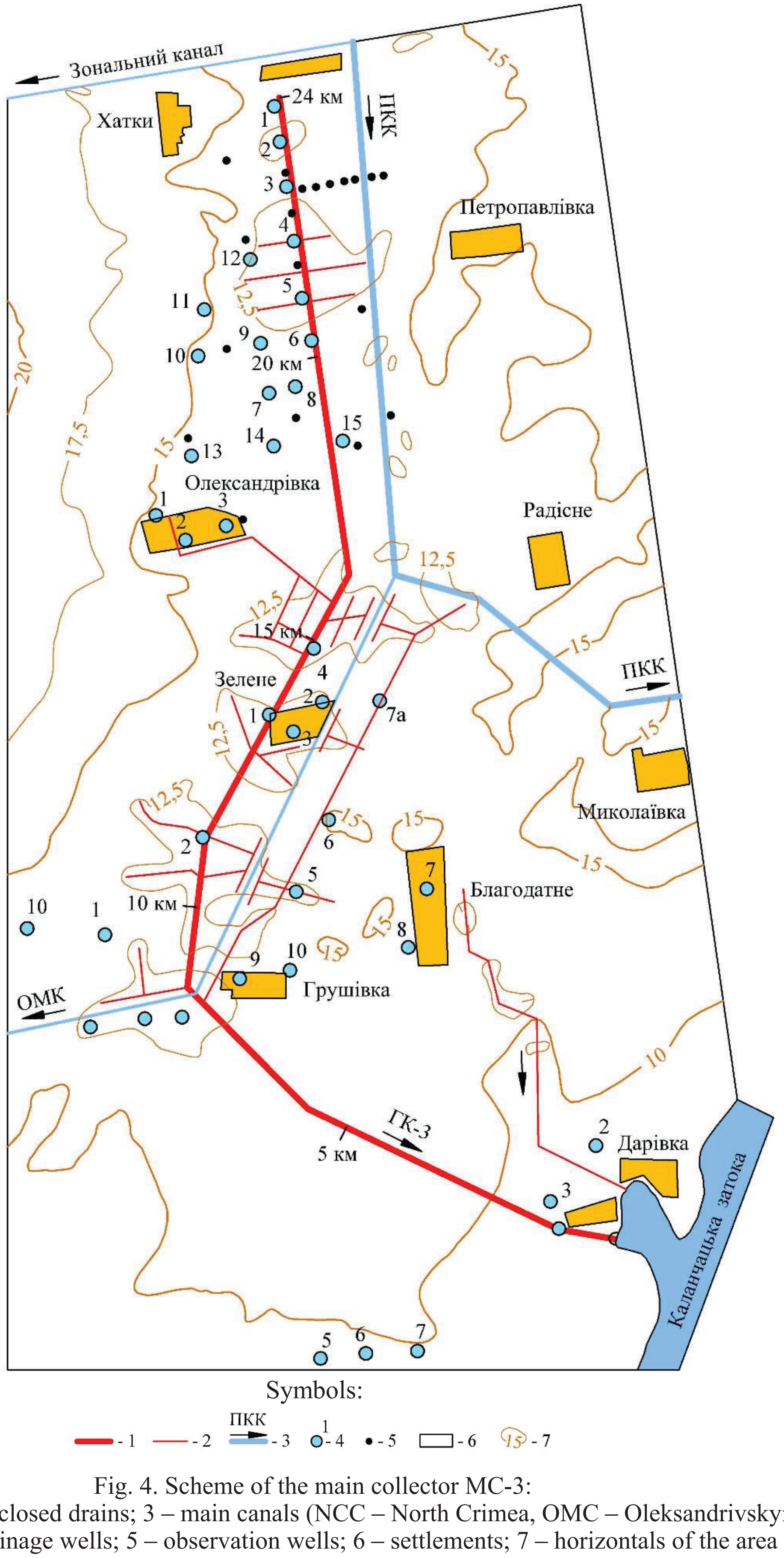

Fig. 4. Scheme of the main collector MC-3:
1 – collector; 2 – closed drains; 3 – main canals (NCC – North Crimea, OMC – Oleksandrivskyi);
4 – vertical drainage wells; 5 – observation wells; 6 – settlements; 7 – horizontals of the area

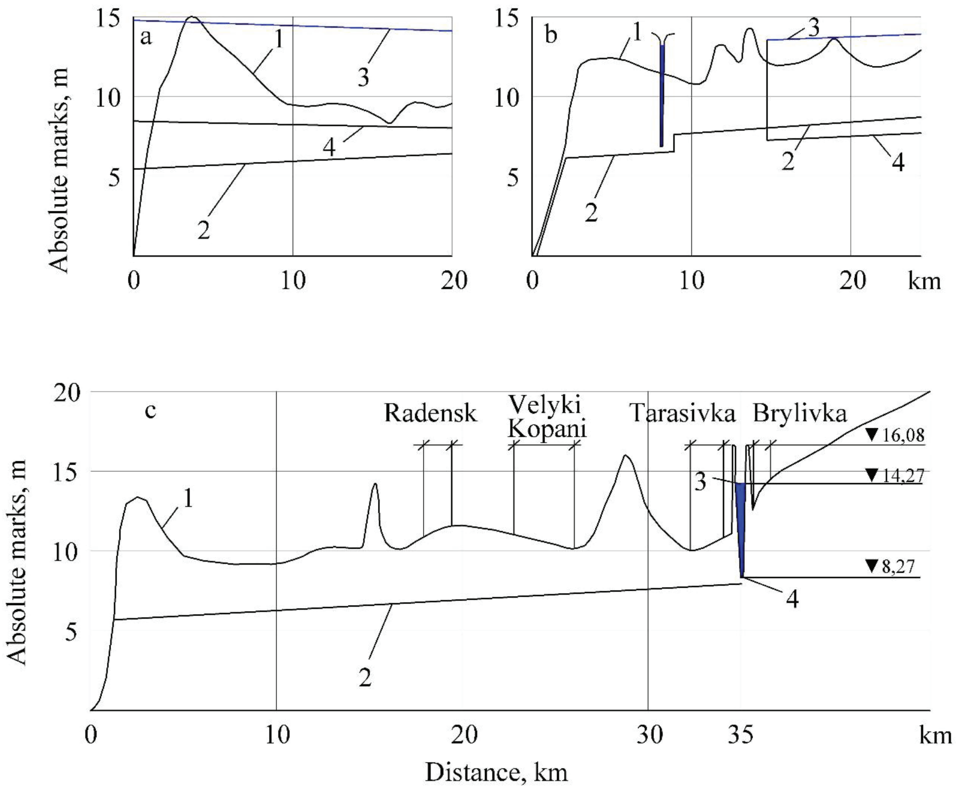

Fig. 5 Longitudinal profiles of the main collectors:
a – Novomayatskyi; b – Tarasivskyi; c – Darivskyi;
1 – the surface of the earth along the route of the collectors; 2 – the bottom of the collector;
3 – the water level in the NCC; 4 – the bottom of the NCC

2. Approximate characteristics of closed horizontal drainage in the zone of NCC

Collectors	Drainage area, thousand ha	Laying depth, m	Drainage length, km	
			main collectors	drains
MC-1	19,6	2,5–11,0	16	183
MC-2	10,0	2,5–9,0	38	135
MC-3	9,6	3,0–6,0	24	60
Total	39,2	2,5–11,0	78	378

Conclusions. Research has established that under the current mode of operation, vertical drainage does not provide reliable and effective protection of territories from the harmful effects of water in the zone of the North Crimean Canal of the Kherson region. Groundwater levels in the areas currently protected by vertical drainage are mainly at depths of 1–2 m, which is subject to waterlogging, and in some wet and extremely wet periods, temporary flooding is observed. To ensure the protection of territories from waterlogging and flooding, it is proposed to strengthen the protective effect of vertical drainage with systems of closed horizontal drainage of the gravity type. The area of such drainage will be about 40,000 hectares, the estimated length of the collector and drainage network is 456 km, and the depth of its laying is 2,5–11,0 m.

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УДК 631.67; 626.86

ЗАХИСТ ТЕРИТОРІЙ ВІД ПІДТОПЛЕННЯ В ЗОНІ ПІВНІЧНО-КРИМСЬКОГО КАНАЛУ ХЕРСОНСЬКОЇ ОБЛАСТІ ТА ШЛЯХИ ЙОГО УДОСКОНАЛЕННЯ

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Анотація. *Розглянуто системи захисту територій від шкідливої дії вод за допомогою вертикального дренажу в зоні Північно-Кримського каналу Херсонської області та обґрунтовано пропозиції щодо їх удосконалення шляхом створення додаткових систем горизонтального дренажу з самопливним водовідведенням. Натурні дослідження дренажу проводили на 8 дослідно-виробничих ділянках загальною площею 4763 га і терміном експлуатації 48–55 років і більше. Проведені дослідження містили обстеження дренажу на ділянках, вимірювання дренажного стоку та глибин залягання рівнів ґрунтових вод, визначення ефективності роботи. Дослідження охопили населені пункти: Чорнянка, Нова Маячка, Стара Маячка, Подо-Калинівка, Тарасівка, Великі Копані, Каланчак та Скадовськ, для захисту яких облаштовано 119 водозабірних свердловин глибиною 26–70 м. Показано ефективну роботу вертикального дренажу у період його повноцінної роботи та недостатню у періоди вибіркової роботи, коли рівні ґрунтових вод знаходились на глибинах 2–3 м і 1–2 м відповідно. Для забезпечення надійного захисту територій від підтоплення та затоплення в сучасних умовах у зв'язку з неможливістю та економічною недоцільністю відновлення роботи всіх наявних свердловин вертикального дренажу запропоновано існуючі системи захисту на його основі доповнити системами закритого горизонтального дренажу самопливного типу з малопохиловим та безпохиловим водовідведенням стоку. Площа додаткового горизонтального дренажу становить близько 40 тис. га, орієнтовна довжина колекторно-дренажної мережі – 456 км, глибина закладання дрен та колекторів – 2,5–11,0 м.*
Ключові слова: *вертикальний дренаж, ефективність роботи горизонтальний дренаж, самопливне водовідведення*

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WATER REGIME AND EFFICIENCY OF GROWING SUNFLOWER HYBRIDS DEPENDING ON THE ELEMENTS OF DRIP IRRIGATION TECHNOLOGY

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Abstract. *The article presents the results of experimental research on the influence of micro-irrigation system designs on the water regime, productivity, and efficiency of sunflower cultivation. Based on this, the main economic parameters of agrotechnologies of sunflower cultivation were calculated. Short-term field research was carried out in the period 2020–2022 on the lands of the Brylivske experimental field of the Institute of Water Problems and Reclamation of the National Academy of Agrarian Sciences (Kherson Region, Dry Steppe subzone). Analytical and statistical methods were used to process experimental data. The scheme of field experiments provided different options for laying irrigation pipelines of micro-irrigation systems (in the horizontal and vertical planes) and the implementation of a pulsed water supply mode (standard). The control was the variant without irrigation. According to the results of experimental studies, it was proved that the method of laying irrigation pipelines of micro-irrigation systems significantly affects the parameters of the formation of the soil water regime and the yield of sunflower hybrids in the conditions of the Dry Steppe. It has been established that the introduction of subsurface drip irrigation is more appropriate than the cultivation of sunflower hybrids, which is explained by the drought resistance of this crop. When growing sunflowers, the variant with the subsurface laying of drip irrigation pipelines provided almost identical yield parameters at lower plant water consumption coefficients. The minimum water consumption coefficient (1077.8 m^3/t) was obtained by implementing the pulse water supply mode. The highest economic parameters of agricultural technology for growing sunflower hybrids were obtained with the subsurface drip irrigation: conditionally net profit (17.11–18.17 thousand UAH/ha), lower cost (11.03–10.90 thousand UAH/ton), and also a higher level of production profitability (31.10–32.62%) (laying irrigation pipelines every 1,0 m, regardless of the sunflower hybrid). Due to the higher grain yield and specific savings of irrigation water in the pulse mode of water supply, the highest economic parameters were achieved: gross income amounted to 80.51 thousand UAH/ha, conditionally net profit – 21.24 thousand UAH/ha, cost of 1 ton of grain – UAH 10.6 thousand and the level of profitability of production – 35,8%.*

Keywords: *drip irrigation, subsurface drip irrigation, pulse mode of water supply, evapotranspiration, soil water regime, economic efficiency, sunflower*

Relevance of research. It is known, that sunflower is one of the main technical agricultural crops in Ukraine, the cultivated area under which in 2021 amounted to 6.43 million hectares [1], which is almost 20% of the total arable land. It should be noted that as of 1990, sunflower occupied only 1.57 million hectares, in the early 2000s – 3.0–3.2 million hectares, which amounted to 5–10% of the total area of field crops in Ukraine. (Fig. 1). It is obvious, that such a large area is absolutely unjustified and leads to a decrease in soil fertility [2].

Current trends of climate changes towards aridity [3; 4; 5] may lead to a further increase in sunflower acreage, as the crop, compared to others, is quite drought-resistant. Possible directions for obtaining high and stable yields in these conditions are the creation of new drought-resistant varieties and hybrids and the development of more effective methods of adaptive growing technologies, the introduction of tillage technologies aimed at maximizing moisture conservation – mini-till, strip-till and no-till, mulching and slotting of the soil, etc. However, as evidenced by practice and scientific research, the most effective use of irrigation melioration is in combination with fertigation. The increase in yield from the optimization of water and nutrient regimes is the most effective and ranges from 100 to 380% compared with non-irrigated conditions [7]. It should be especially noted, that in recent years, the irrigated area under sunflowers has increased sharply (by 65% in the last 7 years) and amounted to about 72 thousand ha in 2020 [8]. Therefore, the main method of irrigating this culture is sprinkling.

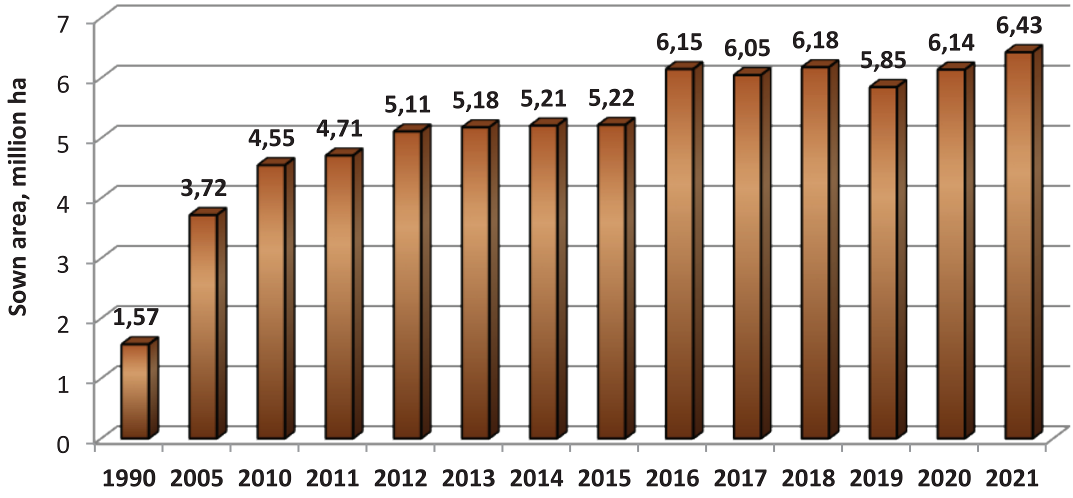

Fig. 1. Dynamics of sunflower acreage in Ukraine (1990–2021)

Therefore, the substantiation of the water regime of the soil and the evaluation of the effectiveness of sunflower cultivation with the introduction of micro-irrigation methods are relevant today.

Analysis of recent research and publications. Given the relevance of the subject, in different years a significant complex of diverse studies was carried out on the introduction of irrigation in agricultural technologies for growing sunflowers. Preferably, these studies concerned sprinkling [9; 10; 11]. As for studies on the study of the water regime with various methods of micro-irrigation, they are more thoroughly carried out by foreign scientists [12; 13; 14], while in Ukraine they are only fragmentary [15; 16].

Therefore, **the purpose of the study** was to establish the parameters of the water regime of the soil and to substantiate the effectiveness of growing sunflower hybrids depending on the various designs of micro-irrigation systems.

Materials and methods of research. Field research was carried out on the lands of the Brylivske experimental field of the National Academy of Agrarian Sciences of the Russian Academy of Sciences (Privytne village, Vynogradivska rural community of Kherson district, Kherson region, Dry Steppe subzone, 46°40´N. 33°12´E.) during 2020–2022. The three-factor field experiment envisages the following designs of micro-irrigation systems: drip irrigation (DI) with ground laying of irrigation pipelines (IP), subsurface drip irrigation (SDI) with laying of IP to a depth of 30 cm (factor C). In addition, the design parameter was the distance between IP (factor B) – 0.7 m (1,0 m) and 1.4 m. The reference was the option of subsurface drip irrigation with pulse water supply mode (SDIP), and the conditional control was the option of natural moisture supply – without irrigation (W/I). The studies were carried out according to generally accepted methods: placement of plots – systematic, replication – four times, the area of accounting plots – 32 m^2 [17; 18], sunflower hybrids for confectionery use – Ukrainian F1 and Rimisol F1 (factor A).

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, the content of humus is 1.44 %, and alkaline hydrolyzed nitrogen (the method of determination is according to Kornfield) is 7.0 mg/100 g of soil, mobile compounds of phosphorus and potassium in the soil according to the Chirykov method – 32.3 mg/100 g and 9.3 mg/100 g of soil, respectively.

The amount of productive rainfall during the growing season of sunflowers and chickpeas varied over the years of research. So, in 2020, only 68.0 mm fell, which is only 31.9 % of the climatic norm for the growing season, during 2021–205.5 % of the climatic norm, which is also an anomalous phenomenon for the conditions of the Dry Steppe, and in 2022 – 167.6 mm or 121.9 % of the climatic norm. The level of pre-irrigation moisture in the experiments was -21 kPa in a 0–50 cm soil layer. To set the irrigation time, instrumental complexes were used: the Drill and Drop moisture meter from Sentek and the iMetos soil moisture station with Echo Probe EC-5 sensors [19]. Statistical analysis of research results was carried out by dispersion, correlation and regression methods using the “Statistica 6.0” program.

Economic efficiency was calculated based on the accepted standards, norms and prices [20] of the current year, energy efficiency – according to the methodology for energy assessment of technologies for growing crops [21]. The depreciation period for components and parts of irrigation systems (except for the PT of the annual period of use of drip irrigation) is 10 years.

Results of the study and their discussion. The results of the field studies showed that the water regime of the soil and the evapotranspiration of sunflower hybrids were formed depending on the design of micro-irrigation systems and meteorological conditions of the growing season in a particular year. We averaged the number of vegetation irrigations, the values of irrigation rates and evapotranspiration in the context of years of research (Table 1).

So, on average, over three years of research, in order to maintain soil moisture reserves at a level of minus 21 kPa (80 % of the lowest soil moisture capacity), from 11 to 14 vegetation irrigations were carried out for growing sunflower hybrids with an irrigation rate of 1.67–1.96 thousand m^3/ ha with subsoil irrigation and 14–19 irrigations with an irrigation rate of 1.96–2.43 thousand m^3/ha with drip irrigation. Consequently, according to the averaged data, the irrigation rate for subsurface irrigation was less by 0.384 thousand m^3/ha or 17.4 % than with ground-based irrigation pipelines.

Sunflower evapotranspiration parameters were at the level of 2.94–3.05 thousand m^3/ha in non-irrigated conditions, 4.36–4.62 thousand m^3/ha under subsurface irrigation (IP placement at a depth of 0.3 m) and 4.73–5.24 thousand m^3/ha for ground placement of irrigation pipelines. Evapotranspiration among hybrids was almost the same: 4.35 thousand m^3/ha Rimisol F1 and 4.44 thousand m^3/ha – Ukrainian F1.

When implementing the pulse mode of water supply, on average, 148 vegetation irrigations were carried out with a total irrigation rate of 2.22 thousand m^3/ha. The value of evapotranspiration at the same time amounted to 4.85 thousand m^3/ha. The lowest water consumption coefficient (WCC) for sunflower is typical for options with subsoil drip irrigation – 1088.7–1254.2 m^3/t. The maximum WCC was in rainfed growing conditions – 1839.8–1847.8 m^3/t.

It should be noted the relatively low value of the water consumption coefficient in the experimental version with pulsed water supply mode according to SDI – 1077.8 m^3/t, which indicates the most efficient use of moisture by sunflower plants.

The key motivational mechanism for the introduction of drip irrigation technologies is obtaining economic profit on the basis of preserving the ecological sustainability of reclaimed agricultural landscapes [22]. Therefore, there is a need to evaluate the most effective combinations of the studied factors not only according to the productivity criterion, but also according to a number of basic (basic) economic indicators. The economic evaluation of the effectiveness of the investigated options was carried out according to the actual costs of material funds for the cultivation of products as of September 2022 (Table 2).

The key aspect in the calculation of economic parameters was the total cost of growing products. Thus, regardless of the higher yield of sunflower

1. Parameters of soil water regime and evapotranspiration (ETc) of sunflower hybrids depending on micro-irrigation system designs (2020–2022)

A variant of the experiment			The number of waterings	Irrigation rate, m^3/ha	Precipitation, m^3/ha	Soil moisture, m^3/ha			ETc, m^3/ha	WCC, m^3/ha
factor A	factor B	factor C				begining	final	balans		
Rimisol F1	DI	0.7	18	1960	2098	1363	693	670	4728	1127.5
		1.4	14	2313		1317	490	827	5238	1414.4
	SDI (-30 cm)	1.0	13	1667		1380	783	597	4362	1088.7
		1.4	11	1872		1303	813	490	4460	1226.4
	control (W/I)		–	–		1327	487	840	2938	1847.8
Ukr. F1	DI	0.7	19	2140		1377	753	624	4862	1102.5
		1.4	14	2427		1307	750	557	5082	1298.6
	SDI (-30 cm)	1.0	14	1803		1403	700	703	4604	1125.7
		1.4	11	1963		1310	747	563	4624	1254.2
	control (W/I)		–	–		1317	367	950	3048	1839.8
Impulse mode of water supply in subsurface drip irrigation										
Ukr. F1	SDIP (-30 cm)	1.0	148	2222	2098	1335	805	530	4850	**1077.8**

2. The main economic parameters of growing sunflower hybrids depending on the designs of micro-irrigation systems (2022)

A variant of the experiment			Costs, thousand UAH/ha, for:				Gross income, thousand UAH/ha*	Conditionally net profit, UAH/ha	Cost price, thousand UAH/t	Profitability level, %
factor A	factor B	factor C	cultivation technology	micro-irrigation system (depreciation, operation)	harvest & logistics	general				
Rimisol F1	DI	0.7	36.76	27.85	2.62	67.23	75.60	8.37	12.85	12.45
		1.4	38.82	20.79	2.31	61.92	66.78	4.86	13.40	7.85
	SDI (-30 cm)	1.0	34.98	17.69	2.50	55.17	72.28	17.11	11.03	31.10
		1.4	36.47	11.32	2.27	50.06	65.63	15.57	11.03	31.01
	control (W/I)	25.37	–	1.02	26.39	29.63	3.24	12.87	12.28	
Ukrainian F1	DI	0.7	37.20	27.85	2.75	67.8	79.50	11.7	12.33	17.26
		1.4	39.41	20.79	2.44	62.64	70.54	7.9	12.84	12.61
	SDI (-30 cm)	1.0	35.45	17.69	2.56	55.7	73.87	18.17	10.90	32.62
		1.4	37.07	11.32	2.30	50.69	66.49	15.8	11.02	31.17
	control (W/I)	25.69	–	1.08	26.77	31.37	4.6	12.34	17.18	
Pulse mode of water supply in subsurface drip irrigation										
Ukr. F1	SDIP (-30 cm)	1.0	38.79	17.69	2.79	59.27	5.57	80.51	21.24	10.64

In the calculations, the selling price of sunflower seeds is 14.455 thousand UAH/t (as of September 6, 2022).
Source: https://tripoli.land/analytics/podsolnechnik

under surface drip irrigation, the higher economic indicators were under the underground laying of pipelines. The highest are conditionally net profit (17.11–18.17 thousand UAH/ha), lower cost price (11.03–10.90 thousand UAH/ton), as well as a higher level of profitability of production (31.10–32.62 %) provided the option with subsurface laying of irrigation pipelines every 1.0 m regardless of the sunflower hybrid.

The analysis of the calculations shows that, basically, such parameters according to the PCZ were achieved by optimizing the operating costs of the micro-irrigation system against the background of almost the same crop yield. Without an irrigation, the sunflower cultivation was at the minimum level of profitability (+12.2 – +12.6 %).

It is necessary to note the economic parameters in the variant with the implementation of the pulse water supply mode, where due to the higher grain yield and the specific saving of irrigation water, the highest indicators of the technology were achieved: gross income – 80.51 thousand UAH/ha, conditional net profit – 21.24 thousand UAH/ha, the cost of 1 ton is UAH 10.6 thousand and the level of profitability of production is 35.8 %.

Conclusions. The results of experimental studies proved that the method of laying irrigation pipelines of micro-irrigation systems reliably affects the parameters of the formation of the water regime of the soil and the yield of sunflower hybrids in the conditions of the Dry Steppe. It was established that the introduction of subsoil drip irrigation is more appropriate for growing sunflower hybrids, which is explained by the drought resistance of the culture. For the cultivation of this agricultural crop, the variant with in-soil laying of irrigation pipelines of drip irrigation provided almost identical yield parameters with lower coefficients of plant water consumption. The minimum coefficient of water consumption (1077.8 m^3/t) was obtained under the condition of implementation of the pulse water supply mode.

Higher economic parameters of agrotechnology for growing sunflower hybrids were also obtained with subsurface drip irrigation: conditionally net profit (17.11–18.17 thousand UAH/ha), lower cost price (11.03–10.90 thousand UAH/t), and a higher level of profitability of production (31.10–32.62 %) (laying of irrigation pipelines after 1.0 m regardless of the sunflower hybrid). Due to the higher grain yield and the specific saving of irrigation water under the impulse mode of water supply, the highest economic parameters of the technology were achieved: gross income – 80.51 thousand UAH/ha, conditional net profit – 21.24 thousand UAH/ha, cost price of 1 ton – 10.6 thousand UAH and the level of profitability of production – 35.8 %.

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ВОДНИЙ РЕЖИМ ТА ЕФЕКТИВНІСТЬ ВИРОЩУВАННЯ ГІБРИДІВ СОНЯШНИКУ ЗАЛЕЖНО ВІД ЕЛЕМЕНТІВ ТЕХНОЛОГІЇ КРАПЛИННОГО ЗРОШЕННЯ

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Анотація. *У статті наведено результати експериментальних досліджень з вивчення впливу конструкцій систем мікрозрошення на водний режим, продуктивність та ефективність вирощування соняшника. За цього розраховано основні економічні параметри агротехнологій вирощування соняшника. Польові короткотермінові дослідження проведено у період 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 і статистичні методи. Схемою польових дослідів було передбачено різні варіанти укладання поливних трубопроводів систем мікрозрошення (у горизонтальній та вертикальній площині) та реалізація імпульсного режиму водоподачі (еталон). Контрольним був варіант без зрошення. За результатами експериментальних досліджень доведено, що спосіб укладання поливних трубопроводів систем мікрозрошення достовірно впливає на параметри формування водного режиму ґрунту та врожайність гібридів соняшнику в умовах Степу Сухого. Встановлено, що впровадження підґрунтового краплинного зрошення є більш доцільним за вирощування гібридів соняшнику, що пояснюється посухостійкістю цієї культури. За вирощування соняшнику варіант із внутрішньоґрунтовим укладанням поливних трубопроводів краплинного зрошення забезпечив практично ідентичні параметри врожайності за нижчих коефіцієнтів водоспоживання рослин. Мінімальний коефіцієнт водоспоживання (1077,8 м^3/т) отримано за умови реалізації імпульсного режиму водоподачі. Вищі економічні параметри агротехнології вирощування гібридів соняшника отримано за підґрунтового краплинного зрошення: умовно чистий прибуток (17,11–18,17 тис. грн/га), нижчу собівартість (11,03–10,90 тис. грн/тонну), а також вищий рівень рентабельності виробництва (31,10–32,62 %) (укладання поливних трубопроводів через 1,0 м не залежно від гібриду соняшника). За рахунок вищої врожайності зерна і питомої економії поливної води за імпульсного режиму водоподачі досягнуто найвищих економічних параметрів: валовий дохід становив 80,51 тис. грн/га, умовно чистий прибуток – 21,24 тис. грн/га, собівартість 1 тонни зерна – 10,6 тис. грн та рівень рентабельності виробництва – 35,8 %.*

Ключові слова: *краплинне зрошення, підґрунтове краплинне зрошення, імпульсний режим водоподачі, евапотранспірація, водний режим ґрунту, економічна ефективність, соняшник*

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METHODICAL APPROACHES TO THE DETERMINATION OF EVALUATION CRITERIA AND SELECTION OF THE DESIGN OF ANTI-FILTRATION SCREENS OF RESERVOIRS

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Abstract. *The relevance of the issue is caused by the presence of significant (more than 20% of the normative indicators) filtration losses from most reservoirs built in Ukraine without anti-filtration protection. Based on the results of analytical and experimental field studies of the constructive elements of anti-filtration protection of reservoirs, calculations of structural parameters, and generalization of scientific research materials, the main areas and trends of improving screen structures of these reservoirs have been determined. It was established that the selection of the designs of anti-filtration screens is based on the optimization of the main indicators of the evaluation criteria of technically and economically expedient designs. The criteria for evaluating the anti-filtration protection design are filtration losses, filtration coefficient, coefficient of performance, coefficient of anti-filtration efficiency, filtering resistance of the structure, optimal parameters of the soil base (density and moisture) of different types of soils, an indicator of environmental safety, and technical and economic efficiency. Creating new types of designs of anti-filtration screens for reservoirs was justified, and the trends of their improvement were specified. Methodical approaches to the selection of optimal screen designs were developed. Prospective designs of anti-filtration screens of reservoirs when using the latest materials and modern technologies are proposed. The design parameters of anti-filtration screens of artificial reservoirs were established depending on the depth of their filling and the physical and mechanical properties of the soil of the reservoir bowl base. The economic efficiency of new types of designs of anti-filtration screens, compared to the traditional ones, is in reducing filtration losses and increasing the efficiency water reservoirs.*

Keywords**:** *reservoir, protective structures, filtration coefficient, methodology, methodical approaches, anti-filtration screen, types of screens*

Introduction. More than 350 large reservoirs were built in Ukraine. About 90% of them are not equipped with anti-filtration protection structures; which leads to significant losses of water as a result of filtration.

According to the "Irrigation and Drainage Strategy in Ukraine for the period up to 2030" [1], the restoration of existing irrigation systems in an area of 1.0–1.2 million hectares is planned. The implementation of this Strategy requires a significant amount of restoration, capital repair, reconstruction, and construction of artificial reservoirs and canals with high and reliable anti-filtration properties.

Analysis of the latest research and publications. The research shows [2; 3; 4] that the performance coefficient of the reservoirs in an earthen bowl is 0.77, and when using traditional anti-filtration protection it is 0.85, which does not correspond to the normative indicators according to SBS B.2.4–1–99 within 20% [5]. In this regard, the development of reliable anti-filtration structures of reservoir screens, which would ensure not only high anti-filtration efficiency but also high operational reliability and durability, is relevant.

In international practice, one of the modern ways of increasing anti-filtration efficiency is the use of geomembranes in combination with protective geosynthetic materials, which are used in Europe, the USA, and also in Ukraine [6; 7].

However, in Ukraine, their use is limited due to insufficient regulatory, methodological, and technical support for the use of these materials and technologies.

The purpose of the research is to analyze methodical approaches to the assessment of the technical condition of the designs of anti-filtration screens of reservoirs and to justify their promising types.

This goal can be realized following the working hypothesis of creating new types of anti-filtration screens in the form of a multilayer structure, which takes into account both the anti-filtration and protective functions of the screen and the base, which would allow combining the anti-filtration properties of new polymeric materials and the protective properties of geosynthetics and traditional local materials to ensure optimal waterproofing, strength, and reliability.

This especially applies to the latest materials and technologies, the use of which requires an update of methodological approaches regarding the determination of physical and mechanical properties, calculation and application of these materials in prospective designs of anti-filtration screens, evaluation of their criteria, selection, and justification.

Research materials and methods. Analytical and experimental field research methods were applied. The research methodology includes examination and assessment of the technical condition of anti-filtration screen structures of reservoirs under current requirements [8; 9]. To calculate the parameters of anti-filtration screen structures all types of loads during their construction and operation were taken into account. The values of filtration losses of different types of linings were obtained when monitoring the technical condition of the HTS on the main irrigation systems of Ukraine (Kakhovska, North-Rohachytska, Krasnoznamyanska, Inguletska, Danube-Dnistrovska, Nyzhnyodnistrovska), as well as hydrotechnical structures of the cascade of protective facilities of the Dnieper reservoirs (Orilska protective dam, Western-Kryukivska, and Verkhnyodniprovska dams) [9; 10].

Research results. In the course of the research, an assessment of the technical condition of anti-filtration screen structures of the reservoirs was carried out, the main types of damage were identified, and methodical approaches to the creation of new screen designs were developed.

It was established that the selection of anti-filtration screen designs is based on the optimization of the main indicators of the design evaluation criteria.

The following criteria for evaluating screen designs were considered: filtration losses, $Q_{обл.}$; filtration coefficient, $K_{обл.}$; performance coefficient, η; coefficient of anti-filtration efficiency, E; filtration resistance of the structure, $\Phi_{обл.}$; optimal parameters of the soil base: density (ρ_d) and moisture *(W)* for different types of soils; environmental safety factor; technical and economic efficiency [10].

Filtration losses. According to the data of long-term field studies carried out at the Institute of Water Problems and Land Reclamation, the filtration losses of various types of screens, which were widely implemented in the 50–80s of the last century on irrigation systems, were developed and evaluated, and by normative and methodical recommendations [10; 11], the filtration coefficients of linings were determined (Table 1).

It should be noted that the filtration losses of these structures vary from 0.0015 to 0.250 m^3/day from the reservoir bowl of 1 m^2. Monolithic concrete coatings with or without a film have the smallest filtration losses (filtration losses q = 0.0015 or 0.003 m^3/day from the reservoir bowl of 1 m^2). Coverings made of reinforced concrete NPK slabs have the largest losses, from q = 0.010 to 0.020 m^3/day from the reservoir bowl of 1 m^2. This also applies to the designs of anti-filtration screens of irrigation canals, which are practically identical in their technical and economic characteristics [7].

Filtration losses from reservoirs in an earthen bowl are 0.25–0.30 m^3/day from 1 m^2 of surface [13; 14].

However, the screen filtration coefficient is not a sufficient characteristic of efficiency, as it does not take into account the properties of the "screen-soil base" system, which makes it necessary to determine the anti-filtration efficiency coefficient, especially for the designs of anti-filtration screens of reservoirs.

Coefficient of anti-filtration efficiency. The anti-filtration efficiency of screens of various designs, regardless of soil conditions, is characterized by the coefficient of anti-filtration efficiency of the screen E [11]:

$$E = \frac{Q_{гр} - Q_{обл}}{Q_{гр}},$$

where $Q_{гр}$ – filtration losses from the reservoir in the earth bed, m^3/day; $Q_{обл}$ – filtration losses in reservoirs with a screen, m^3/day.

The coefficient of anti-filtration screen efficiency *(E)* takes into account the combined efficiency of the screen and the soil base and varies within $0 < E < 1$: $E = 1$ – there are no filtration losses (if there is a screen); $E = 0$ – filtration losses did not decrease after installing the screen.

The conducted research on determining the coefficient of anti-filtration efficiency led to the need to fundamentally change methodological

1. Filtering properties of screen linings of various designs

Lining type	Filtration losses q, m^3/day from 1 m^2 of reservoir bowl	Filtration coefficient of lining, $K_{обл}$, m/s
Monolithic reinforced concrete of 0.12–0.15 m, loam preparation of 0.20 m, ρ_d = 1.67 g/cm^3	0.009	2.35×10^{-8}
Monolithic reinforced concrete of 0.12–0.15 m, polyethylene film of 0.2 mm, loam preparation of 0.20 m, ρ_d = 1.67 g/cm^3	0.002	5.23×10^{-9}
NPK slabs, polyethylene wide film of 8 m wide, loam preparation of 0.20 m, ρ_d = 1.67 g/cm^3. Highly careful execution of work	0.004	8.24×10^{-9}
NPK slabs, polyethylene film of 3 m wide, loam preparation of 0.20 m, ρ_d = 1.67 g/cm^3. Usual execution of works	0.020	4.36×10^{-8}
Monolithic reinforced concrete of 0.12–0.15 m, polyethylene film of 0.2 mm, loam preparation of 0.20 m, ρ_d = 1.67 g/cm^3	0.0028	5.06 10-7
NPK slabs, polyethylene film of 3 m wide, loam preparation of 0.20 m, ρ_d = 1.67 g/cm^3. Usual execution of work, pouring of cement mortar into the sub-slab space	0.010	1.8×10^{-8}
Monolithic concrete of 0.08 m, polyvinyl chloride film of 0.27 mm	0.0017	0.9×10^{-9}
Monolithic concrete of 0.08 m, polyethylene film of 0.25 mm	0.0024	1.62×10^{-9}
Monolithic concrete of 0.08 m, polyolefin film of 0.52 mm	0.0015	0.88×10^{-9}
Precast and monolithic (along the bottom with an outlet at 0.7 m of canal slope – monolithic reinforced concrete 0.14 m; on the slopes – NPK slabs), along the entire perimeter of the canal there is polyolefin film of 0.52 mm	0.003	2.08×10^{-9}
Precast and monolithic (similar design), polyvinyl chloride film of 0.27 mm	0.008	6.48×10^{-9}
Precast and monolithic (similar design), polyvinyl chloride film of 0.25 mm	0.015	1.38×10^{-8}
Reservoir without lining in loamy soils	0.250	–

approaches to the use of the latest materials, which would ensure the improvement of the quality of various types of screen structures (Table 2). This especially applies to the increase in filtration resistance when using the latest materials for lining structures, the dynamics of changes in the anti-filtration effect, and the assessment of the state of the structures during their operation.

It was established that, by the coefficient of anti-filtration efficiency, monolithic concrete

2. The coefficient of anti-filtration efficiency of various types of lining structures

Lining type	Coefficient of anti-filtration efficiency, E
Monolithic concrete lining, t = 0.12 m	0.94
Monolithic concrete, t = 0.15 m	0.90
Monolithic reinforced concrete t = 0.12–0.15 m, polyethylene film of 0.2 mm	0.90
Monolithic concrete t = 0.07 m, polyvinyl chloride film of 0.27 mm	0.87
Soil film lining (Geosynthetic materials)	0.85
Monolithic concrete lining, t = 0.07 m	0.84
Reinforced concrete slabs, 0.2 mm polyethylene film of 8 m wide	0.80
Polyolefin film of 0.52 mm, sand layer t = 0.38 m	0.70
Polyvinyl chloride film of 0.27 mm under a sand-gravel layer t = 0.38 m	0.60
Reinforced concrete slabs, cement-sand joints, polyethylene film of 0.4 mm	0.54
Polyethylene film of 0.52 mm under the sand-gravel layer t = 0.38 m	0.50
Reinforced concrete slabs with reinforcement outlets with a thickness of t = 0.08 m	0.40
Monolithic concrete t = 0.05 m	0.38
Precast fastening with plates, polyethylene film of 0.2 mm	0.35

anti-filtration coatings with or without a polymer film (E = 0.87–0.94) are the most effective ones among traditional screen designs. The precast reinforced concrete coatings (E = 0.35–0.40), which are used in hydrotechnical structures of the reclamation facilities of Ukraine, have the lowest anti-filtration efficiency [11; 12; 13; 14].

The main shortcomings of the structures were identified, the elimination of which requires improvement of the quality characteristics of the structural components of the screen structure and compatible work in general. To compare the filtration resistance parameters of different designs of screens, both traditional and modern designs were considered.

Filtration resistance of the structure. The anti-filtration effect of various screen designs is characterized by the value of the filtration resistance of the screen design $Φ_{обл}$.

The filtration resistance of various designs of anti-filtration screens of reservoirs based on the research and analytical calculation data and analysis of the materials of design solutions is given in Table 3 [5; 10; 11].

Current building regulations in Ukraine CH 551–82 (Instructions for the design and construction of anti-filtration screens made of polyethylene film for artificial water bodies) is the only normative document that regulates the entire process of design and construction of film screens of traditional structures. The use of polymer films with a thickness of 0.2–0.4 mm provided by this document currently does not meet modern requirements for reliability, safety, and anti-filtration efficiency, and screen lining structures based on them are out-of-date. This is confirmed by the research materials of traditional structures of anti-filtration screens, which are currently subject to reconstruction and overhaul.

Recently, polymer geomembranes began to be used, which, compared to films, were developed and are widely used as anti-filtration screens on reservoirs. Based on field, laboratory, and theoretical (including analytical) studies, technical conditions, requirements, and recommendations for the use of polymer geomembranes along with geosynthetic materials have been developed.

When choosing optimal screen designs when using the latest geosynthetic materials, there is a need for normative provision and refinement of methodological approaches to the calculation and generalization of evaluation criteria, which will make it possible to perform the selection and justification of certain materials and types of structures.

It is proposed to use the coefficient of filtration losses and performance indicators as generalized criteria. They were used when calculating technical and economic indicators both for traditional and modern structures on reservoirs of reclamation and water management area. Table 4 shows the results of calculations of the assessment of the anti-filtration efficiency of screen designs (traditional and modern structures) by the above criteria.

Based on the results of the analysis of technical and economic indicators given in Table 4, it can be stated that the latest designs of anti-filtration screens when using geomembranes and protective geosynthetic materials increase the maximum service life by 1.5–2.0 times (up to

3. Filtration resistance of various designs of anti-filtration screens of reservoirs

Lining type	Filtration resistance $Φ_{обл}$
Traditional designs	
Monolithic concrete, t = 0.15 m	95
Polyolefin film of 0.52 mm under precast monolithic concrete (along the bottom with an outlet at 0.7 m of canal slope – monolithic reinforced concrete of 0.14 m	80
Polyvinyl chloride film of 0.20 mm under precast monolithic concrete (the design of the concrete lining is similar to the previous one)	72
Polyethylene film of 0.25 mm under precast monolithic concrete (the design of the concrete lining is similar to the previous one)	36
Reinforced concrete slabs, polyethylene film of 0.2 mm, 8 m wide, loam preparation t = 0.2 m, ρ_d = 1.67 g/cm^3	65
The latest designs (structures of anti-filtration linings with the use of geosynthetic materials)	
Geomembrane with a protective coating made of concrete	96
Geomembrane with a protective coating made of soil	95
Geomembrane with a protective coating made of a stone coat	96
Geomembrane with a protective coating made of gabions and geogrids	96
Anti-filtration coating when using bentomats	97

4. Technical and economic indicators of various types of anti-filtration screen designs of reservoirs

№	Anti-filtration screens	Service life *t*, years	Reduction of filtration losses compared to an earthen bed *σ*, %
	Traditional designs		
1	Monolithic concrete with polyethylene film of 0.2 mm thick	20–40	up to 95
2	Reinforced concrete monolithic with polyethylene film of 0.2 mm thick	30–40	up to 93
3	Precast monolithic reinforced concrete with polyethylene film of 0.2 mm thick	30–40	88
4	Precast reinforced concrete with polyethylene film of 0.2 mm thick	30–40	85
5	Asphalt concrete with a polyethylene film of 0.2 mm thick	5–10	90
6	Clay	10	70
7	Soil compaction	3–5	50
8	Soil colmatation	12–15	60
	Latest designs		
9	Monolithic concrete with geomembrane of 0.4 mm thick at least	70–85	98
10	Reinforced concrete monolithic with geomembrane of 0.4 mm thick at least	70–85	92
11	Precast monolithic reinforced concrete with geomembrane of 0.4 mm thick at least, protected by geosynthetic material	70–80	98
12	Geomembrane with a protective soil layer, protected by geosynthetic material	80–90	97

90 years) compared to the traditional ones and reduce filtration losses by 1.5 times (96–98 %).

Conclusions

1. Based on the results of analytical and experimental studies on the assessment of the technical condition of hydrotechnical structures during their operation within the main irrigation systems of Ukraine, when using traditional designs of anti-filtration screens, it was established their being unable to provide effective anti-filtration protection, and the filtration losses at that exceed the standard indicators by an average of 20 %.

2. Based on the results of the research, the coefficient of filtration losses and performance indicators as generalized criteria for selection and justification of prospective designs of anti-filtration screens when using geomembranes and protective geosynthetic materials has been justified.

3. The use of the proposed methodical approaches to the selection and justification of promising designs of anti-filtration linings enables to increase in the anti-filtration capacity of the screens by 1,5 times as well as their service life up to 90 years.

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МЕТОДИЧНІ ПІДХОДИ ДО ВИЗНАЧЕННЯ КРИТЕРІЇВ ОЦІНЮВАННЯ ТА ВИБОРУ КОНСТРУКЦІЙ ПРОТИФІЛЬТРАЦІЙНИХ ЕКРАНІВ ВОДОЙМ

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Анотація. *Актуальність питання викликана наявністю значних, понад 20 % від нормативних, фільтраційних втрат з більшості водойм, побудованих в Україні без протифільтраційного захисту. За результатами аналітичних та експериментально-польових досліджень конструктивних елементів протифільтраційного захисту водойм, розрахунків параметрів конструкцій та узагальнення матеріалів наукових досліджень визначено основні напрями і тенденції удосконалення конструкцій екранів цих водойм. Встановлено, що вибір конструкцій протифільтраційних екранів базується на оптимізації основних показників критеріїв оцінювання технічно й економічно доцільних конструкцій. За критерії оцінювання конструкції протифільтраційного захисту прийнято: фільтраційні втрати; коефіцієнт фільтрації; коефіцієнт корисної дії; коефіцієнт протифільтраційної ефективності; фільтраційний опір конструкції; оптимальні параметри ґрунтової основи (щільність і вологість) різних типів ґрунтів; показник екологічної безпеки; техніко-економічна ефективність. Обґрунтовано можливість створення нових типів конструкцій протифільтраційних екранів водойм та встановлено тенденції їх удосконалення. Сформовано методичні підходи щодо вибору оптимальних конструкцій екранів. Запропоновано перспективні конструкції протифільтраційних екранів водойм із використанням новітніх матеріалів та сучасних технологій. Встановлено конструктивні параметри протифільтраційних екранів штучних водойм залежно від глибини їх наповнення та фізико-механічних властивостей грунтів основи чаші водойми. Економічна ефективність нових типів конструкцій протифільтраційних екранів, порівняно з традиційними, полягає у зменшенні фільтраційних втрат та підвищенні коефіцієнта корисної дії водойм.*

Ключові слова: *водойма, захисні конструкції, коефіцієнт фільтрації, методика, методичні підходи, протифільтраційний екран, типи екранів*

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INVESTIGATION OF WATER DISINFECTION PROCESSES USING PULSE ELECTRIC DISCHARGE

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Abstract. *As a result of Russian military aggression in the south-eastern region of Ukraine, water supply pipes and structures of centralized water supply systems were destroyed, and therefore water supply was practically stopped. The solution to the problem can be the use of mobile water treatment stations which use local sources of water: canals, lakes, ponds, or underground water. A feature of water treatment technologies in the field is the need to reliably ensure the process of water disinfection. Existing water disinfection technologies have low efficiency, taking into account the growing number of chlorine-resistant microorganisms, therefore, the implementation of alternative methods of disinfection during water treatment is urgent. One of these methods is liquid disinfection by electric current discharge. The results of the research on disinfection of different types of surface water in Kyiv and water contaminated with E. coli (Escherichia coli (E. coli)) are described. The research was carried out on a laboratory setup with a circulation pump and an ejector-type reactor with integrated electrodes where a water-air mixture is formed through which an electric discharge passes. The discharges initiate the formation of various highly reactive chemicals such as radicals (OH•, H•, O•) and molecules (H_2O_2, H_2, O_2, O_3). All physical and chemical processes that occur during discharge ensure the formation and action of short-term radicals and relatively long-term oxidants. The study of the influence of the concentration of microorganisms on the speed and completeness of water disinfection was carried out on technical (tap) water with the addition of washings from two tubes with test culture to the reaction tank, which provided the initial concentration of E. coli equal to $3.4 \cdot 10^6$ CFU/cm^3. Water treatment for 30 seconds reduced the number of microorganisms to $5.4 \cdot 10^4$ CFU/cm^3. After 1 minute of treatment this indicator decreased to $1.7 \cdot 10^2$ and after 3 minutes the value of 5.2 CFU/cm^3 was recorded in the samples, that is, the treated water had indicators of practically pure water. Experiments have proven the effectiveness of plasma disinfection for liquids with high concentration of microorganisms.*

Key words: *water, water supply, disinfection, bacteria, plasma, electric discharge*

Relevance of the problem. As a result of the military aggression of Russian Federation in the south-eastern region of Ukraine, water pipes and structures were destroyed, and, as a result, water supply in Donbas, Zaporizhzhia, Luhansk, Mykolaiv, and Kherson regions was practically stopped. First of all, rural settlements were affected to which water was transported tens of kilometers by big group agricultural water pipelines that include water intake and treatment facilities, transfer pumping stations, water discharge facilities. Such powerful objects, due to their considerable dispersion, are prone to damage and therefore to the cessation of functioning.

An effective alternative solution for restoring water supply can be mobile water treatment stations which can use existing local water sources: canals, lakes, rivers, ponds, or underground (especially mineralized) water. A specific feature of water treatment technologies under war conditions is the need to reliably ensure the process of effective water disinfection.

Analysis of recent research and publications. In recent years, studies on the quality of tap drinking water in Ukraine have revealed a tendency towards an increase in the frequency of deviations from hygienic requirements in terms of sanitary-chemical and bacteriological indicators [1–4]. The increase in the number of samples that do not meet the regulatory sanitary and chemical parameters is due to organochlorine compounds (OCs). Trihalomethanes, the marker of which is chloroform (CH), are considered prioritized among OCs. The largest share of tap drinking water samples (according to the data of the laboratory of natural and drinking water hygiene of the State Enterprise «Institute of Public Health named after O.M. Marzeev of the National Academy of Medical Sciences of Ukraine») [5; 6], the quality of which does not meet the hygienic requirements according to sanitary and toxicological indicators, belongs to CH (36.6 %).

The current sanitary-epidemic situation is caused by a number of factors including the decrease in the effectiveness of classic chlorine-containing disinfectants. This is explained by the mass spread of chlorine-resistant forms of pathogenic microorganisms. The problem is currently being solved by using new water treatment technologies [5–7] as well as increasingly expensive, toxic, but insufficiently effective disinfectants [8–10]. Therefore, it is necessary to develop new technological principles that guarantee stable disinfection of a wide range of microorganisms in natural waters.

One of the possible technological directions is the use of high-energy water treatment during electric discharge. The authors of the paper proposed water purification technology when using local water sources. The schematic diagram of the water treatment station is shown in Fig. 1. In this technological solution the question of the efficiency of the generator of complex oxidizers is insufficiently investigated.

The goal of the work is to experimentally determine the effectiveness of the method of inactivating microorganisms in water using the influence of cold plasma of pulsed electric discharge in a heterogeneous water-air environment.

Materials and methods. The research was carried out on a laboratory setup (Fig. 2) at the Institute of Environmental Geochemistry of the National Academy of Sciences together with the employees of the Institute of Water Problems and Land Reclamation of NAAS [11; 12]. The setup ensures a cyclic flow of water into the reactor where the decontamination process takes place. The decontamination reactor is served by an ejector with inserted electrodes to which electric current pulses are transmitted.

The electrodes are located in the vacuum zone of the mixing chamber of the ejector. Cavitation «boiling» of the treated water flow occurs in the ejector ensuring the formation of a water-air mixture in the ejector's vacuum zone. The water-air mixture formed in this way makes it possible to significantly reduce the cost of electricity for the generation and maintenance of plasma compared to discharges in a purely aqueous environment [2–4].

Discharges initiate a large spectrum of different physicochemical phenomena, such as a strong electric field, intense ultraviolet radiation, shock waves of excess pressure, and, especially, the formation of various highly active chemical compounds such as radicals (OH•, H•, O•, HO_2•) and molecules (H_2O_2,

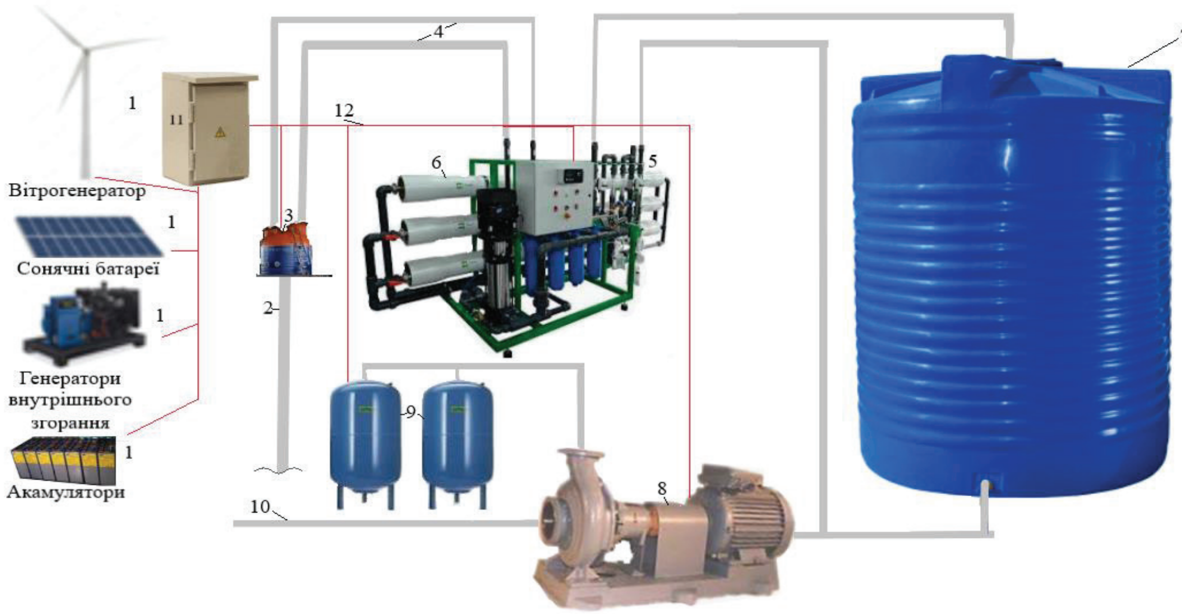

Fig. 1 Schematic diagram of a mobile water treatment station:
1 – power sources; 2 – line of input water supply; 3 – pump; 4 – lines of water supply for treatment; 5 – generator of complex oxidizers; 6 – microfiltration module; 7 – tank of clean water; 8 – pump of second lift; 9 – hydropneumatic accumulators; 10 – line of clean water supply; 11 – automated power supply cabinet with ARS, inventor, and stabilizer; 12 – line of power supply

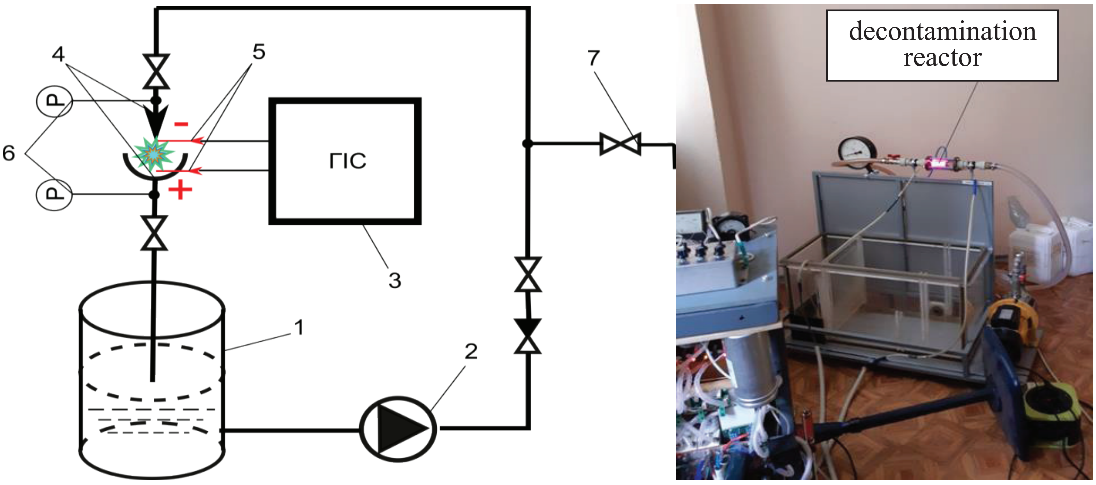

Fig. 2 Scheme of the experimental electric discharge installation for water disinfection: 1 – tank of input water; 2 – circulation pump; 3 – power supply unit; 4– discharge chamber – ejector; 5 – electrodes; 6 – manometers; 7 – tap for sampling

H_2, O_2, O_3) [3; 5; 7]. These physic-chemical processes, which occur during the discharge itself, determine the effect of disinfecting water from microorganisms. Accordingly, there is an assumption that the use of such processing will ensure high efficiency in disinfecting water from virtually all types and forms of microorganisms: viruses, bacteria, fungi, algae, cysts, protozoa, etc. The productivity of the experimental setup was Q = 0.45 m^3/h at the working pressure at the ejector inlet equal to 0.3 MPa. The volume of treated water was 5 liters. The total duration of the output pulses of the current generator was 5 ÷ 7 μs, the frequency of the pulses was 15 kHz, the amplitude of the pulses was about 5 kV.

The test object was the culture of E. Coli, strain B-926, from the collection of the Institute of Microbiology and Virology named after D.K. Zabolotny National Academy of Sciences of Ukraine.

Experiments were carried out on model samples of tap water (here and further referred to as «technical») with the sowing of E. coli culture grown on meat peptone agar (MPA), as well as on natural water: river water – the Dnipro River, which was collected in mid-July in the coastal zone of park named after Primakov, and from lake Seredne, which is part of the cascade of Holosiiv Lakes in Kyiv.

For tap water, cultures were washed in a sterile vial and shaken thoroughly. After introducing the bacterial culture, the content of the container was mixed well and a sample was taken aseptically to determine the initial concentration of the test culture in the water. The initial concentration of the microbial culture, as well as the content of microorganisms after exposure to plasma in the experiments was determined by the method of water limit dilutions.

The effect of the concentration of microbial contamination was studied on technical water samples, where the washings from two test tubes of E. coli B-926 culture on MPA were added.

The total microbial number of the initial water samples and after exposing them to plasma was calculated by the method of limiting dilutions, i. e., in all conducted experiments, tenfold dilutions were prepared from the selected samples. Next, 0.1 cm^3 of water of each dilution was sown on the appropriate medium (Endo or MPA) with three repetitions. The cultures were incubated for 24 hours at the temperature of 37 °C. After incubation, the total number of colonies was counted and the total microbial number was calculated according to the formula:

$$X = \frac{AB}{C}, \quad (1)$$

where X is the total microbial number of colony-forming units of viable microorganisms (CFU)/cm^3; A is the average colony count from replicates; B is the sample dilution; C is the amount of seed material, cm^3.

Technical water was inoculated on E. coli-selective Endo medium and natural water samples were inoculated on MPA to determine total microbial numbers, as well as on Endo medium to record the presence of fresh faecal contamination.

Samples were coded as follows: total microbial number – ZM; D – a sample of river water from the Dnipro river; O – sample from the lake; T – technical water sample; content of E. coli – Ecol.

Results and discussion. The study of the influence of the concentration of microorganisms on the speed and completeness of water disinfection was carried out on technical (tap) water with the addition of washings from two test-culture tubes to the reaction tank. This provided an initial E. Coli concentration of $3.4 \cdot 10^6$ CFU/cm^3. Water treatment for 30 seconds reduced the concentration of microorganisms by two orders of magnitude (down to $5.4 \cdot 10^4$). After 1 minute of treatment, this indicator decreased to $1.7 \cdot 10^2$ CFU/cm^3, and after 3 minutes, the value of 5.2 CFU/cm^3 was recorded in the samples, that is, the treated water corresponded to the parameters of practically pure water [13].

To find out the influence of the degree of pollution on the nature of water disinfection, an increased amount of test culture was introduced into the technical water. This provided an initial cell concentration of $8 \cdot 10^7$ CFU/cm^3, which corresponds to the characteristic of «heavily polluted water» [14]. This led to a decrease in the speed of water disinfection. The results of the experiments are presented in the form of graphs (Figs. 3, 4) of the dependence of the change in the amount of CFU in the studied samples on the time of exposure to the electric discharge plasma.

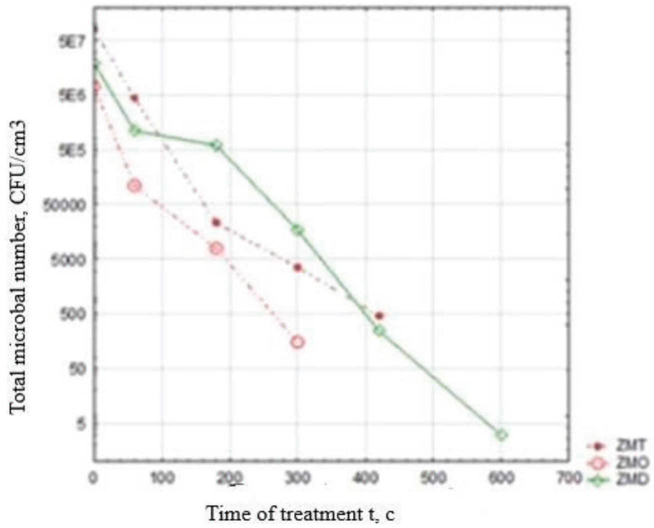

Fig. 3. Change in the total microbial number of CFU in the process of water treatment by electrical discharges

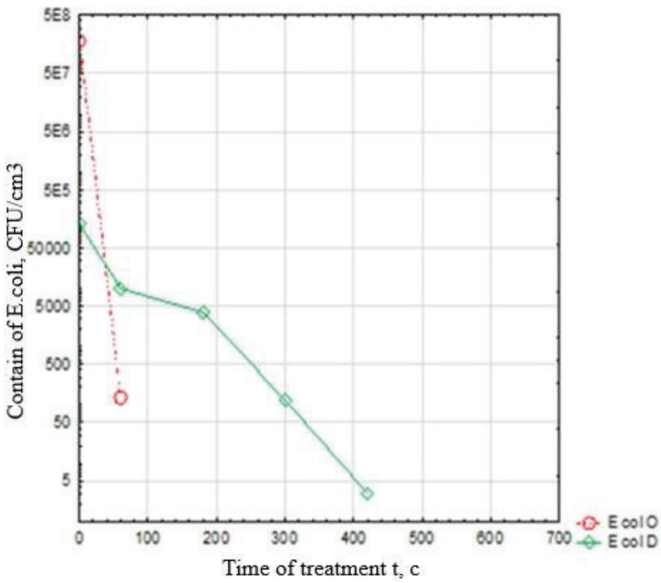

Fig. 4. Trends in changes in the CFU content of E.coli in the process of water treatment by electric discharges

Lake water samples were tested for total microbial numbers. Analyzes showed that the water sampled in the park zone far from the sources of pollution was quite clean according to microbiological indicators, the CFU in the samples was not many orders of magnitude higher than the requirements for drinking water – 100 CFU/cm^3 [13].

Experiments have established that 7–12 colonies of different species could be observed on one cup when sowing fresh river water. On Endo's medium, Escherichia coli ceases to germinate quite quickly; the growth of gram-negative, oxidase-positive microorganisms was observed, however, for a final conclusion about the belonging of these bacteria to the intestinal group additional studies must be conducted.

At the same time, water treated with plasma and stored for 7 days in the laboratory without sterile conditions showed a spike in insemination, including E. coli. Sowing of this water on MPA showed the value of $1.9 \cdot 10^5$, on Endo medium – $4.1 \cdot 10^5$ CFU/cm^3.

Conclusions. 1. A significant relationship between the time of plasma treatment and the amount of CFU was confirmed, regardless of the genesis of the sample, species and type of microorganisms.

2. The water treatment time is influences not only by the initial concentration of microorganisms, but also by the presence of an additional organic component. This can be explained by the fact that significant part of the synthesized oxidants is activated to oxidize the organic component.

3. Under the studied conditions, the use of high-energy water treatment proved its high water disinfection efficiency and, therefore, confirmed the hypothesis about the feasibility of using this method of water disinfection in mobile water purification plants in modern conditions.

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ДОСЛІДЖЕННЯ ПРОЦЕСІВ ЗНЕЗАРАЖЕННЯ ВОДИ ПРИ ЗАСТОСУВАННІ ІМПУЛЬСНОГО ЕЛЕКТРИЧНОГО РОЗРЯДУ

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Анотація. *Внаслідок військової агресії рф у південно-східному регіоні України відбулось руйнування водоводів і споруд централізованих систем водопостачання, а отже практично припинено водопостачання. Вирішенням проблеми може стати застосування мобільних станцій водопідготовки з використанням місцевих джерел водопостачання: каналів, озер, ставків або підземних вод. Особливістю технологій водопідготовки в польових умовах є необхідність надійного забезпечення процесу знезараження води. Існуючі технології знезараження води мають низьку ефективність, враховуючи зростаючу кількість хлоррезистентних мікроорганізмів, отже актуальним є впровадження альтернативних методів знезараження при водопідготовці. Одним із таких методів є знезараження рідини розрядом електричного струму. Описано результати досліджень знезараження води різних типів із поверхневих джерел м. Києва та води, зараженої кишковою паличкою (Escherichia coli (E. coli)). Дослідження здійснені на лабораторній установці з циркуляційним насосом і реактором ежекторного типу з інтегрованими електродами, де формується водоповітряна суміш, через яку проходить електричний розряд. Розряди ініціюють утворення різних високоактивних хімічних речовин, таких як радикали (OH•, H•, O•) та молекули (H_2O_2, H_2, O_2, O_3). Усі фізико-хімічні процеси, які відбуваються протягом розряду, забезпечують утворення та дію короткотермінових радикалів і порівняно довготривалих окислювачів. Вивчення впливу концентрації мікроорганізмів на швидкість і повноту знезараження води проводили на технічній (водопровідній) воді із внесенням до реакційної ємності змиву з двох пробірок тест-культури, що забезпечило початкову концентрацію E. coli 3,4 · 106 КУО/см^3. Обробка води протягом 30 секунд знизила кількість мікроорганізмів до 5,4 · 104 КУО/см^3. Через 1 хвилину обробки цей показник знизився до 1,7 · 102, а після закінчення 3 хвилин у пробах реєстрували 5,2 КУО/см^3, тобто оброблена вода мала показники практично чистої води. Досліди довели ефективність знезараження плазмовим методом для рідин із високою концентрацією мікроорганізмів.*

Ключові слова: *вода, водопостачання, знезараження, бактерії, плазма, електричний розряд*

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DETERMINATION OF HYDRAULIC GRAIN SIZE OF NATURAL AND ARTIFICIAL SORBENTS FOR SIMULATION OF SETTLE FACILITY

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Abstract. *In the conditions of progressive contamination of surface sources of water supply and inefficient wastewater treatment when using existing water treatment technologies, the research problem and the justification of the use of sorption materials for the retention of specific pollutants, in particular heavy metal ions and radionuclides, is urgent. The parameters that determine the efficiency of sorbents are indicators of their sedimentation rate. The purpose of the experiments was to determine the sedimentation rate indicators for bentonite and copper ferrocyanide, build sorbent sedimentation graphs, and establish the estimated sedimentation rate of sorbents in the sedimentation tank based on the studied data considering temperature regime. Deposition of the sorbent in settling tanks occurs with the non-stop movement of water at a low speed in the direction from the inlet to the outlet. The experiments are aimed at substantiating the efficiency and criteria of a universal facility, which is able to work equally effectively with sorbents in different aggregate states. The process of sorbent sedimentation in water is characterized by the kinetics of sorbent flakes conglomerates sedimentation. These processes are displayed in the form of deposition kinetics graphs. The experiment used powdered bentonite and a solution of copper ferrocyanide, consisting of yellow blood salt and copper sulphate in a given proportional ratio. In the course of the study the following parameters were determined: the hydraulic grain size of bentonite powdery clay, the dependence of the sedimentation rate on the temperature regime. The liquid layer was divided into layers that show changes in the amount of suspended substances depending on the depth, which made it possible to determine the dimensions of the settling tank, the height of the liquid overflow, which, in turn, made it possible to conduct simulation experiments on virtual machines with a full-scale clarifier-absorber in accordance to geometric parameters.*

Key words**:** *water treatment facilities, preliminary water treatment, bentonite, clarifier-absorber, hydraulic gain size, suspended particles, sorbent*

Actuality of problem. In the conditions of progressive contamination of surface sources of water supply and inefficient wastewater treatment by existing water treatment technologies, problems of the study on the use of various sorption materials for the retention of heavy metal ions and radionuclides with further development on the basis of these studies of the appropriate technological facilities where adsorption and sedimentation processes will take place are urgent.

The results of studies of the effectiveness of various sorbents are necessary for choosing the most effective of them; it is their hydrodynamic characteristics that will directly determine the design of the facility. In modern conditions, it has become possible to set the parameters of a technological facility with the help of computer Computational Fluid Dynamics modeling by Volume of Fluid technique – the modeling of the free flow of liquid by the free surface method. To reduce the model to the permissible 30–50 million elements, it is necessary to accurately determine the hydrodynamic characteristics of sorbent particles. Currently, there are no data on the hydrodynamic characteristics of the vast majority of sorbents in the reference literature. This especially applies to colloidal conglomerates formed during the introduction of liquid reagents, the combination of which causes the formation of solid phases of uncertain hydrodynamic properties. An example is one of the most effective sorbents, copper ferrocyanide ($Cu_2[Fe(CN_6)]$), which is formed from a mixture of two solutions: potassium ferrocyanide (yellow blood salt) ($K_4(Fe(CN)_6)$) and copper sulphate ($CuSO_4$) directly in purified water. The hydrodynamic characteristics of a promising combination of copper ferrocyanide with bentonite clay powder are also unknown. Exactly the hydrodynamic characteristics of the most promising sorbents were determined for the further development of the universal design of the clarifier-absorber, capable to work effectively both with liquid reagents and with solid fractions of sorbents, similar to powdered bentonites and zeolites.

Analysis of recent research and publications. In papers [1–7] the authors investigated the influence of various sorbents on technologies and water quality during the extraction of heavy metal ions. Technologies based on the use of biological factors are considered in works [8–12] and sorbents based on bentonite clays are considered in [13–16]. Researches [3; 4] show bentonites and zeolites as the most promising sorbents mainly due to their availability and technological convenience.

The aim of the research is to study hydrodynamic characteristics of promising sorption materials for their use in determining the parameters of facilities for effective retention of pollutants in natural and wastewaters.

Methodology of research. The experiments were aimed at studying the hydraulic characteristics of the most available domestic sorbents – powdered bentonite and copper ferrocyanide solution.

The process of sorbent sedimentation in water is characterized by the kinetics of sorbent flakes conglomerates sedimentation. These processes are displayed in the form of deposition kinetics graphs. During the experiment we used bentonite clay powder with fraction size of 0.1–0.072 mm and a solution of copper ferrocyanide ($(Cu_2[Fe(CN_6)])$) consisting of yellow blood salt ($(K_4(Fe(CN)_6))$) and copper sulphate ($CuSO_4$) in proportional ratio of 1.356 g of copper sulphate per 1 g of yellow blood salt. Mixing takes place in a measuring cup with the addition of no more than 50 ml of distilled water per 10 g of dry mixture. The solution of copper ferrocyanide is prepared exclusively before use, otherwise the effectiveness of the solution decreases with a delay.

Fig. 1. shows the laboratory model of a settling tank with the following geometric parameters: height – 700 mm, internal diameter – 176 mm, total volume – 17 dm^3, and working volume – 15 dm^3.

The experiment is carried out as follows: the sedimentation tank is filled with water up to the “working volume” mark with zero indicators of suspended particles and the absence of color, the working volume is 15 dm^3. The sorbent is being added in accordance with the proportion of 20 g/dm^3 to the tank and mixed until the sorbent is evenly distributed over the working volume. After the disturbances caused by mixing have stopped and the suspension has reached a state of rest, the sedimentation time is counted and data is collected according to the accepted time intervals: the amount of sediment at the bottom is measured using a ruler, cm; with the help of a pipette water is taken for the analysis on a photocolorimeter and a pH meter in the zones (Fig. 1) A, B, C, D; temperature measurements are carried out continuously in the working volume of the cylinder, °C. Water sampling was made taking into account the deviation from the classical method [17–18] to increase the reliability of the obtained results.

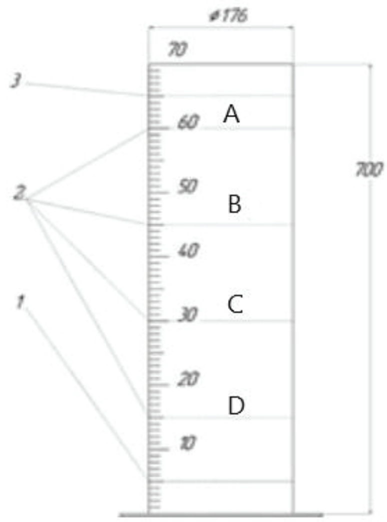

Fig. 1. The model of a vertical clarifier:
1 – the zone of accumulation of precipitated particles, 2 – the zone of collection of material (A, B, C, D) for the analysis with a photocolorimeter (turbidimeter); 3 – the height of the working volume of the settling tank.

The obtained data are summarized in a form of tables and graphs of the dependencies of hydraulic size (Fig. 2–4).

The following devices were used in the experiments: “Milwaukee Mi415” turbidity meter; Photocolorimeter “Hach DR2800”; Electronic thermometer with temperature sensor “NTC10K”; electronic scales with a resolution of 0.01 g; stopwatch.

According to the research results, a model of the sorbents deposition is built and the speed of their deposition is established (Fig. 2–4), Table 1 [18].

Calculation of hydraulic size [17; 18]:

$$U_0 = \frac{1000HK}{t_1\left(H\dfrac{K}{h_1}\right)^n}, \qquad (1)$$

where H is the depth of the working part of the settling tank, m; K is the coefficient of settling volume utilization; t_1 is the duration of settling in a laboratory cylinder at the layer height h_1, during which the required lighting effect is achieved; n is the coefficient of proportionality, which depends

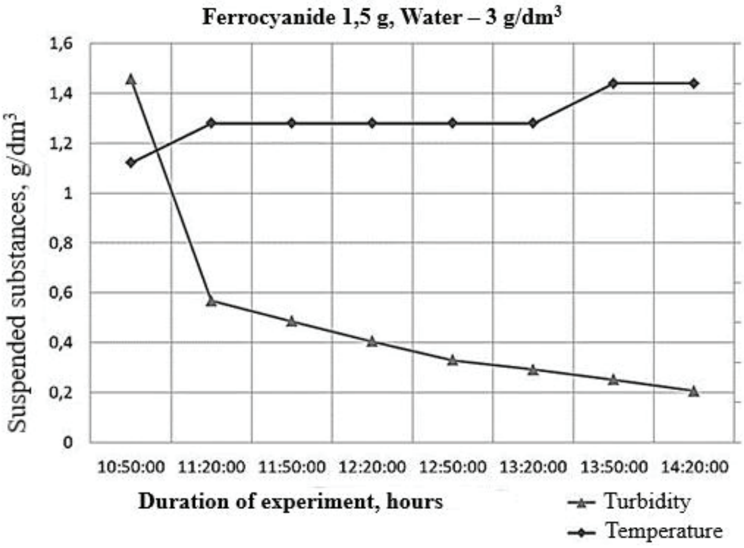

Fig. 2. Dependencies of the hydraulic grain size of the copper ferrocyanide solution for the duration of the experiment of 4 hours and the temperature of the suspensions of 7–9 ºC

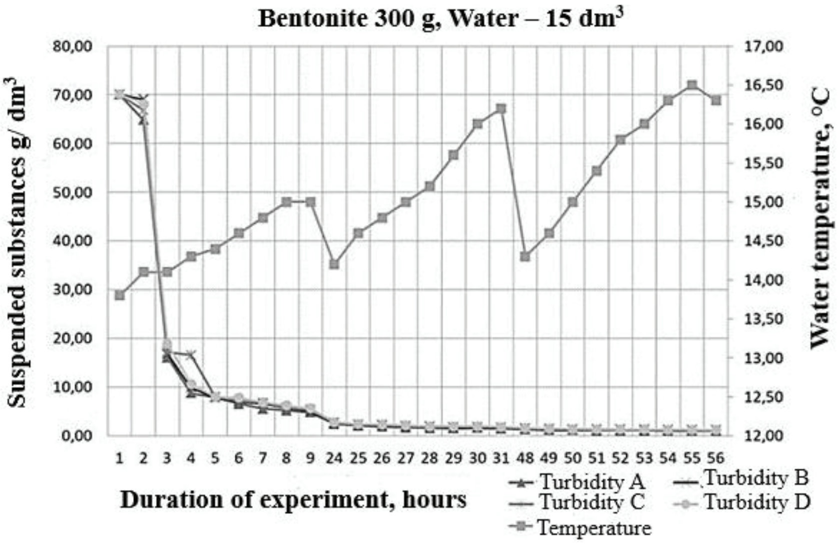

Fig. 3. Dependencies of hydraulic grain size of bentonite for the duration of the experiment of 56 hours and the temperature of suspensions of 14–16 ºC

on the agglomeration of suspended particles of substances in the process of sedimentation in different layers of water ($h_1 > h_2$) and is calculated using the formula:

$$n = \frac{lgt_1 - lgt_2}{lgh_1 - lgh_2}, \quad (2)$$

where h_1 and h_2 are the heights of settling layers, cm; t_1 and t_2 are the durations of settling in the corresponding layers, sec.

The efficiency of the sedimentation of the suspension is calculated as the difference between the values of the concentration of suspended substances in the water before and after the sedimentation:

$$P = \frac{\mu_{input} - \mu_i}{\mu_{input}} \cdot 100, \quad (3)$$

where μ_{input} is the content of suspended substances in the input water; μ_i is the content of suspended substances in settled water, g/dm^3, after the settling time [19].

Research results. During the study, the following parameters were determined: the hydraulic grain size of bentonite powdery clay and copper ferrocyanide, the dependency of the sedimentation rate on the temperature regime, and the full settling cycle.

Note. Turbidity A, Turbidity B, Turbidity C, Turbidity D are the turbidity samples taken at the

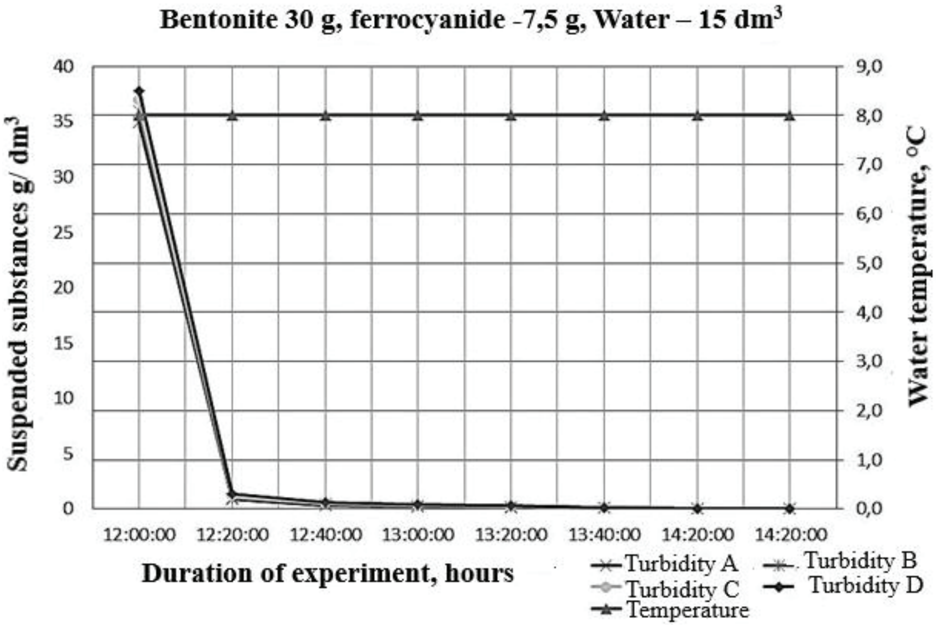

Fig. 4. Graphs of dependencies of the hydraulic grain size of bentonite and copper ferrocyanide mixture for the duration of the experiment of 2 hours and 20 minutes and the suspension temperature of 8 ºC

1. Calculated data of hydraulic grain size (mixtures of bentonite clay powder, zeolite and copper ferrocyanide)

№	Name	Settling time, t, hours	Hydraulic grain size, U_0, mm/sec.	Coefficient of proportionality, n	Concentrations of suspended substances, P, %
1	Copper ferrocyanide	6	1.44	0.54	87.9
2	Bentonite	56	0.11	1.39	98.26
3	Bentonite + copper ferrocyanide	2.20	6.185	0.29	99.8

same time from different depths of the settling tank. From the bottom of the sedimentation model, A = 60 cm, B = 45 cm, C = 30 cm, D = 15 cm (Fig. 1).

The best result of 99.8% precipitation of suspended particles and complete decolorization of purified water from copper ferrocyanide residues was recorded in an experiment with a mixture of bentonite powdery clay and copper ferrocyanide solution in the proportion of 2/0,5 g/dm^3 of dry matter.

Based on the obtained data empirical models were built to describe the change in water turbidity depending on the settling time.

The change in water turbidity over time during settling of the sorbent – copper ferrocyanide – is described by Equation (4)

$$CK = 0,287 + e^{(1,321 - 1,174 \cdot t)}, \qquad (4)$$

where CK is the turbidity concentration, mg/dm^3; t is the settling time, hours.

Multiple correlation of the model is $R = 0.987$; explained variance – 97; $p < 0.00001$

The change in water turbidity over time during settling of the sorbent – dusty bentonite – is described by Equation (5)

$$CK = 16,589 - 0,781 \cdot t + 14,506 \cdot \sqrt{t} - 19,007 \cdot ln(t) - 11,171 \cdot \left(\frac{1}{t}\right), \qquad (5)$$

where CK is the turbidity concentration, mg/dm^3; t is the settling time, hours.

Multiple correlation of the model is $R = 0.983$; coefficient of determination – $R^2 = 0.965$; adjusted determination – $R^2_{adj} = 0,953$; Fisher's $F(4.20) = 139.37$; $p < 0.00000$; standard estimated error – 0.71870.

The change in water turbidity over time during settling of a mixture of sorbents – copper ferrocyanide and dusty bentonite – is described by Equation (6)

$$CK = 0,20267 + e^{(7,377 - 3,799 \cdot t)}, \qquad (6)$$

where CK is the turbidity concentration, mg/dm^3; t is the settling time, hours.

Multiple correlation of the model – R = 0,999; explained variance – 99; p < 0,0001.

These equations in the further modeling of suspension sedimentation processes in the adsorber-settler make it possible to move away from "pseudo bitmaps" arrays of particles with billions of dimensions to "pseudo-vector" calculations already with tens of millions of "vector" particles and thus significantly reduce the requirements for computer performance, which makes it possible to move away from the use of computer clusters and conduct simulations on an individual workstation.

Conclusions. Physical modeling of the sorbent deposition process using a model of settling tank made it possible to determine the hydraulic grain size of the sorbents, which will be used in the future to justify technological and structural parameters of the combined adsorber-clarifier facility, which ensure effective extraction, first of all, of heavy metal ions and radionuclides from natural and sewage water.

The empirical equations of water/sorbent suspension sedimentation built on the basis of experiments will significantly reduce the requirements for computer capabilities.

Prospects for further research. On the basis of the received data, it is planned to carry out simulation experiments using the virtual machine "FlowVision simulation CFD (Computational Fluid Dynamics)", which works on the basis of the finite element method (FEM) and the finite volume method (FME). Experiments are carried out by modeling in a virtual environment using a software package for working with spatial models.

In the virtual experiment, a simplified model of the clarifier-absorber is used, since the clarifier-absorber with a vertical flow has an axisymmetric geometry, the three-dimensional flow modeling mode can be simplified to a two-dimensional model with the corresponding possibilities of saving resources and ease of working with the model.

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ВИЗНАЧЕННЯ ГІДРАВЛІЧНОЇ КРУПНОСТІ ПРИРОДНИХ І ШТУЧНИХ СОРБЕНТІВ ДЛЯ МОДЕЛЮВАННЯ КОНСТРУКЦІЙ ВІДСТІЙНИКА

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Анотація. *В умовах прогресуючого забруднення поверхневих джерел водопостачання та неефективного очищення стічних вод при використанні існуючих технологій водопідготовки актуальним є завдання дослідження та обґрунтування застосування для затримання специфічних забруднень, зокрема іонів важких металів та радіонуклідів, сорбційних матеріалів. Параметрами, що визначають ефективність сорбентів, є показники швидкості їх осаджування. Метою експериментів було визначення показників швидкості осадження для бентоніту та фероціаніду міді, побудова графіків осадження сорбентів та встановлення за досліджуваними даними розрахункової швидкості осадження сорбентів у відстійнику з урахуванням температурних даних. Осадження сорбенту у відстійниках відбувається при безупинному русі води з малою швидкістю в напрямку від входу до виходу. Досліди спрямовані на обґрунтування ефективності та критеріїв універсальної споруди, яка здатна однаково ефективно працювати з сорбентами у різних агрегатних станах. Процес седиментації сорбенту у воді характеризується кінетикою осадження конгломератів пластівців сорбенту. Дані процеси відображаються у вигляді графіків кінетики осадження. В досліді використовувався пудроподібний бентоніт та розчин фероціаніду міді, що складається з жовтої кров'яної солі та сульфату міді у заданому пропорційному співвідношенні. В ході дослідження було визначено наступні параметри: гідравлічна крупність бентонітової пудроподібної глини, залежність швидкості осадження від температурного режиму. Товщу рідини було розділено на шари, які показують перепади кількості завислих речовин в залежності від глибини, що дало змогу визначити розміри відстійника, висоту переливу рідини, що, в свою чергу, дає змогу проводити імітаційні досліди на віртуальних машинах з повномасштабним освітлювачем-адсорбером у відповідності до геометричних параметрів.*

Ключові слова: *водоочисні споруди, водопідготовка, бентоніт, адсорбер-відстійник, гідравлічна крупність, завислі частки, сорбент*

ЗМІСТ

CONTENTS

Наукове видання

Меліорація

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