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У журналі відображено результати теоретичних та експериментальних досліджень із пріоритетних напрямів: агроресурси, водні ресурси, зрошення, осушення, гідрологія, екологія, гідротехніка, агроінженерія тощо. Журнал буде корисним для науковців, фахівців водного та сільського господарства. Два видання журналу за рік публікують оригінальні наукові статті, а також огляди, пов’язані з профілем журналу.

Журнал включено до міжнародних та національних інформаційних і наукометричних баз, репозитаріїв і пошукових систем:

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Адреса редакції:
Інститут водних проблем і меліорації НААН України
вул. Васильківська, 37, Київ, 03022
Тел. +38(044) 257-40-30, +38 (067) 791 67 11
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THE PROBLEM OF IRRIGATION WATER SHORTAGE AS A SYSTEMIC FACTOR LIMITING THE SUSTAINABLE DEVELOPMENT OF IRRIGATED AGRICULTURE IN THE CONTEXT OF CLIMATE CHANGE

V.V. Karuna[1], Ph.D. student, A.P. Shatkovskyi[2], Doctor of Agricultural Sciences

[1] Institute of Water Problems and Land Reclamation of the National Academy of Agricultural Sciences, Kyiv, Ukraine; https://orcid.org/0009-0005-6162-5391; e-mail:karuna@ukr.net;
[2] Institute of Water Problems and Land Reclamation of the National Academy of Agricultural Sciences, Kyiv, Ukraine; https://orcid.org/0000-0002-4366-0397; e-mail:andriy-1804@ukr.net

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Abstract. *Freshwater scarcity is one of the key global challenges for sustainable agricultural development in the context of climate change. The increase in average annual air temperature, changes in precipitation patterns, and the increased frequency of extreme hydrometeorological phenomena lead to an increase in the evapotranspiration needs of agricultural crops and, at the same time, a decrease in the reliability of water supply for irrigation. According to estimates by international organizations, more than 40% of global agricultural production already operates under conditions of moderate or high water stress, and by the middle of the 21st century, this figure could rise to 60%. Ukraine is one of the countries with limited water resources and high regional unevenness in their distribution. The main areas of irrigated land are concentrated in the southern and southeastern regions, where climate change is most intense, creating a persistent water shortage for agricultural production. In the context of military operations, an additional risk factor is the disruption of water management infrastructure and the increase in operating costs for water supply.*

The purpose of this article is to provide a comprehensive analysis of the shortage of fresh water for irrigation on a global scale in general and in Ukraine in particular, taking into account climatic, hydrological, agrotechnological, and economic factors. The work uses methods of climate and water management analysis, economic and mathematical modeling, taking into account potential yield losses and the assessment of irrigation investment efficiency. Particular attention is paid to modern approaches to optimizing water use, in particular phytomonitoring and adaptive irrigation management methods presented in the works of Romashchenko M.I., Shatkovskyi A.P. and co-authors, FAO and IPCC data.

The results confirm that even with the introduction of highly efficient irrigation technologies, the structural deficit of water resources remains a decisive constraint on the development of irrigated agriculture. The need to transition to integrated water resource management models that take into account climate scenarios, economic risks, and institutional constraints is justified.

Keywords: *water scarcity, water supply, water resources, water stress, phytomonitoring, evapotranspiration, water demand assessment*

Relevance of the research. Ensuring food security amid global population growth and climate change is one of the priorities of modern agricultural science. According to UN projections, by 2050 the world population will exceed 9.7 billion people, which will require an increase in food production of at least 50% compared to current levels [1]. At the same time, water resources are becoming a key limiting factor in agricultural production, as agriculture consumes about 70% of global freshwater withdrawals [2, 3].

Irrigated agriculture plays a crucial role in stabilizing crop yields, especially in arid and semi-arid regions. However, the effectiveness of irrigation directly depends on the availability of water resources, which are under increasing pressure due to climate change, urbanization, and the degradation of aquatic ecosystems [4, 5]. According to estimates by Mekonnen and Hoekstra, over 4 billion people live in regions with seasonal or chronic water shortages, which directly or indirectly affect agricultural production [6].

Climate change affects not only the quantitative indicators of water resources but also their temporal and spatial availability. Rising air temperatures lead to an increase

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in potential evapotranspiration (ET_0), which increases the water demand of crops even with unchanged precipitation levels [7]. At the same time, the frequency and duration of droughts are increasing, complicating water supply forecasting and raising risks for the agricultural sector [8, 9].

For Ukraine, the problem of water scarcity for irrigation is particularly acute. The average local river flow per capita is among the lowest in Europe, at approximately 1,000–1,200 m³/year, which is below the water security threshold [10]. According to the UN classification, a country is considered water-scarce if less than 1.7 thousand m³/year of water is available per person [1]. Thus, by international standards, Ukraine is in a state of "water scarcity."

1. Comparison of the average local river flow per capita in European countries

European country	Average local river flow per capita, thousand m³/year
Ukraine	1.1
Poland	1.6
France	3.3
Germany	1.8
Sweden	17
Norway	78

Table 1 presents the average volume of local river runoff per capita in European countries. The average value of this indicator across all European countries is approximately 4,600 m³/year per person [2].

In Ukraine, over 60% of irrigated land is concentrated in the southern regions, where climatic trends toward aridification are most pronounced and the level of local water resource availability is the lowest (Fig. 1) [10, 11].

An additional aspect of the water supply issue is the outdated infrastructure of irrigation systems, significant water losses during transportation, and insufficient implementation of water-saving technologies [11]. Even if the technical aspects of irrigation are modernized without considering the actual water availability in the basins, a "false sense of water security" may develop, leading to economically unjustified investments [12].

Thus, the relevance of this study stems from the need for a comprehensive assessment of the freshwater deficit for irrigation, taking into account climatic, hydrological, agrotechnological, and economic factors, as well as the development of scientifically sound approaches to water resource management in Ukraine's agricultural sector.

Analysis of recent studies and publications. The problem of water scarcity for agriculture is widely covered in the works of international organizations and leading research centers. Reports by the FAO and IPCC emphasize that climate change is a key driver of increasing water stress in the agricultural sector, particularly in regions highly dependent on irrigation [2, 3, 8, 13]. Research by Vörösmarty and co-authors demonstrates that anthropogenic pressure on river basins has reached critical levels, threatening both water security and biodiversity [14].

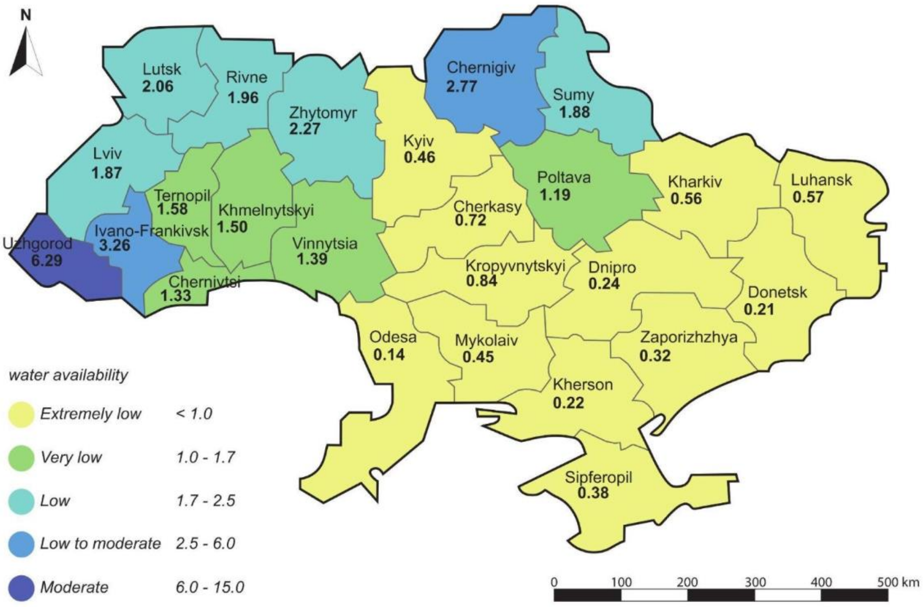

Fig. 1. Availability of local water resources in regions of Ukraine, thousand m³/year per person [10]

Mekonnen and Hoekstra made a significant contribution to the quantitative assessment of global water scarcity by developing the concept of the “water footprint” and determining the extent of seasonal water scarcity for various regions of the world [6]. In their work, Claudia H. and Petra D. proposed integrated hydrological models for assessing water stress, taking climate scenarios into account [15].

In the field of irrigation, significant attention has been paid to improving water use efficiency. Fereres and Soriano substantiated the concept of deficit irrigation as a tool for optimizing water use while maintaining an acceptable level of and yield [16]. Pereira and co-authors emphasize the need to transition from rigid irrigation schedules to adaptive management using plant condition monitoring [17].

In Ukraine, scientific research on irrigation and water supply issues is actively developing within the scientific school of the Institute of Water Problems and Land Reclamation of the National Academy of Agrarian Sciences. In the works of Romashchenko M.I. and co-authors, the impact of climate change on water resources is analyzed, and the need to modernize land reclamation systems is substantiated [10]. Kulbida M.I. and other researchers have demonstrated trends toward rising temperatures and decreasing effective precipitation in the southern regions of Ukraine [7, 19].

In the studies by Shatkovsky A.P. and Zhuravlov O.V., modern phytomonitoring methods for irrigation management based on the physiological state of plants were developed and tested [20, 21, 22]. These studies demonstrate that the use of phytomonitoring allows for the optimization of irrigation regimes, a reduction in evapotranspiration, and an increase in yield stability, which is critically important under conditions of water scarcity.

At the same time, a review of the literature indicates that most studies focus either on climatic aspects or on irrigation technologies, while integrated economic-mathematical assessments of water scarcity for irrigation in Ukraine remain underdeveloped. This necessitates comprehensive research aimed at combining climatic, hydrological, agrotechnological, and economic approaches.

Research objective. The purpose of this study is to conduct a scientifically grounded analysis of the freshwater deficit for irrigation under conditions of climate change, taking into account global trends and regional characteristics of Ukraine, as well as to assess the economic, agrotechnological, and institutional consequences of limited water supply for the development of irrigated agriculture.

To achieve this objective, the study addresses the following tasks:

- analyze current global trends in the formation of water resource shortages for irrigation in the context of climate change;
- assess the impact of climatic factors on changes in the water requirements of agricultural crops;
- to investigate water stress indicators and their application for assessing water scarcity;
- identify the characteristics of freshwater shortages for irrigation in Ukraine, taking into account regional specifics;
- analyze the role of modern irrigation and phytomonitoring technologies in reducing water losses;
- conduct an economic and mathematical assessment of yield losses and the investment efficiency of irrigation under conditions of water scarcity.

The implementation of these tasks allows for the formation of an integrated view of the problem of water scarcity for irrigation and the identification of scientifically sound approaches to its minimization in Ukraine’s agricultural sector.

Materials and research methods. The methodological basis of the study is a systematic approach to analyzing the interrelationships between climate change, water resources, irrigation technologies, and the economic efficiency of agricultural production. The study employs a combination of climatic, hydrological, agronomic, and economic-mathematical research methods.

The study utilized the following information sources:

- global climate and hydrological data from the FAO, IPCC, World Resources Institute, and European Environment Agency [2, 3, 6, 8, 13, 14, 23, 24];
- results of scientific studies on the optimization of irrigation regimes and the application of phytomonitoring [20, 21, 22];
- materials from field and production experiments published in specialized scientific journals [10, 18, 19, 25].

There are several scientifically validated methods for estimating crop water requirements through the calculation of evapotranspiration: the Penman-Monteith method, the methods developed by A.M. and S.M. Alpatyevs, D.A. Shtoyka, M.M. Ivanov, and others. However, since research results have shown that the Penman-Montaut method provides the smallest error (MAE = 9.1%) in determining ET_c and ensures high forecasting accuracy, in this study, plant evapotranspiration is estimated specifically based on this method using the reference

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evapotranspiration index ET_0 [7, 25]. The actual crop evapotranspiration (ET_c) is determined by the formula:

$$ET_c = ET_0 \times K_c,$$

where K_c is the crop coefficient, which accounts for biological characteristics and the stage of plant development.

To analyze the impact of climate change, a scenario-based approach was used, in which ET_0 was adjusted to account for the projected increase in air temperature and changes in the radiation balance [8, 13].

To quantitatively assess the water deficit for irrigation, the Water Stress Index (WSI) is used, which indicates the proportion of withdrawn water resources relative to the total available renewable resources for each region or basin, or its interpretation – the agricultural water stress index, which assesses the pressure on water resources during crop cultivation:

$$WSI_{agr} = \frac{ET_{c,tot}}{W_{irr}^{eff}}$$

where $ET_{c,tot}$ – total water requirement of crops on irrigated areas;

$_{irr}^{eff}$ – effectively available water resources for irrigation, accounting for losses during water transport and delivery.

A WSI value >40% is considered a high level of water stress, 50% is very high, and 80% is critical. In turn, a WSI_{agr} value > 1 is interpreted as the presence of a structural water deficit for irrigation [2, 3, 23].

To assess the economic consequences of water scarcity, the calculation of losses in gross agricultural output is also used:

$$L = \sum_{i=1}^{n} \left(Y_{\max,i} - Y_i \right) * P_i * A_i,$$

where $Y_{\max,i}$ – potential crop yield under optimal water supply;

Y_i – actual yield under water-deficient conditions;

P_i – product sales price;

A_i – planted area [9, 26].

The investment efficiency of irrigation projects is assessed using the net present value (NPV) indicator:

$$NPV = \sum_{i=1}^{T} \frac{B_i - C_i - B_{water,i}}{\left(1+r\right)^i},$$

where B_i – revenue from crop sales;

C_i – total operating and capital costs excluding the cost of water;

$C_{water,i}$ – costs associated with water use [11];

r – discount rate.

Research results and their discussion. The shortage of fresh water for irrigation is one of the most threatening manifestations of the global water crisis. According to FAO data, the area of irrigated land worldwide exceeds 330 million hectares, providing over 40% of global food production while utilizing the majority of available fresh water resources [2, 3].

Climate change is significantly altering the balance of water resources. Rising air temperatures contribute to increased evaporation from soil surfaces and water bodies, as well as plant transpiration, leading to higher water demand by crops [7, 8]. At the same time, annual precipitation variability is increasing, complicating water supply forecasting and irrigation planning [9, 17].

According to IPCC estimates, in regions with Mediterranean and steppe climates, surface water availability is expected to decrease by 10–30% by the middle of the 21st century, which directly threatens the sustainability of irrigated agriculture [8, 13]. Similar trends are observed in the countries of the Black Sea region, including Ukraine [10, 18, 24].

A key feature of the current phase is the combination of climatic and anthropogenic factors contributing to water scarcity. Increased water abstraction for industrial and energy needs, the degradation of aquatic ecosystems, and surface water pollution are limiting the availability of water for irrigation even in regions with relatively abundant resources [14].

Thus, the global shortage of freshwater for irrigation is systemic in nature and requires a shift from traditional approaches to water resource management toward integrated models that combine climate forecasts, technological innovations, and economic regulatory mechanisms.

Climate factors are decisive in shaping the current shortage of freshwater for irrigation, both on a global scale and at the regional level. Rising average annual air temperatures lead to a systematic increase in evapotranspiration (particularly losses due to physical evaporation of moisture), which directly increases the water demand of agricultural crops [7, 8, 13]. According to IPCC estimates, a temperature increase of 1 °C causes a rise in reference evapotranspiration by an average of 5–7%, depending on regional climatic conditions [13].

In Ukraine, climate change manifests itself unevenly. The most intense trends toward rising temperatures and decreasing effective precipitation have been recorded in the southern and southeastern regions, which are also the main areas of irrigated agriculture [18, 19]. According to long-term observations, the average annual air temperature in the steppe zone of Ukraine has risen by 1.3–1.6 °C over the past 30 years, and the number of days with temperatures above 30 °C has nearly doubled [10, 16].

Changes in precipitation patterns are manifested not so much in a decrease in their annual total as in a shift in seasonal distribution. The proportion of intense rainfall events, which are less effective for soil moisture replenishment, is increasing, while precipitation during the growing season is decreasing [9, 17]. This increases the dependence of agricultural production on irrigation even in years with precipitation totals close to the climatic norm.

Thus, climatic factors contribute not only to a quantitative but also to a qualitative deficit of water for irrigation, which complicates the planning of irrigation regimes and increases the risks of yield instability. To quantitatively assess water deficits, scientific studies widely use water stress indices, which reflect the ratio between water demands and available resources [6, 15, 23].

As noted above, one of the most informative indicators of water availability is the water stress index, the dynamics of which for 2000–2022 are shown in Figure 2 for the world and in Figure 3 for European countries [27].

As previously noted, the modified WSI_{agr} index is used to assess the water deficit for irrigation, and a WSI_{agr} value > 1 indicates a structural water deficit, under which even the full utilization of available water does not meet the needs of agricultural crops [23]. On a global scale, such conditions are characteristic of a significant part of Southern Europe, the Middle East, Central Asia, and North Africa [4, 14].

For Ukraine, water stress index calculations show that in years with moderate to high aridity, the WSI_{agr}value in southern regions exceeds 1.2–1.4, indicating a chronic water deficit for irrigation [11]. At the same time, even the modernization of irrigation systems does not fundamentally alter the water balance but merely reduces losses during water transportation and distribution.

The analysis conducted showed that the technical condition of Ukraine's land reclamation infrastructure plays a significant role in shaping the current level of water deficit. A significant portion of irrigation systems was commissioned in the second half of the 20th century and currently requires modernization.

This allows us to conclude that the current stage of land reclamation development in Ukraine is characterized by a transition from a climate-driven water deficit to a combination of climatic and infrastructural constraints on water use.

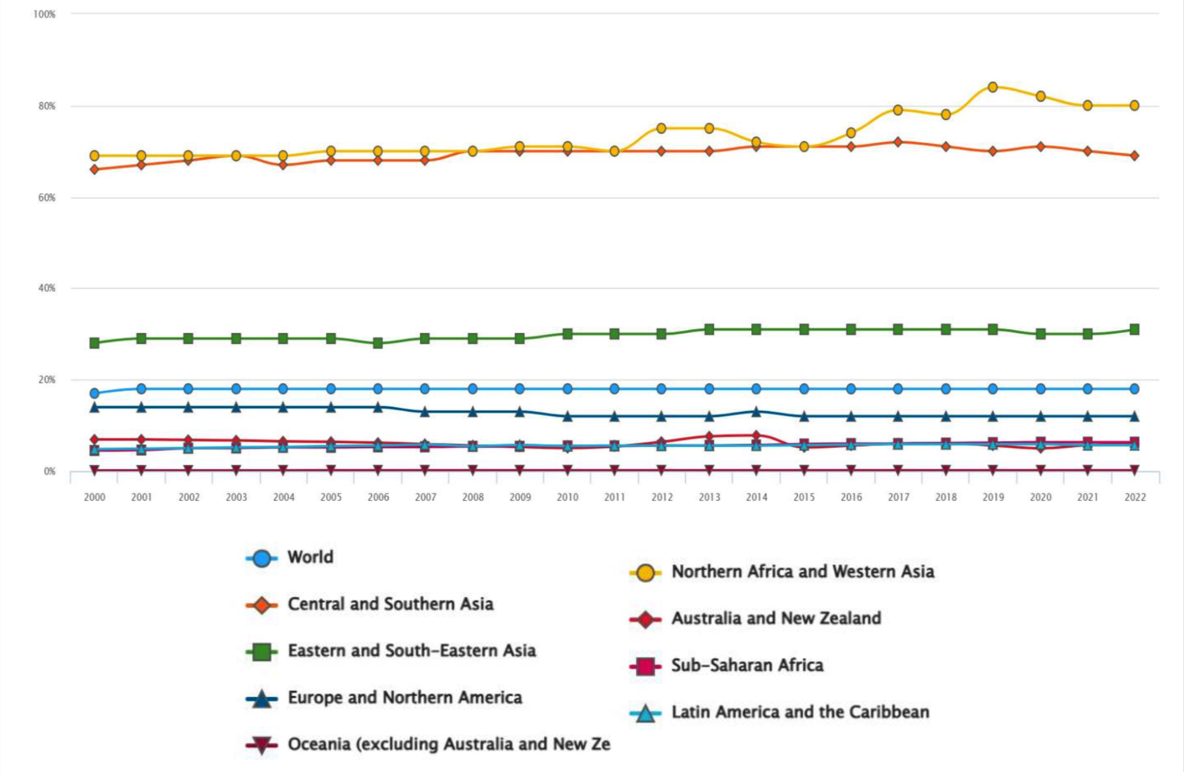

Fig. 2. Dynamics of the Water Stress Index (WSI) worldwide, 2000–2022

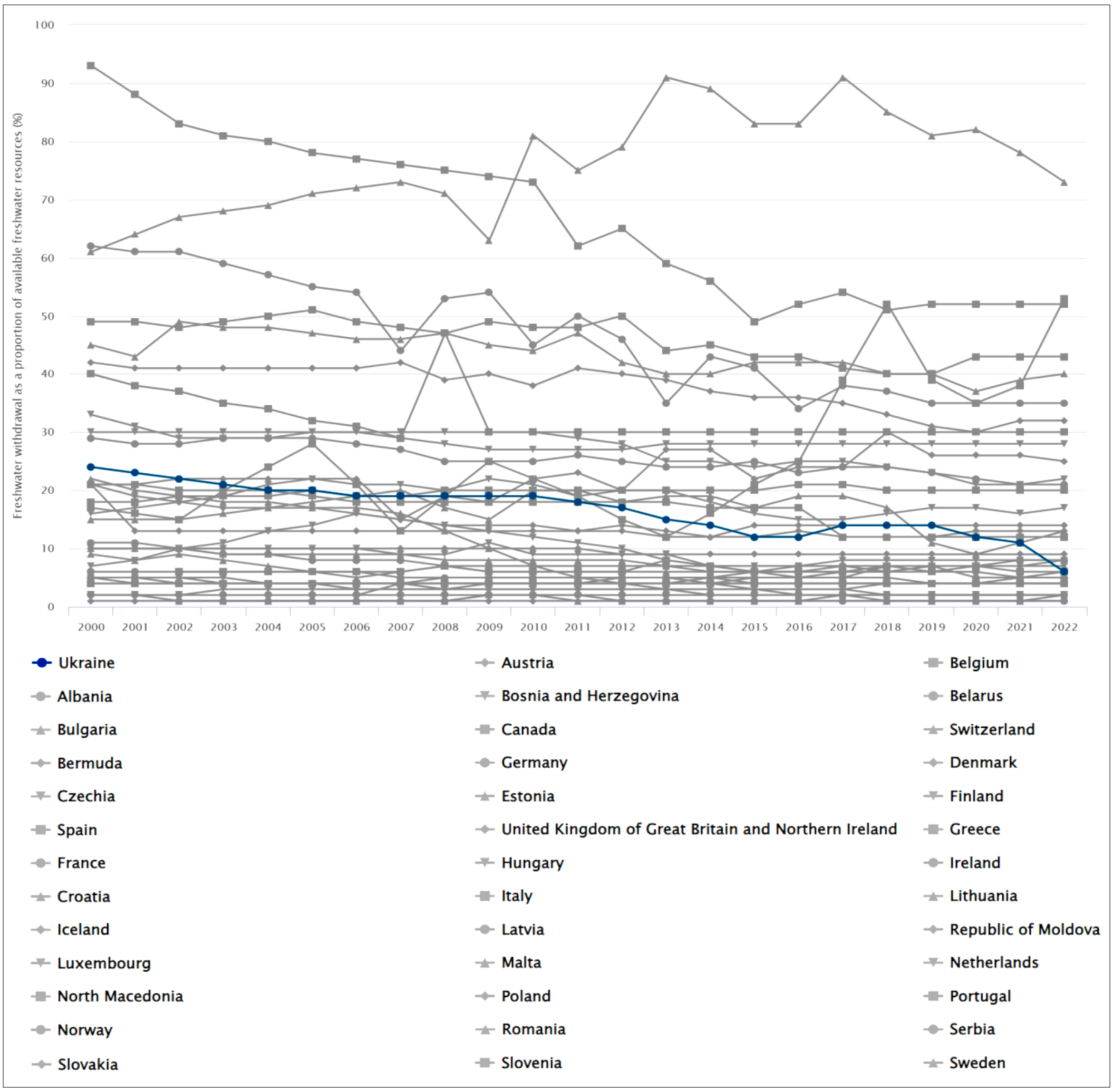

Fig. 3. Dynamics of the Water Stress Index (WSI) in European countries, 2000–2022

The results obtained confirm the tenets of the modern concept of integrated water resources management, according to which improving water use efficiency should be carried out not only at the level of individual farms but also at the level of river basins.

An additional indicator for assessing the level of water supply is the water use efficiency (*WUE*) coefficient, which determines the ratio between crop yield and the volume of water consumed and effectively shows how much produce is obtained per unit of water consumed [7].

$$WUE_y = \frac{Y}{ET_c},$$

where Y – crop yield;

ET_c – crop evapotranspiration during the growing season.

Increasing the WUE index is an important strategy for adapting to water scarcity, but its potential is limited by the biological characteristics of crops and climatic conditions [16, 17].

Ukraine is characterized by one of the lowest levels of local water resource availability in Europe. The average long-term local runoff is approximately 52 $^{\text{km}^3}$, while a significant portion of water consumption is supplied by transit runoff, primarily from the Dnipro River. This structure of water resources increases the agricultural sector's vulnerability to hydrological and climatic changes. In addition, the regional distribution of water resources is extremely uneven: over 60% of local runoff is generated in the northern and western regions, while the main areas of irrigated land are concentrated in the southern regions (Odesa, Mykolaiv, Kherson, and Zaporizhzhia) [10, 11]. This necessitates the inter-basin redistribution of water, which is accompanied by significant losses and energy costs.

Climate change is exacerbating existing imbalances. According to research by Ukrainian scientists, total water demand for major crops in the southern regions is projected to increase by 10–20% by the middle of the 21st century [18, 19]. At the same time, a decrease in guaranteed water supply during the growing season is expected, which increases the risk of crop yield shortfalls even in the presence of irrigation infrastructure. A particular factor at this stage is the impact of military operations, which have led to the disruption or complete cessation of irrigation systems, restricted access to water resources, and increased costs for infrastructure restoration [28, 29]. This further complicates the implementation of investment projects in the field of irrigation and increases the importance of scientifically sound approaches to managing water scarcity.

Modern irrigation technologies play a crucial role in improving the efficiency of water resource use. The transition from sprinkler to drip and subsurface irrigation allows for a reduction in unproductive water losses and an increase in irrigation efficiency [16].

The results obtained are consistent with the findings of recent studies in the field of water resources management, which confirm the high efficiency of localized irrigation methods under conditions of limited water supply.

At the same time, irrigation management methods based on phytomonitoring attract particular attention. In the works of Shatkovskyi A.P. and Zhuravlov O.V., it has been proven that the use of indicators of the physiological state of plants (leaf water potential, canopy temperature, stress indices) allows for the adaptation and optimization of irrigation regimes to the actual needs of agricultural crops [20, 21, 22]. This ensures a reduction in ET_c by 10–25% without reducing yield, which is critically important under conditions of water scarcity.

At the same time, it has been established that even the use of modern irrigation technologies does not fully compensate for water resource deficits in regions with critically high levels of water stress [26].

This indicates the need for a comprehensive approach to water resources management, which involves a combination of technological, organizational, and basin-level measures to regulate water use.

According to Table 2, the total economic losses in Ukraine’s steppe zone alone are estimated at more than $300 million per year.

The economic consequences of freshwater shortages for irrigation are manifested primarily in reduced crop yields, production instability, and increased risks for the agricultural sector. To quantitatively assess these consequences, this study employs an economic-mathematical approach that combines agronomic parameters with economic indicators [9, 26].

The relationship between water scarcity and reduced crop yields is described by the crop’s sensitivity coefficient to water stress, K_y:

$$1-\frac{Y}{Y_{\max}}=K_y*\left(1-\frac{ET_c}{ET_{c,\max}}\right),$$

where Y is the actual yield;

$Y_{\max}$ – potential yield under optimal water supply;

ET_c – actual crop evapotranspiration;

$ET_{c,\max}$ – maximum (potential) evapotranspiration corresponding to the value of ETc in the absence of water deficit [7, 16].

2. Assessment of total economic losses in the steppe zone of Ukraine due to a shortage of water for irrigation (excluding military factors)

Region	Estimated share of irrigation loss, %	Estimated yield losses, %	Estimated economic losses, $ million/year
Kherson	85–95	50–90	120–160
Zaporizhzhia	60–75	40–70	55–80
Mykolaiv	45–60	35–55	40–65
Odesa	30–45	25–45	30–50
Dnipropetrovsk (south)	25–35	20–40	15–30
Donetsk	20–30	20–35	10–25
Kharkiv (southeast)	10–20	10–25	8–15
Kirovograd	5–15	10–20	5–10
Poltava	5–10	8–15	3–7

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For agricultural crops with high K_y values (vegetables, corn, soybeans), even a slight water deficit leads to disproportionately large yield losses, as confirmed by experimental studies conducted in Ukraine [20, 21].

The results obtained indicate the need for a differentiated approach to planning irrigation regimes depending on the biological characteristics of crops and the region's water availability.

Similar results have been obtained in studies by international FAO researchers, confirming the universality of the established patterns of crop productivity formation under water-deficient conditions.

Calculations indicate that an irrigation water deficit of 15–20% can result in gross yield losses of 20–35%, depending on the crop mix and climatic conditions of the year. Under conditions of chronic water scarcity, costs associated with water use increase, which can lead to negative net present value (NPV) values even for technically efficient irrigation systems [11, 26]. This confirms that the economic efficiency of irrigation directly depends on the actual water availability in the basin.

A comparison of the obtained results with international assessments of the economic efficiency of irrigation indicates that the modernization of water distribution systems is one of the most economically viable approaches to adapting the agricultural sector to climate change.

The problem of water scarcity for irrigation in Ukraine is not only of a natural and climatic nature but also has a pronounced institutional character. The water resources management system has historically been oriented toward large-scale inter-basin water redistribution, which is accompanied by significant losses and high energy costs [11, 15].

The implementation of the river basin management approach to water resources, as provided for by European water legislation, is still in its early stages and does not yet fully integrate the interests of the agricultural sector [12, 27]. Insufficient economic incentives for water conservation and the lack of differentiated water tariffs for irrigation reduce the motivation to adopt water-saving technologies.

An additional factor is the significant deterioration of irrigation system infrastructure. According to expert estimates, water losses during transportation in some regions exceed 30%, which significantly reduces efficiency even when sufficient water resources are available [11, 28].

Summarizing the results of the conducted studies, it can be concluded that ensuring the sustainable development of irrigated agriculture in Ukraine requires the implementation of a comprehensive water resources management system, which must take into account climate change, the technical condition of land reclamation infrastructure, regional characteristics of the water balance, and economic aspects of water use.

The results obtained expand current understanding of the mechanisms underlying water resource shortages in Ukraine's irrigated agriculture and can serve as a scientific basis for developing strategies to adapt the agricultural sector to climate change.

Conclusions:

1. It has been confirmed that the shortage of water for irrigation is a systemic problem of global scale, exacerbated by climate changes. Consequently, rising air temperatures and changes in precipitation patterns lead to increased water demand by agricultural crops. The increase in the average annual air temperature by 1.3–1.6 °C over the past decades is accompanied by a 6–12% rise in potential evapotranspiration, which directly correlates with an 8–15% increase in the water demand of agricultural crops. At the same time, in the steppe zone of Ukraine, a 10–22% decrease in effective precipitation during the growing season has been observed, leading to an 18–30% increase in soil moisture deficit**.** As a result, the total demand for irrigation water has increased by an average of 15–25%.
2. In Ukraine, water scarcity has distinct regional characteristics and is exacerbated by institutional and infrastructural constraints.
3. Calculations of the water stress index WSI_{agr}, whose values for the southern regions of Ukraine exceed 1.2–1.4, confirm an acute water deficit.
4. It has been determined that highly efficient irrigation technologies are unable to fully compensate for the structural deficit of water resources.
5. It has been demonstrated that phytomonitoring is one of the most effective tools for optimizing irrigation regimes.
6. It has been determined that economic losses from water shortages can reach 30% or more of the potential gross income from product sales.
7. It has been established that the economic feasibility of irrigation critically depends on actual water availability and the stability of the water supply.

Future research will focus on developing regional integrated models for managing water shortages for irrigation purposes, improving economic incentives for water conservation, and expanding the use of digital technologies and phytomonitoring in irrigation systems.

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Use of artificial intelligence: the authors confirm that they did not use artificial intelligence technologies during the creation of this work.

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ПРОБЛЕМА ДЕФІЦИТУ ВОДИ ДЛЯ ЗРОШЕННЯ ЯК СИСТЕМНИЙ ЧИННИК ОБМЕЖЕННЯ СТАЛОГО РОЗВИТКУ ЗРОШУВАНОГО ЗЕМЛЕРОБСТВА В УМОВАХ ЗМІНИ КЛІМАТУ

В.В. Каруна[1], аспірант, А.П. Шатковський[2], докт. с.-г. наук

[1] Інститут водних проблем і меліорації НААН, Київ, Україна;
https://orcid.org/0009-0005-6162-5391 ; e-mail: karuna@ukr.net
[2] Інститут водних проблем і меліорації НААН, Київ, Україна;
https://orcid.org/0000-0002-4366-0397 ; e-mail: andriy-1804@ukr.net

Анотація. *Дефіцит прісної води є одним із ключових глобальних викликів сталого розвитку сільського господарства в умовах кліматичних змін. Зростання середньорічної температури повітря, зміна режимів атмосферних опадів та збільшення частоти екстремальних гідрометеорологічних явищ зумовлюють підвищення евапотранспіраційних потреб сільськогосподарських культур і водночас зниження надійності водозабезпечення для зрошення. За оцінками міжнародних організацій, понад 40% світового аграрного виробництва вже сьогодні функціонує в умовах середнього або високого водного стресу, а до середини XXI століття цей показник може зрости до 60%. Україна належить до країн з обмеженими власними водними ресурсами та високою регіональною нерівномірністю їх розподілу. Основні площі зрошуваних земель зосереджені в південних і південно-східних регіонах, де кліматичні зміни проявляються найінтенсивніше, що формує стійкий дефіцит води для аграрного виробництва. В умовах воєнних дій додатковим чинником ризику є порушення функціонування водогосподарської інфраструктури та зростання експлуатаційних витрат на подачу води.*

Метою даної статті є комплексний аналіз дефіциту прісної води для зрошення в глобальному вимірі загалом та в Україні безпосередньо з урахуванням кліматичних, гідрологічних, агротехнологічних і економічних чинників. У роботі застосовано методи кліматичного та водогосподарського *аналізу, економіко-математичне моделювання з урахуванням потенційних втрат урожайності і врахування оцінки інвестиційної ефективності зрошення. Особливу увагу приділено сучасним підходам до оптимізації водокористування, зокрема методам фітомоніторингу та адаптивного управління зрошенням, представленим у працях Ромащенка М.І., Шатковського А.П. та співавторів, даних FAO і IPCC.*

Отримані результати підтверджують, що навіть за впровадження високоефективних технологій поливу структурний дефіцит водних ресурсів залишається визначальним обмеженням розвитку зрошуваного землеробства. Обґрунтовано необхідність переходу до інтегрованих моделей управління водними ресурсами з урахуванням кліматичних сценаріїв, економічних ризиків та інституційних обмежень.

Ключові слова: *дефіцит води, водозабезпечення, водні ресурси, водний стрес, фітомоніторинг, евапотранспірація, оцінка водопотреби*

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CURRENT STATE AND DIRECTIONS OF THE USAGE OF REMOTE TOOLS FOR INVENTORY AUDITING OF IRRIGATION SYSTEMS

M.I. Romashchenko[1], Doctor in Technical Science, S.V. Usatyi[2], Ph.D. in Technical Science, V.V. Polishchuk[3], Ph.D. in Agricultural Science, L.G. Usata[4], S.S. Kolomiets[5], Ph.D. in Agricultural Science, I.O. Kovalenko[6], Ph.D., A.S. Sardak[7], Ph.D.

[1] Institute of Water Problems and Land Reclamation of NAAS, Kyiv, Ukraine;
https://orcid.org/0000-0002-9997-1346; e-mail: mi.romashchenko@gmail.com
[2] Institute of Water Problems and Land Reclamation of NAAS, Kyiv, Ukraine;
https://orcid.org/0000-0001-8784-4078; e-mail: s_usatiy@ukr.net;
[3] Institute of Water Problems and Land Reclamation of NAAS, Kyiv, Ukraine;
https://orcid.org/0000-0003-0429-7406; e-mail: vitaliypolishchuk@ukr.net;
[4] Institute of Water Problems and Land Reclamation of NAAS, Kyiv, Ukraine;
https://orcid.org/0000-0002-3265-9024; e-mail: usataya_l@ukr.net;
[5] Institute of Water Problems and Land Reclamation of NAAS, Kyiv, Ukraine;
https://orcid.org/0000-0002-4329-4382; e-mail: kss2006@ukr.net;
[6] Institute of Water Problems and Land Reclamation of NAAS, Kyiv, Ukraine;
https://orcid.org/0000-0003-1548-3992; e-mail: igorok333@ukr.net;
[7] Institute of Water Problems and Land Reclamation of NAAS, Kyiv, Ukraine;
https://orcid.org/0000-0002-0540-9492; e-mail: anastasiabilobrova1993@gmail.com

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Abstract. *The paper examines modern approaches to conducting an inventory audit of irrigation systems using remote tools. The traditional methods of irrigation systems inventory audit require significant financial and labor costs, which complicates large-scale audit and planning of measures for the reconstruction and modernization of irrigation systems. According to the results of the research, it was found that remote technologies are the most appropriate for inventorying such basic elements of irrigation systems as pumping stations, antechambers, open earth and concrete canals, pipelines, hydrants, water distribution facilities, and other components of engineering infrastructure. Based on the analysis, a list of remote tools that can be used to assess the technical condition of irrigation facilities was determined. It includes satellite remote sensing of the Earth, namely the use of optical, multispectral, and hyperspectral images, aerial photography using unmanned aerial vehicles, geophysical research methods, in particular ground penetrating radar (GPR) and electromagnetic methods for tracing underground communications, as well as geographic information systems for integrating, analyzing, modeling, and visualizing the obtained results.*

Our research has shown that a comprehensive approach that combines modern remote sensing, geophysical, and geoinformation methods creates additional opportunities for conducting an effective inventory audit of irrigation systems in Ukraine, increases the efficiency of surveys, the accuracy of determining the technical condition of facilities, and the objectivity of the obtained results. The results of the performed analytical studies can be used to justify the choice of tools and develop recommendations for conducting an inventory audit of irrigation systems by remote means.

Key words: *inventory audit, irrigation systems, remote sensing, GIS, UAV, satellite data*

Relevance of research. The explosion of the Kakhovka reservoir dam by russian troops for a long time left 94 percent of irrigation systems in the Kherson region, 74 percent in the Zaporizhia region, and 30 percent in the Dnipropetrovsk region without an irrigation water source, and reduced the actual irrigated area to only 136,000 ha [1], which is less than 0.6% of the total area of arable land in the regions controlled by Ukraine.

It is clear that with such areas of actual irrigation, irrigated lands has ceased to serve as an insurance fund against the negative impact of weather conditions on crop production volumes. At the same time, climate changes and the loss of more than 18% of the territory, including more than 6.0 million ha of arable land and almost 75.0% of irrigated area and the lands of actual irrigation, necessitate an accelerated increase in irrigation areas, as provided for in the “Strategy for the Restoration of Irrigation and Drainage in Ukraine by 2030” [2] and the “Long-term Plan for the Restoration of the Irrigation Complex of Ukraine for the Period until 2050” [1]. It is the significant increase in the area of irrigation and water regulation using drainage systems, of which, according to the official statistics, 3,3 million ha have been recorded in Ukraine today, that can become an effective mean not only for compensating the losses due to the temporary occupation of significant arable areas, including irrigated lands, but also in increasing the volume and ensuring the sustainability of crop production, primarily grain and leguminous crops, and, due to this, preserving and further increasing Ukraine’s export potential and role in solving the world food problem.

Therefore, both the “Strategy…” and the “Long-term Plan…” determine that the expansion of irrigation and water regulation areas should be carried out by developing and implementing projects for the reconstruction and modernization of existing irrigation and drainage systems, on which irrigation or water regulation is currently not carried out, but whose technical condition allows for the restoration of irrigation and water regulation by carrying out their reconstruction or modernization [1, 2]. As already noted, on the territories controlled by Ukraine, more than 800,000 hectares of irrigated lands are recorded, but irrigation is carried out on only 140,000 hectares, that is, more than 600,000 hectares of land that were once irrigated and had all the engineering infrastructure for irrigation are currently not used for their intended purpose. The actual technical condition of those infrastructure, unfortunately, is also unknown, as the last inventory audit of irrigation systems in Ukraine was conducted in 2013, so its data cannot be used as a starting point for developing both the feasibility studies and the projects for the reconstruction or modernization of existing irrigation systems. On the other hand, not using existing networks to speed up and reduce the cost of expanding irrigation areas is also not justified. Therefore, the “Plan of Actions for the Implementation of the Irrigation and Drainage Strategy in Ukraine for the Period Until 2030” [3], as well as the “Long-term Plan…” [2], provide for an inventory audit of irrigation systems as a basis for establishing their availability and actual technical condition, preparing proposals for the creation of water users organizations (WUO), developing feasibility studies and projects for their reconstruction or modernization.

The approximate scope of work on the inventory audit of inter-farm networks on the territories controlled by Ukraine is indicated by the data presented in Table 1.

1. Composition and main characteristics of the inter-farm irrigation networks and facilities on it on the territories controlled by Ukraine (according to the inventory data of the State Water Agency of Ukraine, 2013)

Region	**Main water intakes from irrigation sources pcs.**	**Permanent irrigation network, km**	**including:**		**Pumping stations, pcs.**	**Water reser-voirs, pcs.**	**Useful storage volume at NRL, million m³**
			canals, km	**pipelines, km**			
Oblast:							
Vinnytsia	16	163,36		163,36	48	1	
Transcarpathian					2		
Zaporizhzhia	18	673,1	478	195,1	213	1	5,7
Kyivska	4	289,881	54,224	235,659	44	10	6,074
Kharkiv	37	426,244	19	407,24	76	14	75,7
Kirovohradska	18	120	1	119	25	6	12,04
Mykolaivska	20	528,72	348	173,92	98	12	62,71
Odesa	23	985,016	515,338	467,2	218	10	33,342
Poltava	4	110,64	19,18	98,88	24	2	13,63
Cherkasy	51	341,1	38,4	302,7	81		
Dnipropetrovsk	42	796,36	209,18	587,18	165		
Kherson	71	844,9	740,6	104,3	228	7	18,5
Total in Ukraine	282	5278,321	2422,922	2827,539	1222	63	227,696

The data in Table 1 are somewhat overestimated, as they do not take into account the losses of irrigation networks in Kharkiv, Kherson, Zaporizhia, Mykolaiv, and Dnipropetrovsk regions due to temporary occupation and destruction.

The engineering infrastructure of irrigation systems includes the collector and drainage networks, which is built in the zone of influence of irrigation systems and are subject of inventory audit. The intra-farm network, the components of which are usually not recorded, also requires audit.

Therefore, solving the problem of accelerated expansion of irrigation areas, the relevance of which is constantly increasing due to progressive warming because of the climate changes, and the need to compensate for the decrease in crop production due to the temporary occupation of more than 18% of the territory of Ukraine, including more than 20% of arable and more than 75% of irrigated land, requires the earliest possible implementation of works on the inventory audit of irrigation networks available on the territory controlled by Ukraine. The development of remote sensing (RS), unmanned aerial vehicles (UAVs) technologies, and GIS systems opens up new opportunities for rapid and systematic mapping of irrigation infrastructure – canals, pipelines, pumping stations, etc.

In this regard, the issue of developing a scientific justification for the practical application of remote methods for irrigation systems inventory audit becomes particularly relevant, which creates the necessary prerequisites for faster, higher-quality, and less costly implementation of irrigation systems inventory audit works and auditing the use of irrigated lands. This paper is aimed at improving the methodology entitled *"Inventory of Engineering Infrastructure Facilities of Reclamation Systems and Audit of Reclaimed Lands"* (Institute of Water Problems and Land Reclamation of the NAAS, 2022) [4], which was developed in accordance with the current standards and regulatory documents [5–14]. The improvement concerns the content of Stage II of the survey process for engineering infrastructure facilities of irrigation systems, with the purpose of assessing their technical condition using remote-based diagnostic techniques, in accordance with the algorithm presented in Figure 1.

According to the proposed algorithm, Stage II of the irrigation system inventory audit process involves a preliminary assessment using remote diagnostic methods based on the analysis of satellite imagery, remote sensing data, and other remote monitoring tools. The assessment is aimed at identifying problem areas (their location, presence of direct damage, waterlogged zones, etc.) and evaluating the technical condition of system components. This approach is particularly relevant because traditional inventory methods are labor-intensive, costly, and time-consuming due to the need for extensive field surveys. This complicates the planning of system rehabilitation and modernization measures and hinders decision-making processes related to the restoration and further development of irrigation infrastructure. The scientifically justified application of remote sensing technologies for the inventory of irrigation systems will ensure:

– reduction of time and costs for surveys conduction;

– the ability to cover large areas in a short time;

– increasing the accuracy and objectivity during the assessment of the technical condition of systems' elements.

Analysis of recent research and publications. Analysis of Ukrainian and international experience shows that remote sensing (remote sensing of the Earth, unmanned aerial vehicles (UAVs), GIS systems, etc.) are widely implemented and used both in scientific research and in the practice of using irrigation systems for:

– assessments of the state of water bodies [15, 16, 17, 18];

– assessment of agricultural lands condition [19, 20, 21, 22, 23, 24];

– assessments of agricultural crops moisture supply [21, 22, 25];

– determination and control of compliance with irrigation regimes [19, 20, 26];

– inventory audit of irrigation systems' components [27-49].

The use of remote tools for the purpose of irrigation systems inventory audit is at the stage of research and testing of the areas of application. Thus, there is a need for additional studies and adaptation of existing approaches to solving inventory audit problems.

The aim of the paper is to analyze the current state and determine the directions of using remote tools and technologies for irrigation systems inventory audit.

Materials and research methods. The methodology of irrigation system inventory audit involves a set of measures to verify the availability and condition of engineering infrastructure, including hydraulic facilities, networks, pumping stations, etc.

The term "irrigation systems inventory audit" is understood as the process of checking the

Stage I Preparation for surveys conduction (preparatory stage)	- familiarization with the object of survey, its design solution, and engineering survey materials; - study and analysis of design and technical documentation; - drawing up a work program based on the technical specifications received from the customer; - development and compilation of large-scale maps of the surface of facilities; - development of survey route schemes.
Stage II preliminary (visual) field surveys/remote diagnostics	- inspection (remote diagnostics, remote sensing of the Earth) of engineering infrastructure facilities of land reclamation systems, detection of defects and damage by external signs with necessary measurements and preliminary assessment of their technical condition; - description, photography, and drawing on scale maps of objects in the conventional designations of identified damage and defects.
Stage III Detailed (instrumental) field surveys/ remote diagnostics	- instrumental determination of defects and damages parameters; - determination of the actual strength characteristics of the materials of the main load-bearing structures and their elements; - determination of actual operational loads and impacts received by the structures under investigation, taking into account the impact of soil deformations; - development of recommendations for ensuring the required values of strength and deformability of structures with a recommended sequence of works execution, if necessary.
Stage IV Assessment of the sustainability of the reclamation system/ operation of the WUO (modeling, economic calculations)	- determining the required minimum service area of the system, which ensures the return of costs for the operation of the reclamation system and ensures profitable farming; - determining the maximum allowable values of the cost of water supply/water disposal services while ensuring a given level of profitability; - development of recommendations to ensure the sustainable operation of reclamation systems and to ensure the self-sufficiency of newly created WUOs.
Stage V Assessment of damages resulting from military aggression (if any)	- loss determination: - direct losses; - lost benefit from the inability to use both systems and land for their intended purpose.

Fig. 1. Algorithm for organizing inspections of engineering infrastructure facilities of irrigation systems to assess their technical condition [4]

actual presence, condition, and compliance of all components of the irrigation system, such as pumps, filters, pipes, canals, etc., with the design and passport technical specifications.

The main components of irrigation systems that require remote inventory include: water source (rivers, lakes, ponds, reservoirs, groundwater, and other available water sources); water intake facility (pumping station); irrigation network consisting of such structural elements as supplying and regulating network (canals, pipelines), temporary irrigation network for distributing irrigation water to the irrigation modules on fields (canals, pipelines), water collecting and discharging network for collecting and regulating storm-water and discharge water, drainage and collector network, to regulate groundwater levels; hydraulic facilities and water shut-off valves that help regulate water flow and speed; water supply, water retention and regulating facilities; the facilities that are intended for environmental protection purposes; access roads for the passage of equipment and carrying out operational activities; technical buildings and facilities, etc.

The used general scientific and special research methods were logical method, generalization, analysis, tabular method, scientific abstraction, deductive and inductive methods.

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The object of the research is the process of organizing the irrigation systems inventory audit using remote means (tools).

The subject of the research is the scientific, methodological, and practical aspects of using remote tools for irrigation systems inventory.

Research results and their discussion. In the process of analytical research, the types and systematization of the existing scientific and methodological approaches, methods, and technical solutions regarding the possible use of remote means for the inventory audit of irrigation systems were determined, their advantages and limitations were assessed, and the main directions and types of works on the inventory audit of irrigation systems were determined. For the implementation these works the following is proposed to be used.

Satellite/aerial imagery (the most widely used satellites: Sentinel, Satellite, Aerial Imagery, Landsat-8/9, PlanetScope, WorldView-3) should be used for large-scale assessment of irrigation systems. This tool allows to identify networks of canals, pipeline routes, irrigation areas, create a map of networks, and assess the overall condition of the irrigation system in terms of its location and the presence of individual components. Retrospective (archival) satellite images and aerial photographs are an important tool for reproducing the state of irrigation infrastructure and analyzing long-term changes within the system.

Based on the results of the analysis of available sources and the practice of using satellite images and aerial photographs, a list of them with possible paths for using available archival satellite images and aerial photographs for the purposes of irrigation systems inventory audit in Ukraine were formed (Table 2).

A methodical approach for the use of satellite images and aerial photographs,

2. The list and the possible paths of use of satellite images and aerial photographs for the purposes of irrigation systems inventory audit

Satellite	Observation period	Spatial resolution	Characteristics	Reference
CORONA (KH series)	1960–1972	≈2–10 m	Panchromatic images with high spatial resolution. Can be used to detect large canals and earthworks; requires geocorrection.	United States Geological Survey (USGS EarthExplorer) [27] US National Archives (CORONA collection) [28]
KH 9 Hexagon	1973–1984	≈5–10 m	Declassified panchromatic images, large coverage, good spatial resolution; used for detailed survey and assessment of local networks.	US National Archives [28] United States Geological Survey (USGS EarthExplorer) [27]
Landsat (Landsat 1–9, MSS/TM)	1972 – till now	≈60 m (MSS) up to ≈30 m (TM)	Multi-spectral image series: MSS (≈60 m), TM (≈30 m). Gives a chronology of vegetation and water surface changes; easy to integrate with modern data.	Earth Resources Observation and Research Center (USGS EROS) [29] United States Geological Survey (USGS EarthExplorer) [27] Google Earth Engine [30]
Aerial photographs (national archives)	≈ 1950 – till now	depends on the source (starting from ≈1 m)	Varying spatial resolution (from ≈0.5–5 m); often the best option for local detailing, if available.	National Archives of Ukraine; State Geocadastre; local cartographic services
Modern satellites (Sentinel 2, VHR)	2015 – till now	10–20 m (multi-spectral)	Sentinel 2 (10–20 m multi-spectral), commercial VHR (up to 0.3–1 m). Used for validation and combination with archives.	Copernicus Open Access Hub [31]

which involves comparing archival images (CORONA, KH-9 Hexagon, early Landsat series, aerial photo archives), allows to track changes in the functioning of irrigation systems, identify hydraulic facilities, track landscape transformations under the influence of irrigation, erosion or urbanization, and solve other tasks of irrigation systems inventory audit and auditing the use of irrigated lands. E.g., Spanish scientists, based on the research conducted by isardSAT and IRTA using remote sensing data, proposed a method for classifying irrigation methods and types: flooding, sprinkling, drip irrigation, and non-irrigated fields [32]. This methodology allowed the creation of maps of irrigation systems in the region of Catalonia (Spain), which provide detailed information about the state and development (modernization) of irrigation methods in the region, which were previously not reflected in existing databases. This study used various machine learning algorithm models, as well as remote sensing data from SMOS/SMAP, Sentinel-2, and Sentinel-3 satellites, related to evapotranspiration and soil moisture (an indirect tool for determining irrigated and non-irrigated areas).

Researchers from the University of Virginia have developed a machine learning system called IGraSS (Iterative Graph-constrained Semantic Segmentation) to identify critical infrastructure networks (irrigation canals and roads, etc.) from satellite images. The system uses RGB imagery along with additional data such as normalized differential water index (NDWI) and digital elevation models (DEM) [33].

In China [34], archival CORONA imagery has been used to locate and map ancient irrigation systems in desert oases, which are not seen on modern imagery due to sand deposits or hydrology changing. Examples of the use of declassified Hexagon images for detecting various objects of irrigation systems are given in the work of Emily Hammer et al. [35]. The use of a methodological approach based on the combination of Landsat series with modern data and creating the prerequisites for tracking long-term chronology of changes made it possible to create an irrigation map for the USA with a resolution of 30 m [36]. The application of this approach to assessing the history of irrigation development in one intensively irrigated valley in India using multi-year Landsat satellite images made it possible to track the expansion of irrigated agricultural areas and determine the time limits of their increasing [37]. A similar approach (Ask Holm Carlsen et al. [38]) has been used to identify and map closed drainage systems, covering a diverse range of imagery, different data collection periods, and detection methods.

In general, a methodological approach that involves the joint use of archival panchromatic images (CORONA, Hexagon), chronological multi-spectral series (Landsat), modern VHR / Sentinel data and GIS analytics methods allows to recreate the history of changes in the functioning of irrigation infrastructure, identify inactive canals, etc.

The disadvantage of this methodological approach (method) when used for irrigation systems inventory audit is the inability to determine the presence of underground pipelines or closed canals due to the low spatial resolution of the images.

The next group (type) of remote tools that are already in use and whose prospects for use in conducting an inventory audit of irrigation systems are constantly and rapidly growing are *drones / unmanned aerial vehicles (UAVs) with multi-spectral / thermal / video cameras* (the most common models: DJI Matrice 350 RTK, DJI Mavic 3 Multispectral, senseFly eBee X, Autel EVOII Dual Rugged BundleV3, Yuneec H850 RTF/RTK T1). The use of drones makes it possible to perform a more detailed inspection of hard-to-reach areas, which allows obtaining highly accurate geospatial data for identifying canals, pipelines, reservoirs, and hydraulic facilities. The use of drones is especially relevant in countries with a developed agricultural sector, as confirmed by the experience of such countries as Spain, Italy, India, and the USA, where national programs for the digitalization of water management are created based on their use [39].

The use of drones is particularly promising given that by adding different types of cameras to them, their capabilities can be significantly expanded [40, 41]. Thus, equipping drones with RGB cameras allows them to be used for high-quality visual surveying for orthophotos, detecting structures, faults, color/structural differences, etc.; equipping with Multi-spectral (MS) cameras allows calculating vegetation indices (NDVI) and other indices that are useful for determining moisture content and the state of vegetation along the canals; thermal cameras are critical for detecting leaks (temperature anomalies) and differentiating wet areas, and LiDAR cameras are used to obtain digital terrain models (DTM/DSM), determine canal profiles, control erosion, and determine the geometry of structures.

An example of using a drone with a LiDAR camera to highlight the main elements of an irrigation network is the results of research by

Mahor and colleagues [42]. The methodology used in this study includes the use of high-resolution digital terrain models (LiDAR with an accuracy of 1 meter horizontally and 0.25 meters vertically) and geographic information systems (GIS) tools such as ArcGIS and Whitebox Geospatial Analysis Tools (Whitebox GAT). Some studies have also demonstrated the effectiveness of using drones with thermal imaging cameras to identify leak locations in irrigation systems in vineyards in Portugal [36], the effectiveness of an approach that involves integrating UAV data with historical satellite imagery to map underground pipelines in agricultural regions in Greece [44], and UAV video analysis algorithms for automatic detection of pipeline leaks [45].

Based on the analysis of the state of use and taking into account the available additional equipment for UAVs, the following main areas of drones usage are proposed when carrying out works on irrigation systems inventory audit:

1. Orthophoto mapping and vectorization: photogrammetric processing (creation of orthophotomap, digital terrain model – DTM), vectorization of linear objects (canals, dams, riverbeds). Used to detect only surface hydraulic facilities in [43, 44].
2. Thermal leak diagnostics: TIR imaging detects temperature anomalies that indicate pipeline leaks, flooding, or damage of the canal foundation [36].
3. Multi-sensor combination (RGB + NIR + TIR + DTM) increases the probability of detecting non-metallic elements (PE pipes, small underground collectors) by detecting changes in vegetation or temperature above the route. For example, an approach with a combined UAV-NIR and historical orthophotos was used to detect underground irrigation pipes [45].
4. Automatic segmentation and ML: The use of computer vision algorithms (U-Net, DeepLab, Random Forest for pixel classification) allows automated detection of canals and defects on orthophotos and thermal layers. The essence of the method is that first the analysis and modeling are carried out on modern images, then the model is adapted during the flight and scanning of the UAV for local conditions [38].

Therefore, the main advantages of using drones are their high spatial-temporal resolution, which allows to see small objects and local defects; flexibility and efficiency, which ensures quick execution of research after detecting a suspected problem, as well as saving time and resources by reducing the number of field trips by personnel.

Despite all the feasibility and advantages, the use of drones has many disadvantages that arise during such research (work). One of the main problems is the flight restrictions in many countries, especially in areas near populations or critical infrastructure; the need for permits and pilot certification. Weather conditions (wind, fog, and precipitation) reduce the quality of the footage or make flights impossible. TIR anomalies or indices can be caused by various factors (shadow, soil type), which is why field confirmations are needed. The processing of the large volumes of images requires powerful hardware and knowledge of photogrammetry, also the geocalibration and georeferencing are necessary. For very large networks (thousands of km), using drones alone can be quite costly [32].

Therefore, the use of UAVs should be considered as an effective addition to traditional methods of irrigation infrastructure inventory audit. Combining drones with retrospective satellite data creates the basis for comprehensive monitoring, performance evaluation, and sustainable water resources management.

Remote tool Geo-radar (GPR)/underground scanning (the most widespread models: Mala, IDS GeoRadar, Leica DSX, Bosch D-tect) is a geophysical device that operates on the principles of radar. It consists of transmitting and receiving antennas that emit short pulses of high-frequency electromagnetic waves and record reflected signals from the boundaries of various environments. Analysis of return time and signal intensity allows to allocate the pipelines placement [47]. Geo-radar is one of the most effective methods for locating and mapping underground pipelines, especially for objects made of non-metallic and fiber-optic materials. The effectiveness of the use of GPR directly depends on the electrophysical properties of the environment. The high electrical conductivity of the soil causes signal absorption, which reduces its penetration depth. Pipelines filled with water or pipelines in very wet soil are also difficult to detect.

The widespread and effective use of geo-radars in conducting irrigation system inventory audits is facilitated by the rapid development of machine learning algorithms and 3D reconstruction of GPR data. The use of deep neural networks allows for automatic recognition of hyperbolic imprints from pipes and distinguishing them from noise. In addition, combining geo-radars with remote sensing methods and analytical models opens up opportunities for automated mapping of underground pipelines and irrigation networks.

The use of *tracers* (the most widespread models: Radiodetection, C.Scope, SebaKMT, Sonel LKZ-2500, Leica, RIDGID) and *locators / metal detectors* (the most widespread models: Fisher, Garrett) can be quite effective when carrying out works on the inventory audit of irrigation systems. Electromagnetic location is currently the most widespread method of searching and tracing underground engineering networks. Unlike geo-radars (GPR, pulse reflection), the EM method is based on the principle of electromagnetic induction. The essence of the method is to create an alternating electromagnetic field near the soil surface, which induces currents in metal objects – pipes or cables. By measuring these fields, the receiving device determines the position and depth of the object [48]. This method is characterized by its universality and considerable practicality, as it allows determining the position, schemes, and depth of pipelines, as well as determining their clogging or damage using transmitter probes [49].

The results of the analytical research conducted on the possibility of using remote tools for irrigation systems inventory indicate that their use is possible only with the application of an integrated approach that combines modern geophysical, remote sensing and geoinformation methods and tools and requires the development of scientific and practical justification (tools, implementation methodology, etc.).

Conclusions. According to the results of the research, it was determined that remote tools are most appropriate to use at the second stage of the inventory audit to identify and preliminary assess the condition of the following main elements of irrigation systems: pumping stations, antechambers, open (earthen and concrete) canals, pipelines, hydrants, water distribution facilities, etc.

Based on the analysis, it was determined that the following remote tools can be used to detect and assess the condition of irrigation system elements: Earth satellite observation (optical, multi-spectral, hyper-spectral images); aerial photography from unmanned aerial vehicles (UAVs, drones); geophysical instruments, GPR and EM methods in combination with GIS modeling, geographic information systems (GIS) for integration, analysis and visualization of results.

The analysis also revealed that satellite or aerial photography should be used for large-scale assessment of irrigation systems; unmanned aerial vehicles should be used for detailed inspection of hard-to-reach areas, identification of canals, pipelines, reservoirs and hydraulic facilities, conducting high-quality visual surveys for orthophotos, detecting structures, faults, color/structural differences, leaks in pipelines, flooding or damage of canals foundations; geo-radars should be used for locating and mapping underground pipelines, especially those made of non-metallic and fiber-optic materials, and tracers and metal detectors should be used for locating and tracing underground irrigation networks.

The results of the analytical research of the experience of using remote tools to conduct an inventory audit of irrigation systems allow us to assert that the use of remote tools in combination with geoinformation methods creates additional opportunities for conducting an inventory audit of irrigation systems in Ukraine.

Conflicts of interest: the authors declare no conflict of interest.

Use of artificial intelligence: the authors confirm that they did not use artificial intelligence technologies during the creation of this work.

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СТАН ТА НАПРЯМИ ВИКОРИСТАННЯ ДИСТАНЦІЙНИХ ЗАСОБІВ ДЛЯ ІНВЕНТАРИЗАЦІЇ ЗРОШУВАЛЬНИХ СИСТЕМ

М.І. Ромащенко[1], докт. техн. наук, С.В. Усатий[2], канд. тех. наук, В.В. Поліщук[3], канд. с.-г. наук, Л.Г. Усата[4], С.С. Коломієць[5], канд. с.-г. наук, І.О. Коваленко[6], доктор філософії, А.С. Сардак[7], доктор філософії

[1] Інститут водних проблем і меліорації НААН, Київ, Україна;
https://orcid.org/0000-0002-9997-1346; e-mail: mi.romashchenko@gmail.com
[2] Інститут водних проблем і меліорації НААН, Київ, Україна;
https://orcid.org/0000-0001-8784-4078; e-mail: s_usatiy@ukr.net;
[3] Інститут водних проблем і меліорації НААН, Київ, Україна;
https://orcid.org/0000-0003-0429-7406; e-mail: vitaliypolishchuk@ukr.net;
[4] Інститут водних проблем і меліорації НААН, Київ, Україна;
https://orcid.org/0000-0002-3265-9024; e-mail: usataya_l@ukr.net;
[5] Інститут водних проблем і меліорації НААН, Київ, Україна;
https://orcid.org/0000-0002-4329-4382; e-mail: kss2006@ukr.net;
[6] Інститут водних проблем і меліорації НААН, Київ, Україна;
https://orcid.org/0000-0003-1548-3992; e-mail: igorok333@ukr.net
[7] Інститут водних проблем і меліорації НААН, Київ, Україна;
https://orcid.org/0000-0002-0540-9492; e-mail: anastasiabilobrova1993@gmail.com

Анотація. *У статті розглянуто сучасні підходи до проведення інвентаризації зрошувальних систем із застосуванням дистанційних засобів. Традиційні методи інвентаризації зрошувальних систем потребують значних фінансових і трудових витрат, що ускладнює проведення масштабної інвентаризації та планування заходів з реконструкції й модернізації систем зрошення. За результатами досліджень встановлено, що дистанційні технології є найбільш доцільними для інвентаризації таких основних елементів зрошувальних систем, як насосні станції, аванкамери, відкриті земляні та бетонні канали, трубопроводи, гідранти, водорозподільні споруди та інші складові інженерної інфраструктури. На основі проведеного аналізу визначено перелік дистанційних засобів, які можуть бути використані для оцінки технічного стану об'єктів зрошення. До них належать супутникове дистанційне зондування Землі, а саме використання оптичних, мультиспектральних і гіперспектральних знімків, аерофотозйомка із застосуванням безпілотних літальних апаратів, геофізичні методи дослідження, зокрема георадарне зондування (GPR) та електромагнітні методи трасування підземних комунікацій, а також геоінформаційні системи для інтеграції, аналізу, моделювання та візуалізації отриманих результатів.*

Дослідженнями встановлено, що комплексний підхід, який поєднує сучасні дистанційні, геофізичні та геоінформаційні методи, створює додаткові можливості для проведення ефективної інвентаризації зрошувальних систем України, підвищує оперативність обстежень, точність визначення технічного стану об'єктів та об'єктивність отриманих результатів. Результати виконаних аналітичних досліджень можуть бути використані для обґрунтування вибору інструментарію та розроблення рекомендацій щодо проведення інвентаризації зрошувальних систем дистанційними засобами.

Ключові слова: *інвентаризація, зрошувальні системи, дистанційне зондування, GIS, БПЛА, супутникові дані*

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TECHNOLOGY PARAMETERS OF SOIL WATER REGIME REGULATION WHEN FUNCTIONING DRAINAGE SYSTEMS OF THE LEFT-BANK FOREST-STEP

G.V. Voropai[1], Doctor of Technical Sciences, N.B. Moleshcha[2], Ph.D. in Technical Sciences, I.V. Kotykovych[3], Ph.D. in Technical Sciences, O.I. Kharlamov[4], Ph.D. in Technical Sciences, Yu.A. Onanko[5], Ph.D., S.V. Yehorova[6], Ph.D. in Historical Sciences, D.O. Styozhka[7]

[1] Institute of Water Problems and Land Reclamation of NAAS, Kyiv, 03022, Ukraine;
https://orcid.org/0000-0002-5004-0727; e-mail: voropaig@ukr.net;
[2] Institute of Water Problems and Land Reclamation of NAAS, Kyiv, 03022, Ukraine;
https://orcid.org/0000-0002-3207-2573; e-mail: sdp_2010@ukr.net;
[3] Institute of Water Problems and Land Reclamation of NAAS, Kyiv, 03022, Ukraine;
https://orcid.org/0000-0002-1492-3557; e-mail: ikotykovych@gmail.com;
[4] Institute of Water Problems and Land Reclamation of NAAS, Kyiv, 03022, Ukraine;
https://orcid.org/0000-0002-9019-3445; e-mail: lharlam911@gmail.com;
[5] Institute of Water Problems and Land Reclamation of NAAS, Kyiv, 03022, Ukraine;
https://orcid.org/0000-0002-7231-1188; e-mail: yaonanko1@gmail.com;
[6] Institute of Water Problems and Land Reclamation of NAAS, Kyiv, 03022, Ukraine;
https://orcid.org/0000-0002-3045-3508; e-mail: racydeer@gmail.com;
[7] Institute of Water Problems and Land Reclamation of NAAS, Kyiv, 03022, Ukraine;
https://orcid.org/0009-0008-5470-9409; e-mail: dimonstyozka@gmail.com

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Abstract. *The results of research on determining the technological parameters of regulating the soil water regime when functioning drainage systems (drainage and irrigation system "Romen", local contour water-accumulating systems – CWAS) of the Left-Bank Forest-Steppe are presented. Priority crops on drained lands (Sumy region) are corn for grain (share in the sown area 35%), sunflower (20%), wheat (16%), soybean (14%) and rapeseed (4%). Weather conditions on research and production plots (State Enterprise "Nadiya" and LLC Agrofirma "Lan") during the growing season 2022–2025 were characterized by extremely uneven distribution of precipitation and significant fluctuations in air temperature. The average hydrothermal coefficient (AHC) during the growing season in 2000–2025 varied within 0,6–1,9, in 2025 it was 0,77 (the conditions of a moderately arid zone). Technological parameters for regulating the soil water regime when cultivating corn for grain, buckwheat, winter wheat, sunflower, soybeans and perennial grasses were obtained, the applying of which ensures an increase in the yield of economically attractive crops up to 25%. During long-term operation (more than 30 years) of the CWASs, the effectiveness of their functioning was confirmed, as well as the possibility of ensuring a favorable soil water regime in areas with developed microrelief, obtaining a stable crop yield and increasing the efficiency of agricultural land use in the areas with micro-depression landforms. The increase in winter wheat yield by 12% compared to the watershed and by 64% compared to micro-depressions without ameliorative measures was observed. Technological parameters for regulating the soil water regime are recommended for use by specialists in agriculture and water management (landowners and land users of drained lands, operational and project water management organizations) when governing the water regime on drained lands of the Left-Bank Forest-Steppe.*

Keywords: *drainage and irrigation system, contour water-accumulating system, drained lands, technological parameters, soil water regime regulation*

The relevance of the study is due to the need to solve modern problems of regulating the soil water regime on drained lands to ensure the sustainability of agricultural production in unstable weather conditions. Climate change, which is observed in the zone of excessive moisture, in particular the Left Bank Forest-Steppe, is accompanied by inefficient accumulation of moisture in the soil, unstable moisture supply and the formation of new conditions for growing crops on drained lands [1, 2, 3]. In such conditions, the importance of agricultural lands with a regulated water regime increases. At the same time, climate change forms not only new conditions for agricultural production on drained lands, but also changes the structure of sown areas due to the shift of crop growing areas [4]. Therefore, given the conditions of modern management on agricultural lands with a regulated water regime, the tasks of effectively using the existing potential and water-regulating capacity of drainage systems as well as developing technological parameters for regulating the soil water regime for growing priority crops on drained lands of the Left Bank Forest-Steppe are relevant.

Analysis of recent research and publications shows that scientists generally pay attention to studying the impact of climate change on modern agricultural production, while a small number of works are devoted to the development of prospects for the effective use of drained lands and regulation of the soil water regime for growing crops, which are currently priority and economically attractive in the Left-Bank Forest-Steppe zone [1, 4–6].

It is noted in literary sources that agricultural production in the Left-Bank Forest-Steppe zone is territorially carried out under different soil and climatic conditions [5, 7]. At the same time, the use of agricultural lands in this region, in particular in Sumy, Kyiv and Chernihiv regions, is closely related to drainage land reclamation. As for regional features, in turn, Sumy region, in terms of heat and moisture supply, is located within two natural zones (mixed forest and forest-steppe) with three territorial parts distinguished by the moisture index [7, 8].

Recent studies show that due to the instability of weather conditions and low regulation of water resources, the active soil layer is constantly overdried or overwetted precisely during the period of active vegetation of cultivated crops, which is the cause of a significant decrease in yield. Therefore, studies aimed at obtaining technological parameters for regulating the soil water regime on agricultural lands are of great importance [9–15].

An analysis of publications has shown that in recent years a small number of scientific developments have been devoted to the problem of regulating the soil water regime during modern agricultural use of drained lands of the Left-Bank Forest-Steppe. In particular, technological parameters for water regulation for growing highly productive fodder crops (Japanese millet, amaranth and fodder beans) on lands with a regulated water regime have been obtained [16–19].

The scientific works also raise the issues of the feasibility of implementing irrigation systems for growing vegetable crops in the Left-Bank Forest-Steppe zone, the assessment of natural resources and their compliance with the crop requirements, possible ways to optimize external factors, with an emphasis on the modern problem of providing sufficient water resources, the volumes of which can be regulated by irrigation [20, 21].

Therefore, to obtain stable yields of priority and economically attractive crops in conditions of increasing instability of weather conditions and the need to solve the problems of modern agricultural production regarding the management of the soil water regime on drained lands of the Left-Bank Forest-Steppe zone, it is relevant to solve the problems of effective use of the potential of drainage systems and obtaining justified technological parameters for regulating the soil water regime on drained lands.

The purpose of the research is to determine the technological parameters of soil water regime regulation under the conditions of drainage systems functioning and modern management on drained lands of the Left-Bank Forest-Steppe.

The main objectives of the scientific research are to conduct analytical studies of modern agricultural use of drained lands, analyze experimental studies on determining the parameters of the soil water regime and substantiate the technological parameters of soil water regime regulation under modern management on drained lands of the Left-Bank Forest-Steppe.

Materials and methods of research. Research work was carried out on the lands with regulated soil water regime (drainage and irrigation system (DIS) "Romen") and in the territories with non-drainage micro-depressions ("saucers"), which are under operation of local contour-water accumulation systems, which provide collection, accumulation, and redistribution of local runoff with its reuse for moistening cultivated crops. Experimental and production plots are located within the lands of SE "Nadiya" and LLC "Agrofirma "Lan" (Romensky district, Sumy region).

On the drained lands of SE "Nadiya", regulation of soil water regime is carried out by subsoil moistening. Micro-depressions ("saucers") are located on the experimental and production sites of Agrofirma "Lan" LLC, where contour water-accumulating systems (CWAS) were built in 1995, Fig. 1. The main structural element of the CWAS is drainless contour water-accumulating trenches with various filtering back fillings (straw, peat, fascines), which provide accumulating excess water within the micro-depressions.

Fig. 1. Layout of the CWAS, Agrofirma "Lan" LLC:

1 – CWAS 1 (straw filtering back filling), 2 – CWAS 2 (straw filtering back filling), 3 – CWAS 3 (peat filtering back filling), 4 – CWAS 4 (fascia filtering back filling), 5 – micro-depression without ameliorative measures

During the research certified and standardized in Ukraine methods, as well as methodological approaches used in domestic and international practice were used. The available equipment was following: disc drill, crackers, electronic laboratory scales, drying oven, thermometers, rain gauge.

The basis of the research methodology is a systematic analysis and generalization of experimental field materials regarding meteorological indicators (air temperature and precipitation), groundwater level (GWL), soil humidity and moisture reserves, biometric indicators of cultivated crops obtained in the period 2022–2025 under production conditions.

Determination and justification of technological parameters for regulating soil water regime during the cultivation of corn for grain, buckwheat, winter wheat, sunflower, soybeans and perennial grasses is based on specifying optimal ranges of groundwater level, soil humidity and moisture reserves, which ensure maximum growth of biometric indicators, in particular linear growth, leaf area, dry mass accumulation and yield of the above-mentioned crops by development phases, as well as during critical periods of their moisture supply, against the background of various methods of regulating soil water regime, in particular, sluicing (groundwater level regulation options – absolute drainage, closed potter's drainage, open channel network) and using local contour water-accumulating systems with various filtering back fillings.

Sowing and monitoring of crops were carried out according to generally accepted technologies for their cultivation when using mechanisms and tools directly used in production conditions. Harvest accounting was carried out using a continuous method from the entire accounting area.

On the drained lands of the SE "Nadiya" (mineral soils), corn for grain (hybrid DK315, FAO 310) was grown on the area of 1,5 hectares and buckwheat (variety "Slobozhanka") on the area of 28 hectares (mineral soils) in 2022. Mineral fertilizers were applied: for corn – at the rate of $N_{60}P_{60}K_{60}$ and for buckwheat – $N_{30}P_{30}K_{30}$. In 2023, winter wheat (variety "Bogdana") was grown on the area of 14 hectares; corn for grain (hybrid DN Pyvykha, FAO 180) on the area of 6 hectares and sunflower (hybrid P62LL109) on an area of 19 hectares. In 2025, sunflower (variety P62LL109) was sown by the SE Nadiya on the area of 20 hectares. Mineral fertilizers were applied in two versions – $N_{30}P_{30}K_{30}$ and $N_{60}P_{90}K_{60}$. On peat soils in the period 2022–2025, the crop grown was perennial grasses.

In 2024, soybeans (variety "Yug 30") were sown on the lands of LLC "Agrofirma "Lan" (mineral soils). Mineral fertilizers were applied at the rate of $N_{12}P_{24}K_{12}$. In 2025, winter wheat (variety NEXT) was grown; fertilizers were applied at the rate of $N_{12}P_{24}K_{12}$ in autumn period and KAS-32 in the spring period.

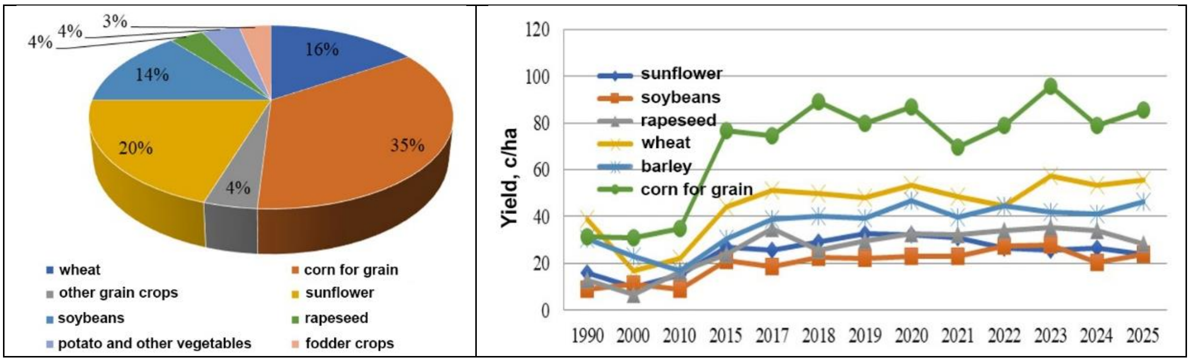
Research results and their discussion. According to the tasks set, analytical studies on the modern agricultural use of drained lands of the Left Bank Forest-Steppe were carried out. It was specified (using the example of Sumy region) that in 2025 the priority crops on drained lands were corn for grain (share in the sown area is 35%), sunflower (20%), wheat (16%), soybeans (14%) and rapeseed (4%), Fig. 2, a. Sowings of industrial crops over the past 35 years have increased due to the expansion of sunflower areas (from 16,8 thousand ha to 199,2 thousand ha or by 11,9 times), soybeans (from 1,3 thousand ha to 136 thousand ha or by 104,6 times) and rapeseed (from 7,8 thousand ha to 35,7 thousand ha or by 4,5 times). The area under sugar beet decreased by almost 239 times, and the yield increased almost twice. In the period 1990–2025, an increase in yield for almost all priority crops was observed (Fig. 2, b).

Experimental studies were conducted to determine the parameters of meteorological factors, rates of the groundwater level (GWL) and the water regime (moisture and moisture reserves) of the soil.

During the growing season of 2025, 256,5 mm of precipitation fell, which is 64,4 mm less than the average long-term values. Precipitation was distributed extremely unevenly both during the growing season and during individual months. The average daily air temperature during the growing season was 15,5 °C, which is 0,7 °C less than the average long-term values. The hydrothermal coefficient (HTC) of the territory of the experimental and production sites (within the lands of the SE "Nadiya" and LLC "Agrofirma "Lan") in 2000–2025 was determined, Fig. 3. The average HTC values for the growing season in the specified period varied widely – from 0,6 to 1,9. In 2025, the HTC was 0,77, which corresponds to the conditions of a moderately arid zone (for an arid zone the HTC is 1,0–0,7).

A study of the dynamics of the GWL and the moisture content of the active soil layer during the growing season 2022–2025 was conducted.

In 2025, at the experimental site of LLC "Agrofirma "Lan" with CWAS № 3 (the filtering back filling is peat), where winter wheat was grown, the GWL in the area with micro-depression without ameliorative measures at the beginning of the growing season was within 20–40 cm, and the root zone was periodically flooded, Fig. 4, a.



a) b)

Fig. 2. Disposition of crops in 2025 (a) and yield of basic crops in 1990–2025 (b), Sumy region

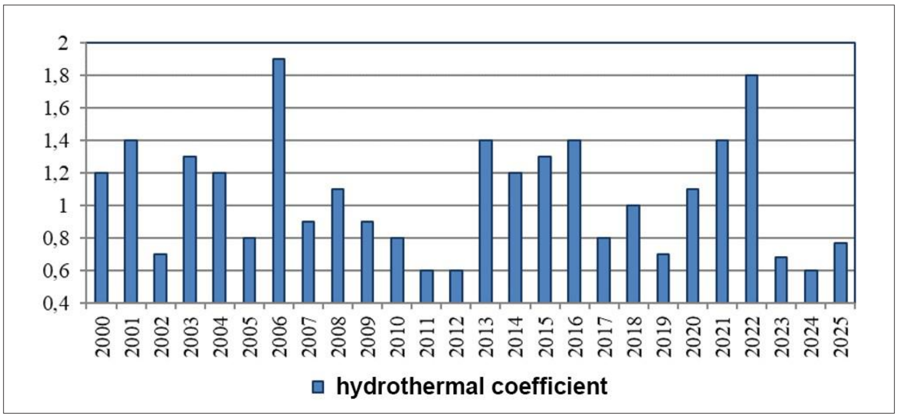
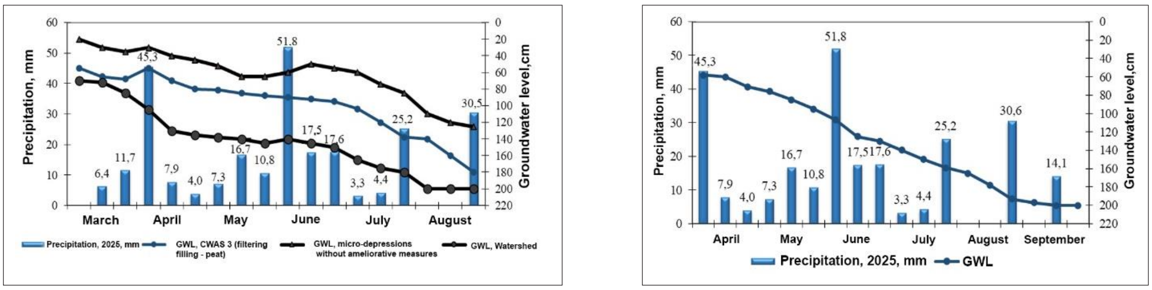
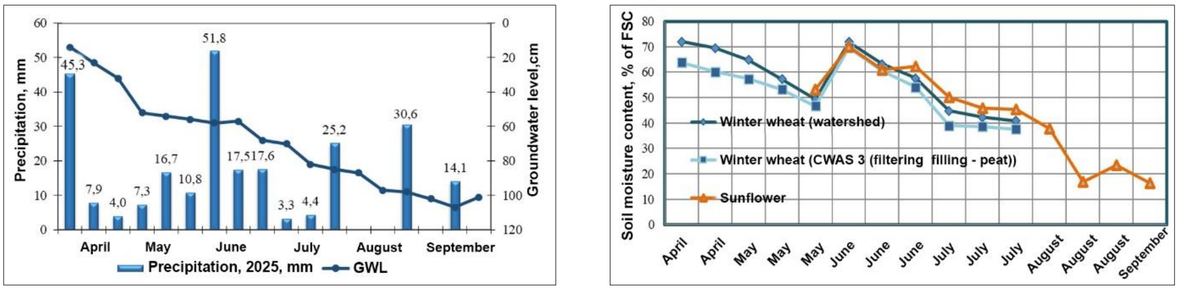


Fig. 3. Hydrothermal coefficient in the period 2000–2025, DIS "Romen"



a) winter wheat (mineral soils),
LLC "Agrofirma "Lan"

b) sunflower (mineral soils),
SE "Nadiya"



c) perennial grasses (peat soils),
SE "Nadiya"

d) winter wheat (mineral soils, LLC
"Agrofirma "Lan", CWAS № 3) and sunflower
(mineral soils, SE "Nadiya")

Fig. 4. Precipitation, dynamics of GWL (a, b, c) and moisture in the soil layer 0–50 cm (d), 2025.

On mineral soils where sunflower was grown (SE "Nadiya"), the GWL in the spring period was at a depth of 55–100 cm, in the summer period at the depth 100–175 cm, and in the autumn period it decreased to 180 cm. The formation of moisture and moisture reserves of the active soil layer depended on the arrival of atmospheric precipitation, Fig. 4, b and d.

On peat soils where perennial grasses were grown (SE "Nadiya"), the actual GWL in April was at a depth 25–45 cm, during the first mowing period it was at a depth of 55–60 cm, and during the second mowing period it was at the depth 90–100 cm, Fig. 4, c.

The dynamics of soil moisture during the cultivation of winter wheat on the lands of LLC Agrofirma "Lan" (CWAS № 3) and sunflower (SE "Nadiya") is shown in Fig. 4, d. Moisture reserves in the soil layer 0-50 cm during the cultivation of winter wheat were: in April – 160–170 mm, in May – 120–150 mm, in June – 120–170 mm, in July – 90–100 mm; during the cultivation of sunflower: in May – 105–110 mm, in June – 140–150 mm, in July – 100–110 mm, in August – 80–100.

According to the tasks set, an analysis of the results of experimental studies on the dynamics of growth and accumulation of dry mass of corn for grain, buckwheat, winter wheat, sunflower, and soybeans was performed in 2022–2025 by the phases of their development; critical periods of their moisture supply were determined.

During the cultivation of corn for grain, it was observed its slow development at the beginning of the growing season (second half of May). The most intensive linear growth of vegetative mass was recorded from 20.06 to 20.07, and by the end of the growing season the plants reached a maximum height of 2,45–2,70 m.

Buckwheat developed slowly in the first half of June, and from 20.06 to the end of July, intensive linear growth of vegetative mass was recorded. By the end of the growing season the plants reached a height of 0,90–1,05 m.

The intensity of the growth of corn leaf surface tended to decrease in May due to low air temperatures. In general, the growth of corn and buckwheat leaf surface depended on fertilizer application. The maximum values of the assimilation surface of corn were recorded on the 40th–50th day after emergence; the most intensive increase in leaf surface was from July 10 to August 20.

To determine critical periods of moisture supply for winter wheat, the results of studies on the accumulation of its dry mass were used, Fig. 5. Winter wheat was grown on drained lands of the "Romen" drainage and irrigation system and in

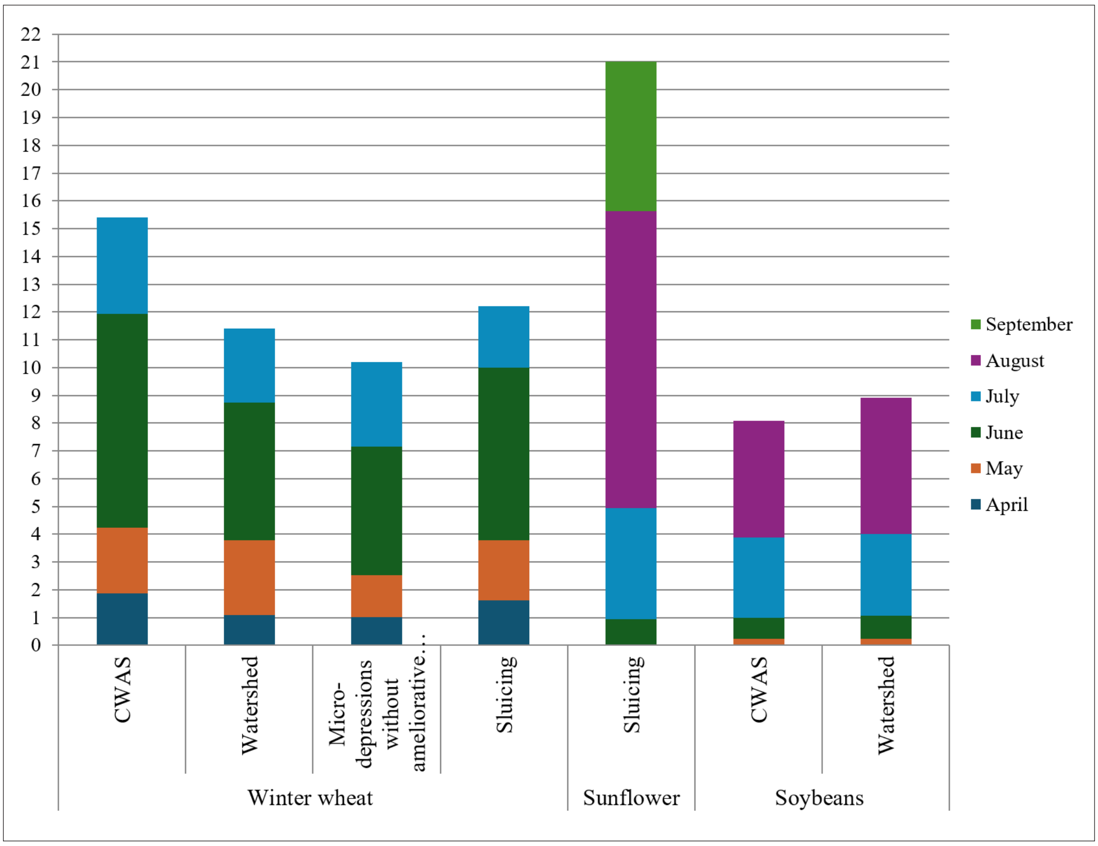


Fig. 5. Dynamics of dry mass growth of winter wheat, sunflower and soybeans when regulating the soil water regime, t/ha

the areas with micro-depressions, where CWAS were built. On the experimental and production plots of the DIS "Romen", the most significant increase in the dry mass of winter wheat was observed in June (the maximum was recorded in the 3rd decade); on the plots with CWAS – also in June, however, the maximums were recorded in the 3rd decade of June and the 1st decade of July.

It was specified that the operation of the CWAS provides a stable and fairly uniform increase in the dry mass of winter wheat, as well as when regulating the soil water regime by sluicing (DIS "Romen"). In the areas without regulation of soil water regime, the increase in the dry mass of winter wheat by decades has a jump-like character, which indicates a significant dependence of crop development on the distribution of precipitation during the growing season.

When growing sunflower, the maximum accumulation of its dry mass is observed in August (the largest increase was in the 3rd decade), while the 1st decade of September is also characterized by high growth rates.

As for soybeans, which were grown in areas of CWAS operation, the monthly maximum was recorded in August (seed ripening phase). Maxima of growth were recorded in all ten days of August and the second ten days of July.

Based on the systematic analysis and generalization of the materials of the experimental studies on the onset of development phases, growth dynamics, accumulation of dry mass of the studied crops, dynamics of groundwater level, soil humidity and moisture reserves, justified technological parameters of regulation of soil water regime for cultivation of corn for grain, buckwheat, winter wheat, sunflower, soybeans and perennial grasses were obtained, Tables 1 and 2.

The yield of corn for grain and buckwheat was determined when regulating soil water regime on the drained lands of the DIS "Romen", which was 7,1 t/ha and 1,4 t/ha, respectively, and when applying fertilizers it was 9,8 t/ha and 1,8 t/ha respectively. Mineral fertilizers were applied at the rate of $N_{30}P_{30}K_{30}$ (for buckwheat) and $N_{60}P_{60}K_{60}$ (for corn for grain), which contributed to an increase in their yield by 26% and 38%, respectively. The yield of winter wheat when regulating water regime was 4 t/ha, and when applying fertilizers $N_{60}P_{60}K_{60}$, the increase in yield was up to 50%.

1. Technological parameters for regulating soil water regime during the cultivation of corn for grain, buckwheat, winter wheat, sunflower and soybeans on drained lands of the Left Bank Forest-Steppe (DIS "Romen")

№	Indicator	Crop					
		Corn for grain	**Buckwheat**	**Winter wheat**		**Sunflower**	**Soybeans**
1	Critical period of moisture supply	3^d ten-day period of June – 2^d ten-day period of July	2^d ten-day period of June – 3^d ten-day period of July	1^{st} ten-day period of June – 1^{st} ten-day period of July		1^{st} ten-day period of August – 1^{st} ten-day period of September	1^{st} ten-day period of July – 3d ten-day period of August
2	Sowing date	14.05	02.06	20.09–06.10		24.05–26.05	27.05
3	Sprouting of crops	3d ten-day period of May	1^{st} ten-day period of June	03–17.10		1^{st} ten-day period of June	1^{st} ten-day period of June
	GWL, cm	45–75	70–80	–		90–95	80–90
	Moisture content, % FMC	40–45	40–50	–		45–65	70–80
	Moisture reserves in a layer of 50 cm, mm	110–120	80–90	–		90–120	250–280
4	The beginning of the period of intensive growth of vegetative mass	2d ten-day period of June	2d ten-day period of June	beginning of June		beginning of August	beginning of July
				contour water-accumulation systems	sluicing		contour water-accumulation systems
	GWL, cm	50–60	100–110		100–110	110–120	140–150
	Moisture content, % FMC	45–70	60–75	55–60	35–55	40–55	45–65
	Moisture reserves in a layer of 50 cm, mm	90–130	70–85	130–135	110–120	90–110	190–220
5	Period of maximum growth of vegetative mass	end of June – 2d ten-day period of July	July	June		August	August
	GWL, cm	80–120	110–120		100–130	130–140	150–170
	Moisture content, % FMC	35–50	35–40	55–70	45–65	30–40	30–40
	Moisture reserves in a layer of 50 cm, mm	70–90	70–80	120–130	90–120	60–80	70–90
6	Period of grain ripening	end of September	end of August – beginning of September	end of July		first part of October	end of August
	GWL, cm	100–120	110–130		120–130	–	–
	Moisture content, % FMC	15–30	30–40	40–45	40–45	–	20–40
	Moisture reserves in a layer of 50 cm, mm	60–80	50–65	80–100	80–100	–	50–60

2. Technological parameters for regulating soil water regime and yield of perennial grasses on drained lands of the Left Bank Forest-Steppe (DIS "Romen")

Crop	**Years of research**			
Perennial grasses	2022–2025			
Harvesting (mowing 1)	10–12.06			
Harvesting (mowing 2)	02–17.08			
Month	May	June	July	August
Soil moisture, % of FMC	90–95	80–85	65–80	60–70
Soil moisture reserves, mm	170–250	260–350	300–350	250–300
GWL, m	0.35–0.45	0.50–0.60	0.70–0.80	0.80–0.90
Options for regulating GWL	level drainage with moistening	open canals with moistening	closed pot drainage without moistening	
Soils	peat			
Yield (mowing 1, without fertilizes), t/ha	21–28	20–26	19–23	
Yield (mowing 1, $N_{30}P_{60}K_{90}$), t/ha	27–35	23–31	22–28	
Yield (mowing 2, without fertilizers), t/ha	15–18	15–17	12–15	
Yield (mowing 2, $N_{30}P_{60}K_{90}$), t/ha	18–27	17–25	15–24	

The yield of sunflower when regulating water regime was 2,3 t/ha, and when applying of $N_{60}P90K_{60}$ fertilizers it was 3,2 t/ha; the yield increase reached 26%.

It was specified that the increase in the yield of corn for grain, buckwheat, winter wheat and sunflower when regulating soil water regime and applying fertilizers on the drained lands of the DIS “Romen” and SE “Nadiya”, was 23%, 19%, 25% and 28%, respectively, compared to the average yield of the above-mentioned crops on this farm.

Harvesting of perennial grasses when applying 3 options for regulating soil water regime (level drainage with moistening, open canals with moistening, closed pot drainage without moistening), was carried out in the following terms: 1st mowing – 10.06–12.06, and 2nd mowing – 02.08–17.08. The highest yield of perennial grasses was obtained in the variant with level drainage with moistening: for 1st mowing – 21–28 t/ha, 2nd mowing – 15–18 t/ha, and when applying fertilizers at the rate of $N_{30}P_{60}K_{90}$ the yield was increased by 27%.

The yield of soybeans and winter wheat by the variants of the study (for CWAS with different back fillings) is presented in Tables 3 and 4. The average soybean yield was 2.6 t/ha, while in areas with micro-depressions without ameliorative measures, soybean crops were damped off.

The yield of winter wheat by the experimental variants (for CWAS with different back fillings) was on average 4,75 t/ha, and in the areas with micro-depressions without ameliorative measures it was 1,7 t/ha, on the watershed – 4,2 t/ha.

It should be noted that the obtained scientific and practical results are a supplement to the data on water regulation parameters previously obtained by the authors, in particular when cultivating highly productive fodder crops on drained lands, and their significance is confirmed by a number of problems that can be solved when using them, in particular, it refers to increasing the efficiency of using agricultural lands with micro-depression landforms, where local contour water-accumulation systems (CWAS) were arranged. At the same time, further studies will take into account the fact that due to the increased sensitivity of new crops to the soil water regime in the active phases of their vegetation, its operational correction is periodically necessary, the justification of which is possible only on the basis of engineering calculation methods based on modern mathematical models of saturated-unsaturated groundwater flows.

Conclusions. By the results of research on the modern agricultural use of drained lands of the Left-Bank Forest-Steppe, it was specified that the priority crops on drained lands are currently corn for grain (share in the sown area 35%), sunflower (20%), wheat (16%), soybeans (14%) and rapeseed (4%).

Based on experimental research of the meteorological factors and a hydrothermal coefficient (HTC) of the area of the experimental and production sites (within the land use of the SE “Nadiya” and LLC “Agrofirma “Lan”), it was determined that the weather conditions in the growing season 2022–2025 were characterized

3. Soybeans yield by the CWAS options, 2024

№	Experiment variant	Yield, t/ha Repeatability I	II	III	Average, t/ha
1	CWAS 1 (filtering filling – straw)	2.4	2.5	2.2	2.4
2	CWAS 2 (filtering filling – straw)	2.3	2.7	2.8	2.6
3	CWAS 3 (filtering filling – peat)	2.8	2.5	2.9	2.7
4	CWAS 4 (filtering filling – fascines)	2.3	2.5	2.7	2.5
5	Micro-depressions without ameliorative measures	–	–	–	–
6	Watershed	2.6	2.5	2.8	2.6

4. Yield of winter wheat by the CWAS options, 2025

№	Experiment variant	GWL, cm	Yield, t/ha Repeatability I	II	III	Average, t/ha
1	Watershed	70–180	4.5	4.2	4	4.2
2	CWAS 1 (filtering filling – straw)	40–115	4.5	3.7	3.9	4.0
3	CWAS 2 (filtering filling – straw)	35–125	4.7	4.6	4.3	4.5
4	CWAS 3 (filtering filling – peat)	55–140	5.4	4.9	5.6	5.3
5	CWAS 4 (filtering filling – fascines)	40–140	5.1	4.8	5.7	5.2
6	Micro-depressions without ameliorative measures	20–80	1.5	1.9	1.8	1.7

by an extremely uneven distribution of precipitation and significant fluctuations in air temperature, and the average HTC coefficient for the growing season in 2000–2025 varied in a wide range – from 0,6 to 1,9. In particular, in 2025, HTC was 0,77, which corresponds to the conditions of a moderately arid zone.

Based on the systematic analysis and generalization of the materials of experimental research on the onset of development phases, growth dynamics, accumulation of dry mass of the studied crops, the results of the analysis of the dynamics of groundwater levels, moisture and soil moisture reserves, justified technological parameters for regulating soil water regime for the cultivation of corn for grain, buckwheat, winter wheat, sunflower, soybeans and perennial grasses when functioning the drainage systems of the Left Bank Forest Steppe, were obtained. Their implementation will ensure an increase in the yield of economically attractive crops (corn for grain, buckwheat, winter wheat and sunflower) up to 25% on average.

It was specified that the effectiveness of the CWAS functioning was confirmed even under the condition of their long-term operation, therefore it makes possible to ensure a favorable soil water regime in areas with developed microrelief, to obtain a stable crop yield of cultivated crops and increase the efficiency of agricultural land use in areas with micro-depression landforms. The arrangement of the CWAS ensured an increase in winter wheat yield by 12% compared to the watershed and by 64% compared to micro-depressions without ameliorative measures [22].

Technological parameters for regulating soil water regime when growing crops on drained lands of the Left-Bank Forest-Steppe are recommended for use by the specialists in the field of agriculture and water management (landowners and land users of drained lands, as well as operational and project water management organizations) when controlling the moisture supply of crops grown on drained lands in the Left-Bank Forest-Steppe zone in the modern conditions of war and the post-war period.

Conflicts of interest: the authors declare no conflict of interest.

Use of artificial intelligence: the authors confirm that they did not use artificial intelligence technologies during the creation of this work.

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ТЕХНОЛОГІЧНІ ПАРАМЕТРИ РЕГУЛЮВАННЯ ВОДНОГО РЕЖИМУ ҐРУНТУ В УМОВАХ ФУНКЦІОНУВАННЯ ДРЕНАЖНИХ СИСТЕМ ЛІВОБЕРЕЖНОГО ЛІСОСТЕПУ

Г.В. Воропай[1], докт. техн. наук, Н.Б. Молеща[2], канд. техн. наук, І.В. Котикович[3], канд. техн. наук, О.І. Харламов[4], канд. техн. наук, Ю.А. Онанко[5], доктор філософії, С.В. Єгорова[6], канд. істор. наук, Д.О. Стьожка[7]

[1] Інститут водних проблем і меліорації НААН, м.Київ, 03022, Україна;
https://orcid.org/0000-0002-5004-0727; e-mail: voropaig@ukr.net
[2] Інститут водних проблем і меліорації НААН, м.Київ, 03022, Україна;
https://orcid.org/0000-0002-3207-2573; e-mail: sdp_2010@ukr.net
[3] Інститут водних проблем і меліорації НААН, м.Київ, 03022, Україна;
https://orcid.org/0000-0002-1492-3557; e-mail: ikotykovych@gmail.com
[4] Інститут водних проблем і меліорації НААН, м.Київ, 03022, Україна;
https://orcid.org/0000-0002-9019-3445; e-mail: lharlam91l@gmail.com
[5] Інститут водних проблем і меліорації НААН, м.Київ, 03022, Україна;
https://orcid.org/0000-0002-7231-1188; e-mail: yaonanko1@gmail.com
[6] Інститут водних проблем і меліорації НААН, м.Київ, 03022, Україна;
https://orcid.org/0000-0002-3045-3508; e-mail: racydeer@gmail.com
[7] Інститут водних проблем і меліорації НААН, м.Київ, 03022, Україна;
https://orcid.org/0009-0008-5470-9409; e-mail: dimonstyozka@gmail.com

Анотація. *Наведено результати досліджень щодо визначення технологічних параметрів регулювання водного режиму ґрунту в умовах функціонування дренажних систем (осушувально-зволожувальна система «Ромен», локальні контурно-водоакумулюючі системи – КВС) Лівобережного Лісостепу. Пріоритетними культурами на осушуваних землях (Сумська обл.) є кукурудза на зерно (частка у посівній площі 35 %), соняшник (20 %), пшениця (16 %), соя (14 %) та ріпак (4 %). Погодні умови у вегетаційний період 2022–2025 рр. (дослідно-виробничі ділянки, ДП «Надія» та ТОВ «Агрофірма «Лан») характеризувалися вкрай нерівномірним розподілом опадів та значним коливанням температурних показників повітря, середній у вегетаційний період показник гідротермічного коефіцієнта (ГТК) у 2000–2025 рр. змінювався у межах 0,6–1,9, у 2025 р. ГТК становив 0,77 (умови помірно посушливої зони). Отримано технологічні параметри регулювання водного режиму ґрунту за вирощування кукурудзи на зерно, гречки, озимої пшениці, соняшнику, сої та багаторічних трав, впровадження яких забезпечує підвищення врожайності економічно привабливих культур до 25 %. За тривалої експлуатації (більше 30 років) КВС підтверджена ефективність їх функціонування, можливість забезпечення сприятливого водного режиму грунту на територіях із розвиненим мікрорельєфом, отримання стабільного врожаю культур та підвищення ефективності використання сільськогосподарських земель на територіях із мікрозападинними формами рельєфу, відмічено зростання врожайності озимої пшениці на 12 % порівняно з водорозділом та на 64% порівняно з мікропониженнями без меліорації. Технологічні параметри регулювання водного режиму ґрунту рекомендовано для використання фахівцями в галузі сільського та водного господарства (землевласникам та землекористувачам осушуваних земель, експлуатаційним та проєктним водогосподарським організаціям) при управлінні водним режимом на осушуваних землях Лівобережного Лісостепу.*

Ключові слова: *осушувально-зволожувальна система, контурно-водоакумулююча система, осушувані землі, технологічні параметри, регулювання водного режиму ґрунту*

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CURRENT ISSUES IN HYDROLOGICAL TERMINOLOGY AND THE CLASSIFICATION OF WATER BODIES IN THE CONTEXT OF UKRAINE'S WATER LEGISLATION

O.M. Kozytskyi[1], A.M. Shevchenko[2], Ph.D. in Agricultural Sciences, I.A. Shevchenko[3], Ph.D. in Technical Sciences, O.O. Sydorenko[4], Ph.D. in Agricultural Sciences

[1] Institute of Water problems and Land Reclamation of NAAS, Kyiv, 03022, Ukraine
https://orcid.org/0000-0002-4459-6331; e-mail: olegkoz@ukr.net;
[2] Institute of Water problems and Land Reclamation of NAAS, Kyiv, 03022, Ukraine
https://orcid.org/0000-0002-2637-6538; e-mail: monitoring_protect@ukr.net;
[3] Institute of Water problems and Land Reclamation of NAAS, Kyiv, 03022, Ukraine
https://orcid.org/0000-0002-7401-8786; e-mail: irashef@ukr.net
[4] Institute of Water problems and Land Reclamation of NAAS, Kyiv, 03022, Ukraine
https://orcid.org/0000-0002-7377-6809; e-mail: 63059@ukr.net;

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Abstract. *As a result of the analysis of legal issues arising in the implementation of the provisions of the Water Code of Ukraine concerning the protection regime of water fund lands, it has been established that these issues are largely caused by the ambiguity of hydrological terminology and the absence of statutory definitions for certain hydrological terms used in, or omitted from, the Water Code. In particular, this includes such terms as "river", "small watercourse", "stream", "low-water period", "slope gradient", "lagoon", "river estuary", etc. The application of the linear approach to determining the outer boundary of waterside protection zones requires the establishment of fixed reference values for their width and for slope gradient. However, the low-water level, which under the Water Code serves as the inner boundary of waterside protection zones, is not a constant value and may vary considerably both from year to year and during the same low-water period. Furthermore, establishing its long-term mean value is practically impossible in the places where long-term hydrological monitoring data for rivers are unavailable. Another reason for legal problems in establishing the boundaries of waterside protection zones is the absence in the Water Code of a classification of natural and artificial water bodies, in particular, the lower limit of the catchment area of small rivers, as well as the area or depth of lakes and ponds. Based on the conducted research, amendments to the statutory river classification of the Water Code have been proposed, along with a classification of lakes according to their water surface area. These proposals would provide a differentiated approach to determining the width of waterside protection zones for specific categories of small watercourses and water bodies. Proposals have been made for changes and additions to the glossary of hydrological terminology given in the Water Code of Ukraine. For the practical implementation of new methodological approaches to determining the boundaries of waterside protection zones, it has been proposed to develop separate regulatory and methodological recommendations that would take into account the peculiarities of the hydrological regime of the river and the morphology of the riverbed.*

Keywords: *river, water body, lake, pond, low-water period, lagoon, waterside protection zone, Water Code, legislation*

Relevance. The main requirements for preserving water resources, ensuring the required water quality, and improving the hydro-morphological state of riverbeds and waterside landscapes are defined by the Water Code of Ukraine (WCU), which provides for the establishment of a regime of limited economic activity on water fund lands located along rivers, seas, and around lakes, reservoirs, and other bodies of water. The lands of the water fund, in particular, include riparian and coastal (further, waterside) protection zones (WPZ), for the determination of which borders in Ukraine, a linear principle has been adopted providing for the establishment of the width of the WPZ within fixed limits, depending on the area of river catchment, the volume of water bodies, and the gradient of adjacent slopes [1]. The provisions of the WCU are mandatory norms [2] and therefore the legislation should establish

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uniform methodological approaches that ensure unambiguous results of determining the width of the WPZ. At the same time, numerous legal actions in recent decades indicate the possibility of ambiguous interpretation of the provisions of the WCU, which is largely due to the ambiguity of the interpretation of hydrological terminology and the lack of regulatory classifications of natural and artificial water bodies according to their hydrographic characteristics. A number of legal inconsistencies in individual provisions of the WCU are due to the lack of a comprehensive, institutionalised classification of water bodies in Ukraine, as well as a glossary that ensures the unambiguity and impartiality of interpretations of hydrological terminology.

The aim of the research is to improve the existing hydrological terminology and classification of water bodies to ensure their unambiguous interpretation in the implementation of the requirements of the water legislation of Ukraine.

Analysis of recent research and publications. The main regulatory documents with definitions of hydrological terminology in Ukraine are DSTU 3517:2024 [3] and Article 1 of the Water Code of Ukraine [4]. A more extensive list of terms is given in the Hydrological Dictionary [5]. The classification of rivers given in Article 79 of the WCU was adopted on the basis of the Soviet classification based on catchment area, which was reflected in the Soviet state standard GOST 19179-73 "Land Hydrology. Terms and Definitions" published in 1975. Before that, classifications based on river length were more widely used, in particular, the classification of V. M. Rodevych, which, in addition to the categories of small, medium, and large rivers, also included the category of the smallest river (for rivers up to 25 km long). In most countries of the European Union, the classification of rivers based on catchment area is adopted according to the typology given in the EU Water Framework Directive 2000/60/EC (WFD) [6]. This typology, compared to the Ukrainian classification, additionally includes the category of "very large rivers" and differs significantly regarding the boundaries of catchment areas compared to the boundaries adopted for river categories in Ukraine. According to the mentioned typology, small rivers include rivers with a catchment area starting from 10 km^2, while in the Ukrainian classification there is no lower limit for river gradation. It should be noted that in connection with the implementation of the provisions of the WFD into Ukrainian legislation, work on auditing rivers in Ukraine according to the criteria of the European Union is already underway [7, 8], in particular, in the process of determining surface water bodies in accordance with the Methodology approved by the Ministry of Ecology and Natural Resources of Ukraine in 2019 [9].

According to WCU, for all lakes, regardless of their parameters, the WPZ width is 100 m, and the WPZ around artificial reservoirs is determined depending on the volume of filling and the category of the river, on which they are built. Their classification depending on morphological parameters is absent in Ukrainian legislation. Generally accepted classifications of lakes, ponds, and reservoirs are also absent in Ukrainian scientific publications, where different authors use individual gradations of morphological parameters of water bodies. Particularly, for the lakes of Ukrainian Polissya L.V. Ilyin proposed a classification that includes 7 categories: from very small (area less than 0.1 km^2) to the largest (area more than 20 km^2) [10, 11]. For reservoirs and ponds, the most common classifications are the ones of V.K. Khilchevsky and V.V. Greben. The classification of reservoirs includes 6 categories depending on their volume: from small (less than 0.01 km^3) to the largest (more than 50 km^3) [12]. The classification of ponds includes 5 categories depending on their area: from very small (less than 2 ha) to very large (more than 50 ha) [13].

Outside Ukraine, there is also no unified classification of water bodies, and different countries use individual criteria for their typification [14, 15]. In the countries of the European Union, for lakes, as well as for the rivers, the WFD typology is used, which is based on the average depth (3 categories) and the area of water surface (4 categories). The lower limit of lake area according to the WFD is 0.5 km^2 [6]. There is no lower limit for the depth of lakes in the typology. An original approach for water bodies classification, based on simultaneous consideration of the depth and area of water bodies, was proposed in India. The category of water bodies is determined by a coefficient calculated from the ratio of average depth and the square root of water surface area [15].

Research methodology. The results of the work were obtained on the basis of an information-analytical research method, which consisted in the analysis of numerous legal actions in Ukraine, which arose as a result of ambiguous interpretations by the parties of conflicts of the normative hydrological terminology and imperfect classification of water bodies. As a result, we formed the proposals and recommendations for their resolution.

Research results and their discussion. Article 1 of the Water Code of Ukraine, which defines the principal terms used in this legislative act, does not provide a definition of the term "*river"* itself, nor does it define other watercourses referred to in the Code, including "*streams"* (Articles 3 and 88) and "small *watercourses"* (Articles 87 and 88). According to DSTU 3517:2024 [3], as well as the Hydrological Dictionary [5], a river is a watercourse of **significant** size that is fed by precipitation from its catchment and has a clearly defined riverbed. This definition does not provide a clear answer to the question of what a river is, since it does not indicate from what specific catchment area or length a surface watercourse acquires **significant** dimensions. Based on this definition, permanent and temporary watercourses of insignificant sizes are not rivers, and the threshold geometric parameters of streams and small watercourses, which are referred to in Article 88 of WCU, are absent from the regulatory framework of terms and definitions in Ukraine.

The definition of a stream in DSTU 3517:2024 as "a small permanent or temporary watercourse", as well as the definition in the Handbook [16] as "a small permanent or temporary watercourse formed by the flow of melted snow or rainwater, as well as by the emergence of groundwater to the surface (length – from several hundred metres to several kilometres)", also does not reflect the boundary between a stream and a small river. In addition, in the aforementioned handbook, the terms "stream" and "small watercourse" are listed as synonyms, while according to the WCU they are different terms. DSTU 3517:2024 defines the term "water stream" as "*a water body characterised by the movement of water in the direction of the slope along a depression on the Earth's surface*," that is, it is broader than the term "river" and covers all terrestrial water streams.

According to the Water Code of Ukraine, the classification of the country's rivers provides for their division into three categories, which are determined depending on the catchment area of their basins. The category of small rivers includes all watercourses with a catchment area of up to 2,000 km^2, i.e. this category includes both rivers with a length of tens of kilometres and streams or small watercourses. The mentioned classification of rivers does not correspond to the classification of the Water Framework Directive, adopted in the European Union and used to determine surface water bodies also in Ukraine according to Appendix 3 of the Methodology [9]. According to Annex II of the WFD (paragraph 1.2.1, system A), for rivers with a catchment area (S) of up to 2000 km^2 ("small rivers", according to the WCU), 3 types of rivers are provided: "small" – S = 10–100 km^2; "medium" – S = 100–1000 km^2, and, partially, "large" – S = 1000–10000 km^2. Accordingly, streams with a catchment area of up to 10 km^2 according to the European typology are not classified as rivers, and the categories of "small rivers" according to the WCU correspond to the WFD types of "small" and "medium" rivers, as well as, partially, "large" rivers with catchment areas of 1000 to 2000 km^2.

The Catalogue of Rivers of Ukraine [17] and the monographs "Materials on River Typification of the Ukrainian SSR" [18] and "Surface Water Resources of the USSR. Hydrological Knowledge" [19] include all rivers of Ukraine with a length of more than 10 km. The area of rivers with a length of less than 10 km mostly does not exceed 100 km^2 and can be classified into the new category of "very small rivers". If the catchment area of a watercourse is less than 10 km^2, it can be classified as a "stream" or "small watercourse". Streams should be classified as watercourses that flow exclusively within river floodplains or on the slope of the first above-floodplain terrace. To ensure a uniform approach to the classification of watercourses by catchment area, the term "stream" may be replaced by "small water stream" or "small watercourses", referring to watercourses with a catchment area that does not exceed 0.2 km^2.

Taking into account the above-mentioned, the following classification of small watercourses in Ukraine is proposed:

- streams are permanent or temporary water streams originating from groundwater springs, flowing within river floodplains and along the slope of the first above-floodplain terrace, that have a catchment area of up to 0.2 km^2;
- watercourses are permanent or temporary water streams with a catchment area that does not exceed 10 km^2, the major part of which is located outside the river floodplain;
- very small rivers are permanent or temporary water streams with a catchment area from 10 km^2 to 100 km^2 ;
- small rivers are permanent or temporary water streams with a catchment area from 100 km^2 to 2000 km^2.

According to Article 88 of the WCU, regardless of size and hydrological regime, for all rivers with a catchment area up to 2,000 km^2, the required width of the WPZ is 25 m or 50 m where a slope gradient is more than 3°. Taking into account the proposed classification, it is advisable to revise the gradation of WPZs, specifically by establishing the width of 5 m for streams (small water streams), 10 m for watercourses, and 15 m for very small rivers, with these widths doubled where the slope gradient exceeds 3°. The justification of the proposed values of WPZ width for the smallest categories of water streams is based on an analysis of their hydrological role, the intensity of anthropogenic impact, and the actual spatial extent in the landscape. For streams (with the WPZ width of 5 m), which flow predominantly within floodplains or along the slopes of the first above-floodplain terrace, the primary environmental protection function is to preserve their water sources and prevent local sedimentation. A width of 5 m is sufficient to form a natural grass and shrub buffer that stabilises the banks without excessive land extraction. For streams with a catchment area of up to 10 km², increasing the width of the WPZ to 10 m provides the minimum required distance for filtering surface run-off from adjacent arable lands, reducing sediment input, and maintaining microclimatic conditions in the mouth areas. For very small rivers with a catchment area of 10–100 km², the proposed width is a compromise between ecological efficiency, hydro-morphological features, and economic feasibility, as increasing the WPZ to 25 m for this category would result in losses of agricultural land disproportionate to the ecological effect. The proposed gradation is consistent with the practice of the EU countries (Poland, Germany, Czech Republic), where for watercourses with a catchment area of <10 km², the width of buffer strips is usually 5–15 m, depending on the type of land use.

A major challenge in delineating WPZ boundaries is determining the elevation reference point that serves as the starting point for calculating slope gradient. In accordance with Article 88 of the WCU, waterside protection zones shall be established along the banks of rivers and around water bodies, extending from the waterline (during the low-water period), regardless of the characteristics of the riverbank, including its configuration and height. For rivers with a slope gradient over 3°, the width of the WPZ doubles, which is due to the higher speed of run-off and, accordingly, a decrease in the time for infiltration of surface waters and a decrease in the level of their natural purification. The shape of river banks primarily depends on the morphological structure of river valleys (type of river valley [20]), soil rocks from which the bank slope is formed, riverbed processes, intensity of wind and wave phenomena, morphological parameters of the riverbed. When determining the boundaries of WPZs, the most important characteristics of the riverbank are its geometric parameters, particularly the height and width of the upper bank slope above the low-water level, the ratio of which determines the gradient of the riverbank slope. In this context, the width of the upper bank slope is defined as the horizontal distance from the low-water level line to the crest of the riverbank slope, i.e., the line marking a distinct break in the bank profile that separates its lower steep section from the floodplain. The waterside protection zones of rivers (except for rivers with gorge-like valleys, where the riverbank slope gradually transitions into a mountain slope) includes the width of the bank slope above the low-water level, whose gradient is always greater than 3°, as well as part of the floodplain. On rivers with steep banks, the waterside protection zones are located almost entirely within the floodplain; therefore, the provision of the WCU stating that "if the slope gradient exceeds 3°, its width is doubled" is incorrect. A more appropriate formulation is "if the slope of the waterside protection zones exceeds 3°, its width is doubled".

In the lowland rivers of Ukraine, riverbed forms are predominantly parabolic and trough-shaped (Fig. 1), with either steep, cliffy, or landslide-prone banks (Fig. 2), or gently sloping banks (Fig. 3). Less commonly, river sections with gorge-like or weakly developed trough-shaped riverbeds occur (Fig. 4). The latter is mostly observed in small lowland rivers with swampy floodplains, whose riverbeds "disappear" within marshy floodplain areas. Various riverbed types may be present even within short segments of the same river, particularly in meandering rivers. According to the WCU, for all of them, the width of the WPZ is measured from the low-water level line. At the same time, the WCU does not specifically indicate from which elevation reference point the slope gradient should be determined, in particular whether it is from the waterline or from the bank crest. The lack of clarity in interpreting the determination of slope gradient leads to legal disputes that often arise in judicial practice when deciding on the requirement to double the width of the WPZ in cases where slope gradient exceeds 3°. Furthermore, Article 1 of the WCU defines the waterline as the boundary of water along the bank of a water body (the coast-line). The clarification placed in brackets, "the coast-line", introduces additional uncertainty, since according to the hydrological dictionary, the coast-line is the boundary between the land and the water surface of a watercourse or water body, which, due to the continuous variation in the elevation (level) of the water surface, forms a more or less **wide stripe** [4].

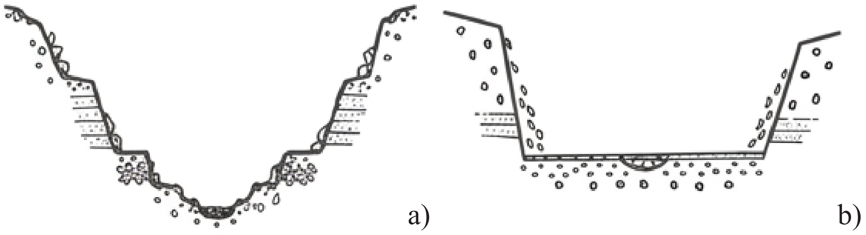

Fig. 1. Riverbeds with a terraced parabolic riverbed (a) and a trough-shaped riverbed (b) [20]

Fig. 2. Steep and landslide-prone banks of the Desna river

Fig. 3. Gently sloping banks of the Desna riverbed

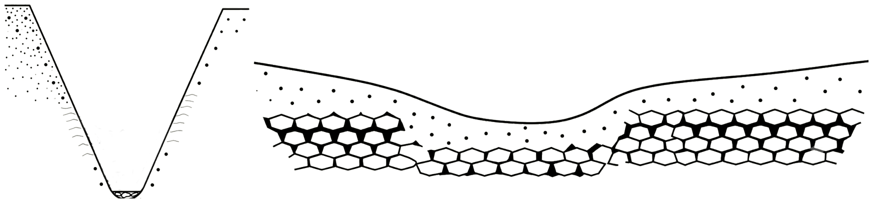

Fig. 4. Gorge-like and weakly expressed trough-shaped riverbed [20]

In practice, in river sections with vertical and steep banks, slope gradient is determined from the coast-line level (without considering the elevation difference between the waterline and the riverbed crest), while in very gently sloping and weakly defined riverbeds it is measured from the waterline. This is entirely logical, since for rivers with steep banks, the distance between the waterline and the bank crest is negligible and therefore has virtually no effect on the width of WPZ. However, in sections with very gently sloping banks, this distance may be of the same order of magnitude as the width of the WPZ. However, such an approach is not legally defined, and parties involved in legal actions, who are interested in doubling the width of WPZ insist on determining slope gradient specifically from the low-water level mark, referring to the WCU. In such cases, on small rivers with a flat floodplain and a steep bank with vertical or very steep slopes, the width of WPZ will be 25 m only if the height of the slope from the waterline to the bank crest is less than 1.31 m; otherwise, when the height of the dry bank slope is greater, the WPZ width should be doubled. For medium-sized rivers, the width of the WPZ under conditions of a horizontal floodplain will be 50 m if the slope height (from the low-water level to the floodplain elevation at a distance of 50 m from the waterline) does not exceed 2.62 m, while for large rivers the WPZ width will be 100 m if the height of the riverbank slope is up to 5.24 m. For higher banks, the width of the WPZ must be doubled. Thus, in river sections with identical floodplain morphological conditions, the WPZ width may differ by a factor of two depending on the bank height. For example, on the section of the Desna river shown in Fig. 2, the width of the WPZ, when slope gradient is measured from the waterline, will be 200 m, of which 197 m corresponds to the floodplain and only about 3 m to the river bank. When slope gradient is measured from the riverbed crest, the width of the WPZ will be twice as small. Another important issue in determining slope gradient is the adoption of a specific scale for detailing the slope micro-relief, as noted in the study [21].

An important term contributing to the ambiguity in delineating WPZ boundaries is the term "low water" (the low-water period). In accordance with Article 1 of the WCU, low water (the low-water period) is defined as the period of the annual cycle during which low flow conditions occur. According to [3] and [5], low water is a phase of a river's hydrological regime that recurs annually in the same seasons and is characterised by low flow, formed as a result of reduced river feeding, which is mainly sustained by groundwater drained by the hydrographic network. The low-water period may be winter and summer-autumn, or only summer. The Water Code does not specify which low-water period should be used when calculating WPZ, although these periods may differ significantly. The issue is caused by the fact that the low-water level is not a constant value. Low-water levels in rivers and water bodies may differ significantly not only between different low-water phases, but also between different months and years within the same phase of the hydrological regime. In particular, the average low-water level of the Desna river at the Chernihiv gauging station during the winter periods of 1996–2010 was 320 cm above the gauge zero, while during the summer–autumn periods it was 206 cm, i.e., 1.16 m lower. For the same period, the amplitude of summer–autumn low-water levels was 152 cm; in particular, the level in 2010 was 125 cm, while in 2006 it was 277 cm (see table 1). The width of the Desna River at the Chernihiv hydrological gauging station is 118 m at the water level of 125 cm, and 145 m at the level of 277 cm, i.e., 27 m wider. In river sections with more gently sloping banks, this difference in width increases significantly.

The determination of the low-water level is particularly problematic for small and medium-sized rivers with a high degree of flow regulation, where, in the downstream sections of ponds and reservoirs, only environmental flow is discharged during low-water periods, which in most cases does not exceed the minimum monthly flow in a year with 95% probability of exceed in the average annual flow. In such cases, the water stream occupies only part of the riverbed, while the unfilled riverbed zone becomes part of the WPZ, according to the WCU (Fig. 5 and 6), thereby reducing its floodplain part.

Average monthly water levels of the Desna river at the Chernihiv gauging station during low-water periods (cm), gauge zero 102.44 m a.s.l. (Baltic System)

Year	**December**	**Winter low-water period**				**Summer low-water period**				
		December of the previous year	**January**	**February**	**average**	**July**	**August**	**October**	**November**	**average**
1996	247		267	234	251	178	143	137	173	158
1997	306	247	234	233	238	198	183	148	209	185
1998	431	306	381	329	339	239	253	259	301	263
1999	303	431	426	436	431	210	223	227	242	226
2000	338	303	367	378	349	247	273	245	263	257
2001	285	338	383	430	384	296	209	200	224	232
2002	275	285	299	405	330	153	128	122	218	155
2003	285	275	237	245	252	198	192	232	249	218
2004	263	285	326	283	298	289	247	182	207	231
2005	317	263	331	361	318	363	257	180	181	245
2006	362	317	375	316	336	270	219	294	324	277
2007	284	362	349	413	375	180	174	158	197	177
2008	279	284	304	280	289	202	171	146	173	173
2009	273	279	315	357	317	200	161	135	154	163
2010	248	273	314	289	292	153	106	111	128	125

a) b)

c) d)

Fig. 5. Low-water riverbeds of the Khorol river (a), the Rostavytsia river (b) and its tributary Pavolochka (c), and the Sovka river in Kyiv (d)

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Fig. 6. Low-water riverbed of the Ros river above the confluence with the Skvyra river

In recent decades, under conditions of a significant reduction in run-off, at many reservoirs during the summer–autumn period the requirements for mandatory environmental flows stipulated by operating rules and Article 76 of the WCU are either not met or are implemented only partially. In many cases, bottom outlets are completely silted up, spillway gates are inoperative, hoisting mechanisms have been removed, and spillway shaft openings have been sealed; consequently, outflow to downstream reaches occurs only through overtopping of the shaft walls during periods of intense and prolonged precipitation (Fig. 7). As a result, in river sections between ponds, riverbeds replenishment during low water occurs only through seepage through the dam body and local runoff from the inter-pond area (Fig. 8).

The reduction in run-off resulting from increased evaporation, ploughing and development of the upper parts of small river catchments, road construction without adequate culverts, siltation of riverbeds and water bodies, excessive withdraw of flow for economic purposes, and other anthropogenic factors has led to a sharp shallowing of rivers, resulting in the complete desiccation not only of riverbeds but also of ponds that were still full of water at the end of the previous century (Fig. 9). Their partial and short-term filling occurs only during spring floods or very intense flood events. Due to the absence of flow during low-water periods, delineating the boundaries of WPZ from the low-water level becomes impossible for such water bodies.

As privatisation of lands in river valleys under Ukrainian legislation is permitted only outside the lands of the water fund, in cases where information is absent from the State Land Cadastre and cadastral maps, the classification of parcels of former riverbeds, vanished water bodies, dried-up areas of shallowing (or disappearing) lakes, and the associated WPZ as lands of the water fund becomes a matter of prolonged court disputes. Accordingly, to avoid legal ambiguity in the interpretation of such controversial situations, it is necessary to establish a fixed value of the low water levels for permanent watercourses and reservoirs, as well as to adopt other approaches to establishing the internal boundary of the WPZ for temporary, drying up or disappeared (with the prospect of restoration) water bodies.

The fixed low level can be taken as its average value for the observation period, for the period of the modern climate norm (1990-2020), for recent decades, etc. It is advisable to set the average level value for the period from July to September, when the lowest levels are observed on the most of the rivers.

Fig. 7. Damaged spillway structure and empty spillway shaft at ponds in the riverbed of the Pavolochka river

Fig. 8. Downstream sections of the Kosiv reservoir dam and the pond dam in the village of Shamraivka on the Rostavytsia river

Fig. 9. Dried-up ponds on the Menzheliia river near the village of Vesela Dolyna

Another option is to take the low water level as the water level in the river with a specifically defined probability of exceeding it (as an option – 90% or 95% of the average annual flow).

The determination of the low-water level at specific cross-sections located away from hydrological gauging stations should be carried out taking into account the river slope along the section between the cross-section and the gauging station. For the rivers where hydrological observations are unavailable, the determination of the long-term average low-water level is possible on the basis of estimating the average annual discharge with a probability corresponding to low-water levels (using observation data from similar rivers), in accordance with the standard methodology for calculations in the absence of hydrometric observations [22], and by means of hydrological calculations to determine water levels using the Chezy–Manning equation together with data obtained from direct hydrometric surveys at the specific cross-sections.

Determining low-water levels using the above-mentioned methodology significantly complicates the process of WPZ boundaries delineation. Therefore, in the absence of direct observations of low-water levels, it is advisable to measure the width of WPZ from the bank crest of rivers and lakes, particularly where the bank slope exceeds 30°. In such a case, Article 1 of the WCU should be amended to include a definition of the term “bank crest” as the line separating a riverbank from its floodplain. For the ponds and reservoirs, it is advisable to adopt, as a fixed low-water reference level, either the normal retention level (NRL) established by the operating rules or the flood retention level (FRL), which is close to the maximum reservoir storage level. For the lakes with gently sloping banks, as well as in cases where the surface area of the water body decreases substantially during the low-water period, the inner boundary of WPZ may be defined as the boundary of aquatic vegetation overgrowing the lake bed.

Article 88 of the WCU states that waterside protection zones are established for rivers regardless of the duration and frequency of their filling. In hydrological practice, the question often arises whether waterside protection zones should be established along temporary or drying rivers. This issue is particularly relevant in mountainous regions of Ukraine, where the riverbeds of low-order tributaries are filled primarily during floods and intense high-water events, as well as in the southern steppe regions, where rivers may dry for the long periods during low-water conditions. According to DSTU 3517:2024, temporary watercourses are those, in which water flow is observed for less than half of the year. This is understandable from a hydrological perspective; however, in legal practice it is necessary to establish a specific period of flow occurrence during the year, averaged over a long-term observation period, since even the largest rivers of the Azov region and Crimea have experienced short periods of complete flow cessation or prolonged periods, during which the river flowed only as a narrow stream occupying a small portion of the riverbed. In the absence of regular hydrological observations on small watercourses, determining whether a watercourse is permanent or temporary is, in many cases, practically impossible. This issue can be addressed through the creation of a unified register (catalogue) of small watercourses within river basins, containing their hydro-morphological characteristics and designated classifications: temporary or permanent stream, watercourse, or small river. The creation of such a catalogue would be advisable on the basis of the State Register of Geographical Names maintained by the State Service of Ukraine for Geodesy, Cartography and Cadastre, in accordance with subparagraph 30 of paragraph 4 of the Regulation on the State Service of Ukraine for Geodesy, Cartography and Cadastre, approved by Resolution No. 15 of the Cabinet of Ministers of Ukraine dated 14 January 2015.

The structure and conciseness of legislative acts do not permit the direct incorporation of the proposed modern methodological approaches to delineating WPZ boundaries into the articles of the Water Code, as these approaches require specific algorithms for hydrological calculations and geodetic measurements. For their practical implementation, it is necessary to develop separate methodological guidelines, adopted at the regulatory level, that would take into account the specific characteristics of river hydrological regimes and riverbeds morphology.

With the entry into force of the Methodology for the Delineation of Surface Water and Groundwater Bodies [9], the provisions of the WFD concerning the determination of lakes types by water surface area were incorporated into Ukrainian legislation. According to this classification, lakes are divided into small lakes with a surface area of 0.5–1 km²; medium-sized lakes with a surface area of 1–10 km²; large lakes with a surface area of 10–100 km²; and very large lakes with a surface area exceeding 100 km². Accordingly, natural closed water bodies with a water surface area of less than 0.5 km² are not taken into account when delineating surface water bodies. According to the WCU, unlike ponds, all lakes are assigned the same width of WPZ, regardless of their size. This is primarily due to the absence of water exchange in closed water bodies, in contrast to riverine water bodies. The processes of self-purification and self-regulation in such water bodies are significantly slowed and occur mainly due to groundwater inflow. The Water Code does not specify minimum size thresholds for lakes requiring the establishment of waterside protection zones. In such cases, strictly adhering to the requirements of legislation, the WPZ with a width of 100 m, or even 200 m (where slope gradient exceeds 3°), must be established even around very small and shallow natural closed water bodies, commonly referred to as "large puddles". In practice, this leads to restrictions on the economical use of large areas of productive agricultural land. Accordingly, taking into account the above-mentioned lake typology [6,9], in order to delineate the outer boundary of water fund lands, it is advisable to introduce a new category ("type", in accordance with the WFD) – "very small lakes" with a water surface area ranging from 0.005 km^2 to 0.5 km^2 (0.5 ha to 5 ha), and to establish the WPZ width of 25 m for them, as for the small rivers. For the small lakes with a water surface area from 0.5 to 1 km^2, the width of the WPZ should be set at 50 m, while for all other types (medium-sized, large, and very large, according to the Methodology [3]) the WPZ width may remain 100 m, as defined in Article 88 of the WCU.

For water bodies with a water surface area of less than 0.005 km^2, the establishment of the WPZ is not required, if their depth during the low-water period does not exceed 3 m ("shallow lakes" according to the WFD classification). Similar restrictions should also be introduced for ponds, since according to the definition in Article 1 of the WCU, they include all artificially created water bodies with a capacity not exceeding 1 million m^3. Accordingly, under a strict interpretation of this principle, the waterside protection zones would have to be established even around individual swimming pools or water-filled household excavations. Since the width of the WPZ around ponds with an area of less than 3 ha is determined depending on the category of the rivers, on which they are constructed, it is necessary to normatively establish only their minimum area, approximately, as for lakes, at 0.005 km^2. Smaller water bodies may be classified as basins, if they do not fall under the category of technological water bodies.

Article 3 of the WCU stipulates that the lands of the water fund of Ukraine include artificial water bodies (reservoirs and ponds) and canals, except the canals within irrigation and drainage systems. At the same time, in 2013, following the adoption of the Law of Ukraine 'On Aquaculture', the term "technological water body" was introduced into Article 1 of the WCU. It refers to a water body artificially created for a special technological purpose, defined by a technical project and/or passport, which is filled artificially using hydraulic structures and facilities. Previously, such technological water bodies as irrigation storage reservoirs, settling ponds, fire-fighting basins, cooling basins for energy facilities, and fish-farming water bodies were classified as "ponds" and, accordingly, belonged to the lands of the water fund, and the WPZ had to be established around them in accordance with Article 88 of the WCU. With the introduction of the term "technological water body" into the WCU, the above-mentioned water bodies now form a separate category of water bodies created to serve specific production purposes that differ from ponds by their specific functional designation, which is defined by a technical project or passport. The Water Code does not explicitly state that this category of the water bodies **does not** belong to the lands of the water fund, as is specified for the canals within irrigation and drainage systems. This has led to legal disputes, and in order to resolve them it is necessary to ensure legislative clarity regarding the classification of technological water bodies as part of the water fund. In particular, paragraph 4 of clause 1 of Article 3 of the WCU should specify either that the water fund of Ukraine includes "artificial water bodies (reservoirs, ponds, **technological water bodies**…)" or that it includes "artificial water bodies (reservoirs and ponds), the canals, except the canals within irrigation and drainage systems, **and technological water bodies"**, depending on the adopted regulatory decision. Another option is to designate their inclusion in the water fund within the definition of the term "technological water body" in Article 1 of the WCU itself.

The most part of the existing classifications of the lakes based on their origin includes a category of "quarry-type lakes"; however, according to Article 1 of the WCU, the lakes may be of natural origin only, and therefore quarry-type water bodies are classified as ponds, despite the fact that in terms of their hydrological regime, water exchange, and feeding conditions they are practically indistinguishable from the lakes. Accordingly, the boundaries of WPZ around the quarry-type water bodies, as well as the other artificially created enclosed non-technological

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water bodies, should be defined in the same way as for the lakes.

In accordance with Article 88 of the WCU, along seas and around sea bays and estuaries, a waterside protection zone shall be established with a width of not less than 2 km from the waterline. This article does not mention such a water body as a lagoon (a closed estuary [9]), which, according to the dictionary [4], is an elongated, shallow water body along the coast with saline or brackish water, connected to the sea by one or several channels or separated from it by a sandbar; in other words, it differs from an estuary only in the part that it is not totally open to the sea. Such water bodies include a number of water bodies in the interfluve between the Danube and the Dniester, in particular the Budak Estuary, the Tuzly Estuaries, and others, which are differently referred to in maps and reference sources either as estuaries, lakes, or lagoon-type estuaries (Fig. 10). The WCU does not contain the term “lagoon” or “closed estuary”; therefore, when determining the width of a waterside protection zone, the question arises whether it should be set at 100 m, as for a lake, or at 2 km, as for an estuary.

Article 1 of the WCU defines an estuary as “a river valley or ravine mouth inundated by **sea waters**”. From this definition, it follows that this term refers to inundated river-mouth sections only of those rivers that flow into the sea. The term “river estuary” is absent in the regulatory framework, which creates legal uncertainty in judicial practice whether river mouths inundated by water reservoirs should be considered as the part of the river or of the reservoir (e.g., the Teteriv, Stuhna, Sula, Samara rivers, etc.). For example, if the width of the WPZ along the mouth of the Stuhna river is calculated as for a river, it will be 25 m, whereas if it is calculated as for a reservoir, it will be 100 m. The water level regime of such sections is similar to that of reservoirs; in fact, they constitute parts of reservoirs, and therefore the WPZ for them should be determined from the inundation threshold at the normal retention level (NRL) (or flood retention level, FRL) of the reservoir. Accordingly, hydrological terminology should be supplemented with the terms “marine estuary” and “river estuary”, and the definition of an estuary in Article 1 of the WCU should be revised as follows: “*a river valley or gully mouth inundated by sea waters, reservoir waters, or pond waters*”. Appropriate amendments should also be introduced to Article 88 of the WCU. For polder-type estuaries (e.g., the Irpin, Trubizh, and Tiasmyn rivers), the width of the WPZ should be determined as for rivers, as their hydrological regime more closely corresponds to that of the river systems.

Study limitations and prospects for further research. The limitations of the conducted research lie in the predominant use

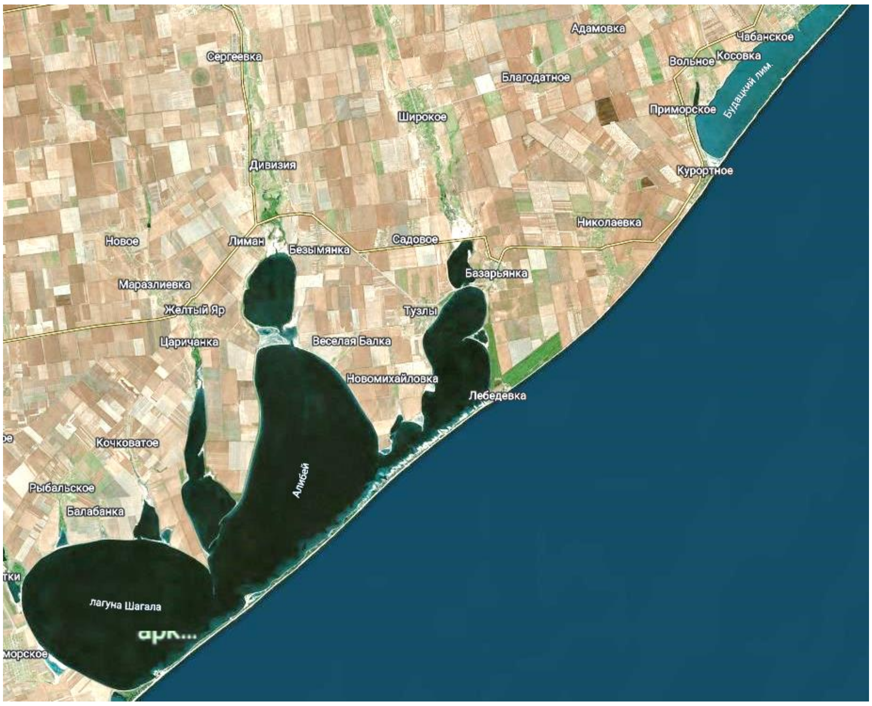

Fig. 10. The Budak and Tuzly estuaries (lagoons)

of an information-analytical method based on the analysis of legal actions and regulatory frameworks, without the involvement of extensive field measurements. The proposed classification approaches require further validation at the regional scale, taking into account the diversity of natural conditions of Ukraine. The future research prospects lie in the development of comprehensive regulatory and methodological guidelines integrating hydrological, geomorphological, and legal aspects, as well as in the creation of a unified database of small watercourses and water bodies to ensure transparency and unambiguous determination of their legal status.

Conclusions. The analysis of the provisions of the Water Code of Ukraine has shown that most legal conflicts in the delineation of waterside protection zones are caused by the absence of a clear classification of water bodies and by the ambiguity of terminology. The lack of clear definitions of the terms “river”, “stream”, “small watercourse”, “low water”, “slope gradient”, “lagoon”, and others creates conditions for divergent interpretations in law enforcement and judicial practice.

The necessity of classifying small watercourses with the identification of such categories (types) as “streams”, “watercourses”, “very small rivers”, and “small rivers” has been substantiated. This will allow to introduce a differentiated approach to determining the width of waterside protection zones and to minimise the unjustified withdrawal of land from economical use, while maintaining environmental effectiveness.

One of the key problems is the absence of a unified approach to the determination of the low-water level and the reference point for measuring slope gradient. Due to the difficulties in calculating the variable low-water level, an alternative approach is proposed for determining the width of waterside protection zones from the bank crest or the normal or flood retention level for artificial water bodies.

The need for regulatory clarification of the status of temporary and drying watercourses through the creation of a state register of small watercourses has been identified. The classification of lakes by water surface area has also been substantiated, along with the clarification of the legal status of technological water bodies, quarry-type water bodies, river estuaries, and lagoons.

The implementation of these approaches requires the development of regulatory and methodological guidelines that take into account the hydrological regime, valley morphology, and clear algorithms for geodetic calculations.

Conflicts of interest: the authors declare no conflict of interest.

Use of artificial intelligence: the authors confirm that they did not use artificial intelligence technologies during the creation of this work.

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АКТУАЛЬНІ ПИТАННЯ ГІДРОЛОГІЧНОЇ ТЕРМІНОЛОГІЇ ТА КЛАСИФІКАЦІЇ ВОДНИХ ОБ'ЄКТІВ У КОНТЕКСТІ ВОДНОГО ЗАКОНОДАВСТВА УКРАЇНИ

О.М. Козицький[1], А.М. Шевченко[2], канд. с.-г. наук, І.А. Шевченко[3], канд. техн. наук, О.О. Сидоренко[4], канд. с.-г. наук

[1] Інститут водних проблем і меліорації НААН, Київ, 03022, Україна
https://orcid. org/0000-0002-4459-6331; e-mail: olegkoz@ukr.net;
[2] Інститут водних проблем і меліорації НААН, Київ, 03022, Україна
https://orcid.org/0000-0002-2637-6538; e-mail: monitoring_protect@ukr.net;
[3] Інститут водних проблем і меліорації НААН, Київ, 03022, Україна
https://orcid.org/0000-0002-7401-8786; e-mail: irashef@ukr.net
[4] Інститут водних проблем і меліорації НААН, Київ, 03022, Україна
https://orcid.org/0000-0002-7377-6809; e-mail: 63059@ukr.net;

Анотація. *У результаті аналізу юридичних проблем, які виникають при реалізації положень Водного кодексу України щодо забезпечення природоохоронного режиму на землях водного фонду встановлено, що вони значною мірою зумовлені неоднозначністю трактування гідрологічної термінології та відсутністю нормативних визначень окремих гідрологічних термінів, що використані або не наведені у Водному кодексі, зокрема, таких понять як річка, потічок, струмок, межень, крутизна схилу, лагуна, річковий лиман тощо. Використання лінійного принципу при визначенні зовнішньої межі прибережних захисних смуг вимагає встановлення фіксованих значень точок відліку їх ширини та крутизни схилу, тоді як меженний рівень, що згідно з Водним кодексом є внутрішньою межею прибережних захисних смуг, не має постійного значення і може значно змінюватися як у різні роки, так і протягом одної межені. Крім того, встановлення його середнього багаторічного значення за відсутності тривалих спостережень на річках є практично неможливим. Оскільки положення Водного кодексу є імперативними нормами, для недопущення їх різнобічного трактування в статті запропоновані новітні методичні підходи щодо встановлення меж прибережних захисних смуг з урахуванням гідроморфологічних умов річкової долини. Іншою причиною юридичних проблем при встановленні меж прибережних захисних смуг є відсутність у Водному кодексі класифікації природних і штучних водойм, зокрема, нижньої граничної межі площі водозбору малих річок, а також площі чи глибини озер і ставків. На основі виконаних досліджень запропоновано доповнення до класифікації річок, що наведена у Водному кодексі, а також класифікація озер за площею водного дзеркала, що забезпечить диференційований підхід до визначення ширини прибережних захисних смуг окремих категорій малих водотоків і водойм. Внесено пропозиції щодо змін і доповнень до глосарію гідрологічної термінології, що наведений у Водному кодексі України. Для практичної реалізації нових методологічних підходів до визначення меж прибережних захисних смуг запропоновано розробити окремі нормативно-методичні рекомендацій, які враховували б особливості гідрологічного режиму річки і морфології русел.*

Ключові слова: *річка, водойма, озеро, ставок, межень, лагуна, прибережна захисна смуга, Водний кодекс, законодавство*

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EFFECTIVENESS OF GROWTH REGULATORS ON IRRIGATED SORGHUM CROPS

Yu.O. Tarariko[1], Dr. of Agricultural Sciences, P.V. Pysarenko[2], Dr. of Agricultural Sciences, R.M. Vasylenko[3], Ph.D. in Agricultural Sciences, R.V. Saydak[4], Ph.D. in Agricultural Sciences, Yu.V. Soroka[5], Ph.D. in Agricultural Sciences, I.O. Bidnyna[6], Ph.D. in Agricultural Sciences

[1] Institute of Water Problems and Land Reclamation of NAAS, Kyiv, 03022, Ukraine;
https://orcid.org/0000-0001-8475-240X; e-mail: urtar@bigmir.net;
[2] Institute of Water Problems and Land Reclamation of NAAS, Kyiv, 03022, Ukraine;
https://orcid.org/0000-0002-2104-2301; email: pavel_pisarenko74@ukr.net;
[3] Institute of Climate-Oriented Agriculture of NAAS, Odesa, Ukraine;
https://orcid.org/0009-0000-1903-4444; e-mail: ruslan-18a@ukr.net;
[4] Institute of Water Problems and Land Reclamation of NAAS, Kyiv, 03022, Ukraine;
https://orcid.org/0000-0002-0213-0496;e-mail: saidak_r@ukr.net;
[5] Institute of Water Problems and Land Reclamation of NAAS, Kyiv, 03022, Ukraine;
https://orcid.org/0000-0001-6228-4131; e-mail: agroresurs@bigmir.net;
[6] Institute of Water Problems and Land Reclamation of NAAS, Kyiv, 03022, Ukraine;
https://orcid.org/0000-0001-8351-2519; e-mail: irinabidnina@ukr.net

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Abstract. *In the conditions of increasing climatic aridity of the southern region of Ukraine, the relevance of improving grain sorghum cultivation technologies aimed at increasing the efficiency of water use and forming stable crop productivity is increasing. The aim of the study was to determine the impact of growth regulators and complex Nanovit super fertilizer in chelate form on water consumption, the formation of crop structure and grain productivity of grain sorghum under irrigation conditions.*

Field studies were conducted in 2016–2018 at the experimental field of the Institute of Climate-Oriented Agriculture of the NAAS on dark chestnut medium loamy slightly saline soil. The object of the study was the early-ripening grain sorghum variety Pivdenne. The effect of growth regulators Regoplant, Grainactiv-C and Vermystym on the background of N_{90} *application, as well as their combination with foliar feeding with the Nanovit super complex fertilizer, was studied.*

It was found that the use of the studied preparations did not cause significant changes in the total plant water consumption (4104–4296 m³/ha), but contributed to an increase in the efficiency of water use. The lowest water consumption coefficient was obtained with the combined use of the Regoplant preparation and the Nanovit super fertilizer – 477,3 m³/t, which is 32,5% less compared to the control. The use of biostimulants had a positive effect on the formation of crop structure, in particular, it increased the length of the panicle, the number and weight of grains in it, as well as the weight of 1000 seeds. The highest grain productivity was provided by the combined use of the Regoplant preparation with foliar feeding with Nanovit super fertilizer on the background of N_{90} *application, when the grain yield was 9,2 t/ha, which was 55,9% higher than in control variant. Under these conditions, the feed value of the products also increased: the yield of feed units reached 12,4 t/ha, digestible protein – 0,59 t/ha, and the protein content in grain – 10,8%.*

The results obtained indicate the high efficiency of using growth regulators in combination with chelate microfertilizers in the technology of growing grain sorghum under irrigation conditions and confirm the feasibility of their use to increase crop productivity and optimize the use of water resources.

Keywords: *grain sorghum, growth regulators, chelate microfertilizers, irrigation, water consumption, yield, feed value*

Problem statement. In the conditions of climate change in the southern region of Ukraine, characterized by a significant increase in temperature and unstable and insufficient precipitation, the cultivation of drought-resistant and highly productive grain sorghum is of extremely important in grain production. It is successfully used for feeding cattle, pigs, horses, sheep, poultry and pond fish.

In terms of nutritional value, grain sorghum does not differ significantly from barley and corn [9]. Its grain contains up to 80% starch, 12–14% protein, 3,5–4,5% fat, 2,4–4,8% fiber and 1,2–3,2% ash. The energy nutritional value of 100 kg of sorghum grain is 118–130 feed units.

It has been established that sorghum grain is more effective in fattening pigs, which is superior to barley in terms of yield and cost [11]. However, in extreme conditions, the crop yield shortfall, as noted by researchers, can reach 30–40% or more [2].

Increasing the resistance of grain sorghum plants to adverse factors is not always possible to solve by selecting varieties or hybrids adapted to local soil and climatic conditions. The maximal potential crop productivity is possible only by using a complex of optimized modern agrotechnical measures. An important component of the technology of growing grain sorghum, which contributes to increasing the resistance of plants to environmental stress factors and increasing yield, can be the use of foliar feeding with complex fertilizers in the form of chelates and growth regulators. In modern crop production, they are increasingly used due to their sufficient efficiency at minimal water consumption rates. As noted, such preparations protect plants from stress, increase resistance to diseases, stimulate the microbiological activity of the rhizosphere, increase yield and improve product quality [2, 3, 4].

Analysis of recent research and publications. The issue of increasing the adaptability and productivity of sorghum (*Sorghum bicolor L.)* in the context of global climate change occupies a prominent place in modern agronomic research. Considerable attention of researchers is focused on water regime management. In particular, B.A. Asmamaw and K. Georgis [14] prove that the use of special agrotechnical measures in combination with deficit irrigation allows maintaining stable yields of green mass of sorghum, maximizing the efficiency of water use. This approach correlates with the conclusions of A. Farhadi et al. [16], who emphasize that moderate water stress not only saves resources, but can also positively affect the nutritional value of feed depending on the genetic characteristics of the crop.

An important direction is the neutralizing of the impact of abiotic stresses. Studies conducted by M.E. Abu-Ria et al. [12, 13] demonstrate the high efficiency of humic acids as mediators of drought tolerance. It has been established that humic compounds stabilize physiological processes of sorghum at critical reproductive stages, providing higher resistance compared to corn. At the same time, M. Chiranjeevi et al. [15] emphasize the role of rhizosphere bacteria in improving the architectonics of the root system and nutrient uptake under biotic conditions.

Modern nutrition strategies are shifting towards highly available forms of elements. P. Huang [18] and P. Niharika [19] substantiate the advantages of chelated forms of microelements, in particular amino acid chelates, which have a higher absorption rate and act as biostimulants. The role of microelement synergism and growth regulators in the formation of quantitative and qualitative indicators of sorghum yield in different climatic zones is described in detail in the works of Z. Rashid [20] and Zahida R. [21].

Studies by Y. Guo et al. [17] indicate the importance of the microbial component of the soil. It was found that partial replacement of mineral nitrogen with organic fertilizers not only increases yield, but also optimizes the structure of microbial organisms, which ensures the sustainability of the agroecosystem.

According to the results of studies in non-irrigated conditions of the South of Ukraine, treatment of grain sorghum plants with a 0,01% solution of succinic acid during the period of inflorescence formation increased the seed productivity of various hybrids by 10,9–13,0% compared to the control [4].

It was also found that complex fertilizers containing macro- and microelements increase crop resistance to moisture deficit and low and high temperatures, as well as promote the absorption of nutrients from the soil and reduce disease susceptibility [8].

Such fertilizers are produced with a different set of nutrients, which makes it possible to apply them given the conditions and characteristics of a particular crop. The use of a new line of foliar fertilizers Nanovit in the form of EDTA chelates based on the active complex "NANO-ACTIV", to which Nanovit Super belongs, is of particular interest. By the manufacturer's characteristics, Nanovit Super stimulates the growth and development of plants, provides intensive absorption of nutrients from the soil, increases crop resistance to drought, diseases, pests and physiological stresses, and also ensures increased yield and product quality. Its composition includes: N – 122 g/l; K (K_2O) – 61; Mg (MgO) – 30; B – 4,50; Cu – 4.50; Fe – 0,90; Mn – 0,44; Mo – 0,024; Zn – 2,60 g/l.

It has been established that, with full provision of plants with nutrients, sorghum requires a significant amount of productive moisture for the formation of vegetative mass, high grain yield and nutrient output [1]. As researchers note, a large amount of it is used by plants in a critical

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period: 10 days before the start of panicle ejection and within 10 days after flowering. The duration of this period is 20–25% of the growing season, and moisture consumption reaches 45–50% of the total water consumption [5]. Lack of moisture during this period affects the physiological processes and the formation of grain yield [10].

Despite thorough studies of individual factors (irrigation, nutrition, biostimulation), the complex effect of a combination of amino acid chelates and humic preparations against the background of various strategies of deficit irrigation in the conditions of specific soil and climatic zones of Ukraine remains insufficiently studied. The efficiency of moisture use by a crop is reflected by the coefficients of water consumption (the amount of water that ensures the formation of a unit of yield) and irrigation efficiency (the amount of water that ensures an increase in yield compared to non-irrigated conditions), as well as the indicator of water use efficiency (the amount of production that a unit of moisture used forms). All of them depend on the amount of total water consumption during the growing season and crop yield [7]. However, the effect of the studied stimulating preparations on water consumption and productivity of grain sorghum under irrigated conditions of the southern region of Ukraine remains unstudied.

Research objectives and methods. The research objective was to determine the effect of growth regulators and complex fertilizer in chelated form Nanovit super on water consumption, grain yield and feed value of grain sorghum under irrigation conditions.

Field and laboratory studies were conducted according to the methods of the research work in 2016–2018 on irrigated lands of the Institute of Climate-Oriented Agriculture of the NAAS of Ukraine [6, 7]. Soils were dark chestnut, slightly saline, medium loamy with a humus layer depth of 45–50 cm. The humus content in the arable soil layer (0–30 cm) was 2,8–3,4%, hydrolyzed nitrogen – 4,5–5,5%, mobile phosphorus – 4,0–6,0 mg, exchangeable potassium – 40 mg/100 g of soil. The lowest moisture content in 0–50 cm soil layer was 23,2%, in 0–100 cm soil layer was 21.5%, and in 0–150 cm soil layer was 21,3%. The wilting moisture content was 11,4; 11,6; 11,9% compared to absolutely dry soil weight, respectively. To determine the feed value of grain, a certified analytical laboratory of the Institute was used. The accounting area of the plot was 20 m^2.

The object of the study was the early-ripening grain sorghum variety Pivdenne. Sowing was carried out in the first decade of May in a wide-row method with a row spacing of 70 cm. Concomitant fertilizer – N_{90} in the form of ammonium nitrate was applied during pre-sowing cultivation. Growth regulators were applied for the first time in the 5–7 leaf phase and for the second time in the 8–10 leaf phase. On average, the total irrigation rate over three years was 1900 m^3. Irrigation was carried out with a DDA-100MA sprinkler. Such preparations as Regoplant (seed treatment rate was 250 ml/t and during vegetation it was 50 ml/ha), Grainaktiv-S (seed treatment rate was 0,1 l/t and during vegetation it was in a ratio of 1:1000), and Vermystym (seed treatment rate was 10 l/t and during vegetation it was 8 l/ha) were used. The active ingredient of the Regoplant preparation is a complex of biologically active compounds (polysaccharides, 15 amino acids, analogues of phytohormones of cytokinin and auxin nature), biogenic trace elements, potassium salt of alpha-naphthylacetic acid and aversectin C. The active ingredient of the Vermistim preparation includes such biocomponents as: humates, fulvic acids, amino acids, vitamins and natural phytohormones. The composition of Grainactiv-C preparation mainly consists of polyguanidine compounds in aqueous solution. Treatment of sorghum plants with Nanovit super fertilizer was carried out in the tillering and panicle ejection phases with a rate of 2 l/ha.

Research results and their discussion. It was established that the use of growth-regulating preparations Regoplant, Grainactiv-S and Vermystim as well as the complex fertilizer Nanovit super when growing grain sorghum of the Pivdenne variety under irrigation conditions did not have a significant impact on the total water consumption of plants, only a tendency to its increase was observed (Fig. 1, Table 1).

Treatment of seeds and vegetative plants with growth-regulating preparations provided moisture consumption on average around 4118–4246 m^3/ha versus 4104 m^3/ha in the control variant, i.e. by 14–142 m^3/ha, or by 0,3–3,5% higher.

The combined use of biostimulants with foliar feeding when applying Nanovit super fertilizer led to an increase in total water consumption to 4209–4296 m^3/ha, which was 1,2–2,2% higher than the variables obtained in the variants when using only growth regulators.

The use of stimulators when applying of nitrogen fertilizer at a dose of N_{90} in the pre-sowing period contributed to a decrease in moisture consumption for the formation of a yield unit.

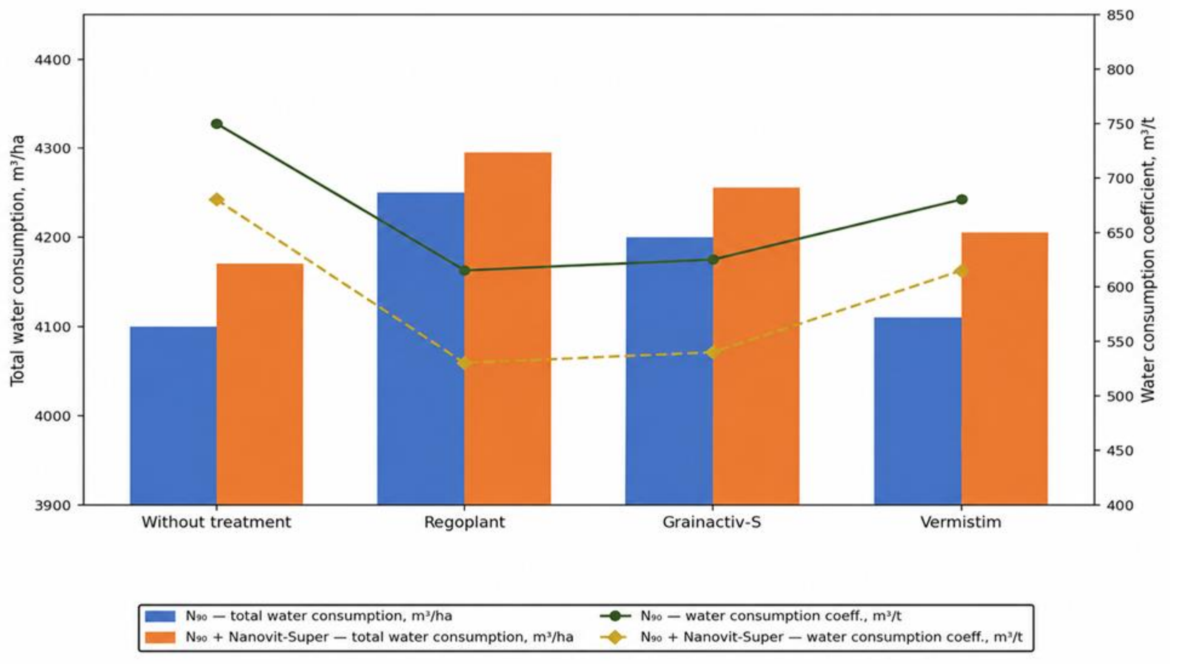

Fig. 1. Water consumption of grain sorghum depending on growth regulators (average for 2016–2018)

1. Effect of growth regulators on water consumption of grain sorghum (soil layer 0–50 cm, average for 2016–2018)

Growth regulators (B)	**Total water consumption, m³/ha**	**Water consumption coefficient, m³/t**	**Share of water consumption components, %**		
			Soil reserves	**Precipitation**	**Irrigation rate**
Ground – N_{90} (A)					
Without treatment	4104	707,6	19,1	34,6	46,3
Regoplant	4246	598,0	21,8	33,5	44,7
Grainactiv-S	4202	627,2	21,0	33,8	45,2
Vermystim	4118	675,1	19,3	34,5	46,2
Ground + Nanovit-super (A)					
Without treatment	4168	622,1	20,3	34,1	45,8
Regoplant	4296	477,3	22,7	33,1	44,2
Grainactiv-S	4255	525,3	21,9	33,4	44,7
Vermystim	4209	601,3	21,1	33,8	45,1
LSD 5%: A	14,9	16,2			
B	21,0	22,9			

The use of the Regoplant biostimulator provided the lowest water consumption coefficient – 598,0 m³/t and in combination with foliar feeding with Nanovit super fertilizer – 477,3 m³/t, which is 15,5 and 32,5% less than in the control variant, respectively.

In the variant with treatment with the Grainactiv-S preparation, water consumption for the formation of a yield unit decreased by 11,4 (in the control) and 25,8% (when applying Nanovit-super fertilizer), and amounted to 627,2 and 525,3 m³/t, respectively.

The use of Vermystim reduced the water consumption coefficient by only 4,6 (in the control) and 15,0% (when applying Nanovit-super fertilizer), and its rate was 675,1 and 601,3 m³/t respectively.

In the structure of total water consumption, the smallest share fell on soil reserves of the 0–50 cm layer – 19,1–22,7%, while the share of precipitation was 33,1–34,6%, and irrigation – 44,2–46,3%. The use of growth regulators contributed to an increase in the share of soil moisture used; when treating with Regoplant, it increased from 19,1% in the control to 21,8%, with Grainactiv-S – to 21,0%, with Vermistim – to 19,3% in irrigated variants.

Under conditions of foliar feeding with Nanovit Super fertilizer, moisture consumption from the 0–50 cm layer increased by 6,3%, and in the case of combined use with Regoplant it increased by 18,8%, with Grainactiv-S – by 14,7%, with Vermystim – by 10,5% and reached the highest values– 22,7, 21,9 and 21,1%, respectively.

The application of growth regulating agents to irrigated grain sorghum crops had a positive effect on plant height and yield components. Plant height increased by 3–9 cm when growth regulators were used, reaching 124–127 cm, and by 7–11 cm when combined with foliar application of the complex fertilizer Nanovit Super, reaching 131–135 cm (Table 2).

The greatest increase in plant height was provided by the Regoplant preparation – both when applying N_{90} (133 cm) and when combining with Nanovit super fertilizer (135 cm).

Growth regulators increased the length of the panicle by 3,7–8,5%, the number of seeds in the panicle by 5,7–16,9%, their mass by 10,0–24,5% (up to 29,6–33,5 g), the mass of 1000 seeds by 4,0–6,8%, which led to an increase in the mass of grain from 1 m^2 by 6,9–24,6% – up to 644,2–751,0 g, depending on the type of growth regulator.

Foliar fertilization of sorghum plants with complex fertilizer in chelate form caused an increase in panicle length, number and mass of grains in it, as well as the mass of 1000 seeds by 4,4–10,8%, while the mass of grains per 1 m^2 increased by 15,2% and reached 694,3 g.

The combined use of growth regulators with foliar feeding with Nanovit super fertilizer turned out to be more effective. Under these conditions, the length of the panicle increased by 4,1–4,5% compared to the variants where the plants were treated only with growth regulators. The number of seeds in the panicle also increased by 3,3–8,1%, their mass by 9,1–13,4% (up to 32.3–38.0 g), the mass of 1000 seeds by 4,1–5,0%, and the mass of grain from 1m^2 by 10,2–24,5% (up to 748,7–935,0 g). The highest efficiency in forming the crop yield was provided by the the Regoplant preparation while the lowest one was recorded when applying the Vermystim preparation.

The use of growth regulators Regoplant, Grainactiv-S, Vermystim and multicomponent fertilizer Nanovit super on irrigated crops contributed to an increase in sorghum grain productivity. In the control variant without the use of growth regulators and fertilizers, the average grain yield over the years of research was 5,9 t/ha, the yield of feed units was 8,0 t/ha, digestible protein was 0,30 t/ha, starch content was 75,2%, and protein content was 8,1% (Table 3).

Treatment of seeds and vegetative plants with growth regulators when applying N_{90} before sowing increased grain yield by 0,5–1,7 t/ha ($NIRP_{05}$ = 0,21 t/ha) compared to the control. At the same time, the yield of feed units increased by 8,7–30,0%, digestible protein – by 30,0–73,3%, starch content – by 1,2–2,8%, and protein content – by 7,4–19,7%.

The highest efficiency was provided by the growth regulators Regoplant and Grainactiv-S, with grain yield of 7,4–7,6 t/ha, feed unit yield of 10,1–10,4 t/ha, digestible protein of 0,45–0,52 t/ha, starch content in grain of 76,3–77,3%, and protein content of 9,1–9,7%. (Fig. 2).

2. Effect of mineral nutrition and growth regulators on the yield of grain sorghum

Growth regulators (B)	**Plant height, cm**	**Grain mass per 1 m^2, g**	**Mass of grain from one panicle, g**	**Number of seeds from one panicle, pcs.**	**Panicle length, cm**	**Weight of 1000 seeds, g**
Ground – N_{90} (A)						
Without treatment	124	602,7	26,9	1090	18,9	24,9
Regoplant	133	751,0	33,5	1274	20,5	26,6
Grainactiv-S	132	718,3	32,1	1233	20,1	26,3
Vermystim	127	644,2	29,6	1152	19,6	25,9
Ground + Nanovit-super (A)						
Without treatment	128	694,3	29,8	1138	20,1	26,3
Regoplant	135	935,0	38,0	1377	21,4	27,7
Grainactiv-S	134	856,7	35,6	1297	21,0	27,6
Vermystim	131	748,7	32,3	1190	20,4	27,2
LSD 5%: A	0,92	32,84	0,68	22,74	0,14	0,10
B	1,3	46,44	0,91	32,16	0,19	0,14

3. Grain sorghum productivity depending on mineral nutrition and the use of growth regulators (average for 2016–2018)

Growth regulators (B)	**Grain yield, t/ha**	**Yeild, t/ha**		**Content, %**	
		feed units	**digestible protein**	**starch**	**protein**
Ground – N_{90} (A)					
Without treatment	5,9	8,0	0,30	75,2	8,1
Regoplant	7,6	10,4	0,52	77,3	9,7
Grainactiv-S	7,4	10,1	0,45	76,3	9,1
Vermystim	6,4	8,7	0,39	76,1	8,7
Ground + Nanovit-super (A)					
Without treatment	6,8	9,1	0,43	76,3	9,5
Regoplant	9,2	12,4	0,59	77,8	10,8
Grainactiv-S	8,6	11,8	0,52	77,6	10,2
Vermystim	7,2	9,8	0,46	77,6	9,8
LSD 5%: A	0,18				
B	0,21				

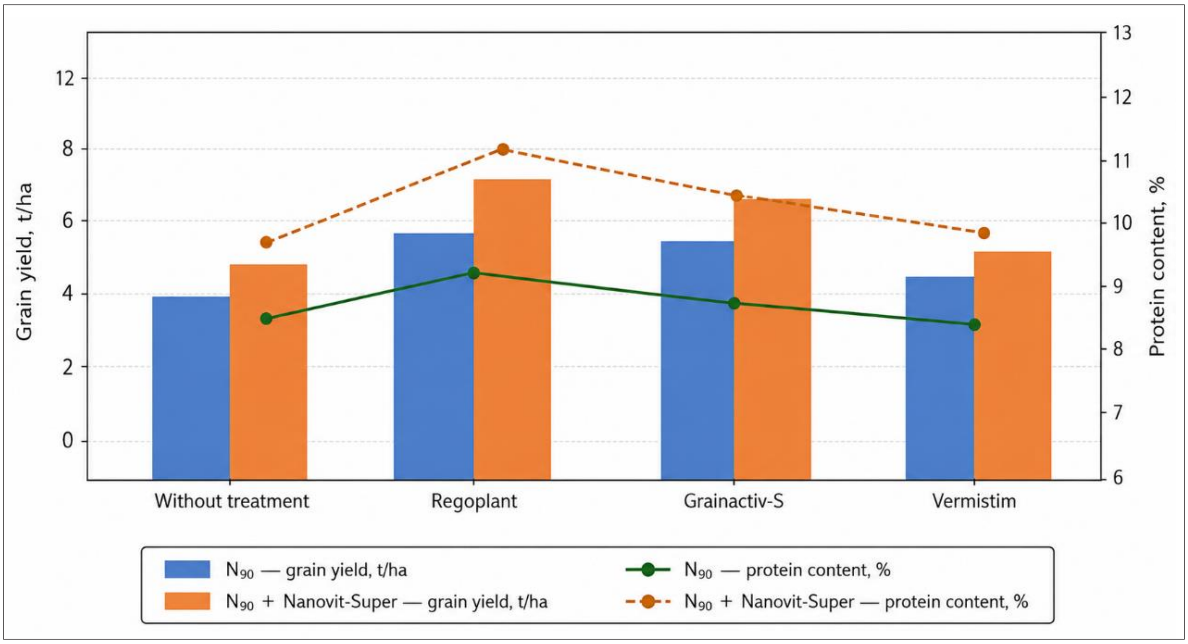

Fig. 2. Yield and protein content of grain sorghum depending on mineral nutrition and the use of growth regulators (average for 2016–2018)

Under these conditions, grain yield decreased within the experimental error (by 0,2 t/ha), feed unit yield by 2,9%, digestible protein by 13,5%, starch content by 1,3%, and protein content by 6,2%. The smallest increase in grain sorghum productivity was provided by the Vermystim preparation, when grain yield was 6,4 t/ha, feed unit yield was 8,7 t/ha, digestible protein was 0,39 t/ha, starch content in grain was 76,1%, and protein content was 8,7%.

Foliar feeding of sorghum plants with Nanovit super fertilizer when applying N_{90} during the pre-sowing period increased grain yield compared to the control by 0,9 t/ha (NIP_{05} = 0,18 t/ha), the yield of feed units by 1,1 t/ha (13,7%), digestible protein by 0,13 t/ha (43,3%), and starch and protein content in grain insignificantly – by 1,1 and 1,4%, respectively. By all indicators, this variant exceeded the results of treatment with the Vermystim preparation.

The highest efficiency was achieved with the combined use of multicomponent fertilizer with growth regulators. Under such conditions, the grain yield was 7,2–9,2 t/ha, which was 22,0–55,9% higher than in the control and 12,5–21,0% higher than in the variants when using only growth regulators. At the same time, the yield of feed units reached 9,8–12,4 t/ha, digestible protein – 0,46–0,59 t/ha, starch content – 77,6–77,8%, protein content in grain – 9,8–10,8%.

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Maximum productivity was provided by the combined use of Nanovit super fertilizer with Regoplant preparation. The increase in grain yield compared to the control was 55,9%, the yield of feed units – 55,0%, digestible protein – 96,7%, starch content – 3,5%, and protein content – 33,3%.

The use of Grainactiv-S prepatation in combination with Nanovit super fertilizer provided a grain yield of 8,6 t/ha, which exceeded the control by 45,8% and was accompanied by a significant increase in the content of nutrients. However, compared to the variant where the Regoplant and Nanovit super preparations were used together, grain yield was lower by 6,5%, the yield of feed units – by 4,8%, digestible protein – by 11,9%, and a tendency to a decrease in the content of starch and protein in grain was also observed.

The combined use of the Vermystim preparation with the Nanovit super fertilizer provided the smallest increase in crop productivity compared to the control variant. Grain yield increased by 22,0% and amounted to 7,2 t/ha, the yield of feed units – by 22,5%, digestible protein – by 53,3%, starch content in grain – by 3,2%, and protein content – by 21,0%.

The obtained research results confirm the important role of biostimulants and chelated forms of microelements in increasing the adaptability and productivity of grain sorghum in irrigated agriculture. Despite the fact that the use of growth regulators did not cause significant changes in the total water consumption of plants, it significantly affected the efficiency of water use, which was manifested in a significant decrease in the water consumption coefficient.

The reduction in water consumption for the formation of a yield unit is probably associated with the activation of physiological processes in plants under the influence of biostimulants. Growth regulators are able to stimulate photosynthetic activity, improve the functioning of the root system and increase the intensity of nutrient absorption. As a result, plants form greater biomass and higher productivity with the same or similar water consumption rates.

The combined use of growth regulators with foliar feeding when applying a complex fertilizer in chelate form turned out to be especially effective. The high efficiency of chelate microelements is explained by their rather high bioavailability and ability to quickly be included in the metabolic processes of plants. This contributes to the intensification of photosynthesis, activation of enzymatic systems and improvement of the transport of assimilates to the generative organs.

Improving the physiological state of plants under the influence of the studied preparations was reflected in the formation of crop structure. In particular, the increase in the length of the panicle, the number of grains in it and their mass indicates a more efficient use of plastic substances during the formation of generative organs. Similar patterns are shown in the works of Z. Rashid [20] and R. Zahida [21], who established the positive effect of growth regulators and microelements on the formation of sorghum productivity.

In addition, the obtained results are consistent with the studies of P. Huang [18] and P. Niharika [19], who proved that the use of chelate forms of trace elements increases the intensity of physiological processes in plants and contributes to an increase in crop yield. According to M.E. Abu-Ria and co-authors [12, 13], the use of organic biostimulants also contributes to an increase in the resistance of sorghum to water stress and optimizes the course of physiological processes during critical periods of crop development.

The obtained results are also consistent with modern concepts of increasing the efficiency of water use in irrigated agriculture, according to which the key role is played not only by the amount of moisture used, but also by the efficiency of its transformation into yield. In this context, a significant reduction in the water consumption coefficient with the use of growth regulators and chelate fertilizers proves the significant potential of such preparations in increasing the water productivity of agrocenoses.

Thus, the results of the conducted studies confirm the feasibility of the integrated use of growth regulators and chelate microfertilizers in the technology of growing grain sorghum. The combination of these agronomic techniques ensures the improvement of the physiological state of plants, increased efficiency of water use and the formation of high crop productivity under irrigated conditions.

Conclusions. The use of growth regulators and complex fertilizers in chelate form Nanovit super when growing grain sorghum of the Pivdenne variety under irrigation did not have a significant effect on the total plant water consumption, but significantly reduced the water consumption coefficient and increased crop grain productivity.

The highest agronomic efficiency was provided by the combined use of the Regoplant preparation along with the Nanovit super fertilizer when applying N_{90}. Under these conditions, the grain yield was 9,2 t/ha, that is by 55,9% higher than in the control, the yield of feed units reached 12,4 t/ha, digestible protein was 0,59 t/ha, grain protein content was 10,8%, grain starch content was 77,8%, and the water consumption coefficient decreased to 477,3 m^3/t, which was the best value among all the studied variants.

Conflicts of interest: the authors declare no conflict of interest.

Use of artificial intelligence: the authors confirm that they did not use artificial intelligence technologies during the creation of this work.

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ЕФЕКТИВНІСТЬ РІСТ-РЕГУЛЮЮЧИХ ПРЕПАРАТІВ НА ЗРОШУВАНИХ ПОСІВАХ СОРГО ЗЕРНОВОГО

Ю.О. Тараріко[1], д-р с.-г. наук, П.В. Писаренко[2], д-р с.-г. наук, Р.М. Василенко[3], канд. с.-г. наук, Р.В. Сайдак[4], канд. с.-г. наук, Ю.В. Сорока[5] канд. с.-г. наук, І.О. Біднина[6], канд. с.-г. наук

[1]Інститут водних проблем і меліорації НААН, Київ, 03022, Україна;
https://orcid.org/0000–0001–8475–240X; e-mail: urtar@bigmir.net
[2] Інститут водних проблем і мельовіорації НААН, Київ, 03022, Україна
https://orcid.org/0000–0002–2104–2301; email pavel_pisarenko74@ukr.net
[3] Інститут кліматично орієнтованого сільського господарства НААН, Одеса, Україна;
https://orcid.org/0009–0000–1903–4444 ; e-mail: ruslan-18a@ukr.net
[4] Інститут водних проблем і меліорації НААН, Київ, 03022, Україна;
https://orcid.org/0000-0002-0213-0496;e-mail: saidak_r@ukr.net
[5] Інститут водних проблем і меліорації НААН, Київ, 03022, Україна;
https://orcid.org/0000-0001-6228-4131; e-mail: agroresurs@bigmir.net
[6] Інститут водних проблем і меліорації НААН, Київ, 03022, Україна
https://orcid.org/0000-0001-8351-2519; e-mail: irinabidnina@ukr.net

Анотація. *В умовах посилення кліматичної посушливості південного регіону України зростає актуальність удосконалення технологій вирощування зернового сорго, спрямованих на підвищення ефективності використання водних ресурсів та формування стабільної продуктивності культури. Метою дослідження було визначити вплив ріст-регулюючих препаратів та комплексного добрива у хелатній формі Нановіт супер на водоспоживання, формування структури врожаю та зернову продуктивність сорго зернового в умовах зрошення. Польові дослідження проводили у 2016–2018 рр. на дослідному полі Інституту кліматично орієнтованого сільського господарства НААН на темно-каштановому середньосуглинковому слабосолонцюватому ґрунті. Об'єктом дослідження був ранньостиглий сорт сорго зернового Південне. Вивчали дію ріст-регулюючих препаратів Регоплант, Грейнактив-С та Вермистим на фоні внесення* N_{90}*, а також їх поєднання з позакореневим підживленням комплексним добривом Нановіт супер.*

Встановлено, що застосування досліджуваних препаратів не спричиняло істотних змін сумарного водоспоживання рослин (4104–4296 м^3*/га), однак сприяло підвищенню ефективності використання водних ресурсів. Найменший коефіцієнт водоспоживання отримано за сумісного застосування препарату Регоплант і добрива Нановіт супер – 477,3 м*^{3}*/т, що на 32,5 % менше порівняно з контролем. Застосування біостимуляторів позитивно впливало на формування елементів структури врожаю, зокрема збільшувало довжину волоті, кількість та масу зерна в ній, а також масу 1000 насінин. Найвищу зернову продуктивність забезпечувало сумісне використання препарату Регоплант із позакореневим підживленням добривом Нановіт супер на фоні* N_{90}*, за якого врожайність зерна становила 9,2 т/га, що на 55,9 % перевищувало контрольний варіант. За цих умов* *також підвищувалися показники кормової цінності продукції: вихід кормових одиниць досягав 12,4 т/га, перетравного протеїну – 0,59 т/га, а вміст білку в зерні – 10,8 %.*

Отримані результати свідчать про високу ефективність використання ріст-регуляторів у поєднанні з хелатними мікродобривами у технології вирощування зернового сорго в умовах зрошення та підтверджують доцільність їх застосування для підвищення продуктивності культури й оптимізації використання водних ресурсів.

Ключові слова: *сорго зернове, ріст-регулятори, хелатні мікродобрива, зрошення, водоспоживання, урожайність, кормова цінність*

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CLIMATE CHANGES IN THE PEAT BOG AREAS OF WESTERN POLISSYA AS ILLUSTRATED BY THE WEATHER STATION AT THE SARNENSKA RESEARCH STATION

M.D. Zosymchuk[1], Ph.D. in Agricultural Sciences, M.G. Stetsiuk[2], O.A. Zosymchuk[3], Ph.D. in Agricultural Sciences, O.A. Danylytskyi[4], O.S. Polischyk[5]

[1] Sarny Experimental Station, Institute of Water Problems and Land Reclamation, National Academy of Agrarian Sciences of Ukraine, Sarny, Ukraine;
https://orcid.org/ 0000-0002-7162-8300; e-mail: zosimchykm@gmail.com;
[2] Sarny Experimental Station of the Institute of Water Problems and Land Reclamation, National Academy of Agrarian Sciences of Ukraine, Sarny, Ukraine;
https://orcid. org/0000-0001-6773-2546; e- mail :nick.stetsiuk@gmail.com;
[3] Sarny Experimental Station of the Institute of Water Problems and Land Reclamation, National Academy of Agrarian Sciences of Ukraine, Sarny, Ukraine;
https://orcid.org/0000-0001-9556-0181; e-mail :oksana.zosimchyk@gmail.com;
[4] Sarny Experimental Station of the Institute of Water Problems and Land Reclamation, National Academy of Agrarian Sciences of Ukraine, Sarny, Ukraine;
https://orcid.org/ 0000-0002-0772-0516; e-mail : tsigan770@gmail.com;
[5] Institute of Water Problems and Land Reclamation of the National Academy of Agrarian Sciences of Ukraine, Kyiv, Ukraine;
https://orcid.org/0009-0002-8831-0662; oleksii.polishchuk.mail@gmail.com

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Abstract. *An analysis of long-term data on average daily air temperature shows that during the period of large-scale land reclamation–1962–1988– a decrease in these values was observed, both compared to the long-term average for 1946–2024 and to the average value for the period prior to large-scale land reclamation–1946–1961. The increase in the area of the evaporating surface caused by land reclamation led to an increase in the intensity of total evaporation and, consequently, to a decrease in air temperature. The average decrease in the mean daily air temperature during the growing season and over the year was, in both cases, 0,1 (°C). In turn, the increase in total evaporation during the period of large-scale land reclamation led to a 48,5 mm increase in precipitation during the growing season compared to the amount that fell before reclamation; on an annual basis, this figure amounts to 57,0 mm. Thus, overall, large-scale land reclamation on drained lands has resulted in positive climatic changes, and the current climate warming in the Polissya region is not associated with these reclamation efforts.*

An analysis of current climate changes shows that the average precipitation during the growing seasons of 2015–2024 is 33,6 mm lower than during 1999–2014. It should be noted that there has been a fairly significant decrease in precipitation during the active growing season for agricultural crops–June through September–which is generally a negative phenomenon for agricultural production. The average monthly air temperature during the growing season in the s of 2015–2024 increased by 0,5 (°C)compared to 1999–2014, and by 0,8 (°C) per year.

Climate changes over the past decades, characterized by a significant increase in heat availability during the growing season, make it possible to grow crops that are non-traditional for the Polissya region – economically attractive forest-steppe and steppe crops such as grain corn, soybeans, and sunflowers– which have recently been rapidly replacing crops previously traditional for this region, such as winter rye, buckwheat, oats, perennial grasses, and others.

Keywords: *Western Polissya, climate change, large-scale land reclamation, precipitation patterns, air temperature, hydrothermal conditions*

Research relevance. Current climate changes in Ukraine have been noticeable over the past 20–30 years and are occurring most intensively in the Polissya region. According to leading climatologists, the boundaries of climatic zones have shifted by at least 200 km, and some estimate the shift to be as much as 400 km [1, 8, 9].

An assessment of changes in the average annual air temperature shows that the greatest increase was recorded in the Polissya region–by

2,3 °C (34,3%)–followed by slightly smaller increases in the Forest-Steppe region–by 1,4 °C (16,3%)–and in the Steppe region–by 1,4 °C (15,9%) [10, 17].

There are various opinions and assertions regarding the causes of rapid climate change specifically in the Polissya region. As for the impact of land reclamation, there are differing views within the scientific community regarding its effect on climate change. According to some researchers, the current climate warming in the Polissya region may be linked to large-scale land reclamation carried out in the 1960s and 1970s [7, 18]. In contrast, there are claims that the impact of large-scale land reclamation on current climate change is minimal [3, 4, 5]. Using a specific site as an example–namely, the "Chemerne" peat bog complex at the Sarny Experimental Station of the Institute of Water Problems and Land Reclamation ofthe National Academy (IWPaLR) of Agrarian Sciences (Rivne Region)–and drawing on long-term meteorological observation data, this claim can be confirmed or refuted.

Analysis of Recent Studies and Publications. It is well known that wetlands significantly mitigate the effects of climate change, act as buffers against extreme natural phenomena such as droughts and floods, regulate humidity, air temperature, and ground surface temperature, and absorb and sequester carbon. At the same time, disturbed wetland ecosystems are vulnerable to climate change [11, 12, 14]. Due to warming, they lose more and more water, dry out, and begin to release previously "stored" carbon, exacerbating the greenhouse gas problem. The drying up of wetlands leads to the degradation and loss of valuable ecosystems that make Polissya so unique [8, 10, 11, 13, 14]. That is why, recently, both in scientific circles and at the government level, there has been a growing consensus on the advisability of partially restoring wetlands in the Polissya region. As one practical means of achieving this, it is proposed to carry out the partial renaturalization of drained peatlands in the Polissya region that are currently used for agricultural production [5, 15].

The aim of this study is to assess climate changes in the peatland complexes of the Western Polissya region, using the weather station of the Sarny Experimental Station of the IWPaLR of the National Academy of Agrarian Sciences (NAAS) as a case study over a long-term period.

Materials and Methods. This study utilized data from instrumental meteorological observations conducted since 1946 at the weather station of the Sarny Experimental Station of the IWPaLR (the only such station in Ukraine), which is located directly on a peatland complex. This provides data–unique in Ukrainian agricultural land reclamation science–on the climatic characteristics of peatland complexes in the Western Polissya region, as well as the nature and patterns of their changes over a long period.

Research Results and Discussion. The initial phase of land drainage work at the Sarny Experimental Station coincided with the period of the Western Expedition led by Lieutenant General Y.I. Zhilinsky, which lasted over 30 years–from 1872 to 1902–and encompassed a total of over 8 million hectares of once-impassable swamps in the Polissya region [6]. In the territory of the former Volyn Governorate alone, a network of drainage canals was constructed across an area of over 500 thousand hectares. Even by modern standards, a vast amount of surveying, topographic, and engineering-hydromeliorative work was carried out in a relatively short period of time, mostly by hand in the conditions of impassable swamps. The land reclamation canals built by the Western Expedition are still in operation today, notably the Khvoshchivansky Main Canal within the land reclamation system of the Sarny Experimental Station of the IWPaLR of the National Academy of Agrarian Sciences (NAAS). Even modern agricultural land reclamation science relies to a significant extent on the scientific and practical work of a team of talented and dedicated scientists and engineers who, in the late 19th and early 20th centuries, laid the foundations for the reclamation of wetlands in the Ukrainian Polissya.

The Sarny Experimental Station was established on the "Chemerne" peat bog complex, the drainage of which began precisely with the Western Expedition's construction of the first drainage canals. The first phase of draining the station's marshlands took place between 1912 and 1917; during this period, approximately 120 hectares of the marshland were drained. The second stage of draining the peatland massif on which the station is located was carried out between 1924 and 1938, when it operated as part of the Second Polish Republic. The area of drained land during this period increased to 260 hectares of peatlands and 15 hectares of mineral soils.

The first reconstruction of the station's land reclamation system took place in 1959–1961, and the second in 1974–1976.

The station's land reclamation system is located in the western, most marshy part of the Ukrainian Polissya and lies directly within the "Chemerne" peat bog complex of the Sarny Experimental Station (Rivne region).

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In terms of morphological characteristics, botanical composition, and hydro-physical and agrochemical properties, this complex is typical of the Western Polissya–a deep, medium-ash, non-floodplain, hypnum-sedge bog of the lowland type.

The system includes a drained area, a water recipient, open canals (main, collector, upland, and catchment) with hydraulic structures, and a closed regulating network. The water recipient is the Sluch River, located at a distance of 5 km from the system.

Of the agricultural land, lowland-type peat soils cover 355 hectares, while mineral soils cover 115 hectares (predominantly sod-podzolic sandy loam).

Peat soils range in thickness from 0,5 to 5,0 m; they are well decomposed (decomposition degree exceeding 40%); they are medium- to high-ash (17–28% ash); and, in terms of botanical composition, they are predominantly sedge-sphagnum. The filtration coefficient ranges from 0,5 to 1,0 m/day. The water-holding capacity of peat soils ranges from 300 to 800%; the soil density is 0,260–0,342 g/cm³.

The peat is underlain by oxic sandy loams; the acidity of the peat soil ranges from 4,1 to 5,5.

Mineral soils consist of sod-podzolic clay-sandy soils on sandy deposits with a humus content of 2,1–2,4% and a pH of 4,5–5,4.

Groundwater levels over the past 3 years during the growing season in the land reclamation system ranged from 41 to117 cm.

The weather station at the Sarny Research Station is the only one in Ukraine located directly on a peat bog complex and has been operating continuously since 1946 (data from 1912 were partially lost during World War II).

To assess the potential impact of large-scale land reclamation on current climate change, the period of instrumental observations–1946–2024– has been divided into the following stages:

- the period prior to large-scale land reclamation–1946–1961;
- the period of large-scale land reclamation–1962–1988;
- the period of winter-spring (I–III) warming–1989–1998;
- the period of a steady increase in monthly and annual average daily air temperatures–1999–2014;
- the current period – 2015–2024

Data on air temperature and precipitation for the specified periods are presented in Tables 1–2.

1. Average daily air temperature based on data from the Sarny Research Station of the IWPaLR, °C

Period	**Months**												**Spring (IV–IX) (average)**	**Year (average)**
	I	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Before land reclamation, 1946–1961	–4,4	–4,5	–0,3	7,4	13,5	17,5	18,8	17,4	12,5	6,4	1,9	–1,8	14,5	7,0
Period of large-scale land reclamation, 1962–1988	–5,9	–4,7	0,0	7,6	14,1	16,9	18,1	17,0	12,6	7,3	2,2	–2,3	14,4	6,9
Winter-spring (I–III) warming period, 1989–1998	–2,3	–1,1	1,9	7,9	14,4	17,7	18,8	18,2	12,1	7,3	1,1	–3,0	14,9	7,8
Period of sustained increase in monthly and annual average daily air temperatures, 1999–2014	–3,7	–3,0	1,8	9,1	14,6	18,1	20,3	18,7	13,1	7,5	3,3	–2,1	15,7	8,1
Current period, 2015–2024	–2,7	–0,5	2,6	8,5	14,1	19,6	20,2	19,8	14,1	8,1	3,0	–0,4	16,1	8,9
Average annual values of average daily air temperatures for the observation period (normal), 1946–2024	–4,3	–3,3	0,9	8,0	14,1	17,7	19,0	17,9	12,8	7,3	2,3	–2,0	14,9	7,5

Continuation of Table 1

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Deviation from long-term averages (+ increase, – decrease)														
1946–1961	–0,1	–1,2	–1,2	–0,6	–0,6	–0,2	–0,2	–0,5	–0,3	–0,9	–0,4	0,2	–0,4	–0,5
1962–1988	–1,6	–1,4	–0,9	–0,4	0,0	–0,8	–0,9	–0,9	–0,2	0,0	–0,1	–0,3	–0,5	–0,6
1989–1998	+2,0	+2,2	+1,0	–0,1	+0,3	0,0	–0,2	+0,3	–0,7	0,0	–1,2	–1,0	–0,1	0,2
1999–2014	+0,6	+0,3	+0,9	+1,1	+0,5	+0,4	+1,3	+0,8	+0,3	+0,2	+1,0	–0,1	+0,7	+0,6
2015–2024	+1,6	+2,8	+1,7	+0,5	0,0	+1,9	+1,2	+1,9	+1,3	+0,8	+0,7	+1,6	+1,1	+1,3
Temperature deviations in the period after 1999														
2015–2024 compared to 1999–2014	+1,0	+2,5	+0,8	–0,6	–0,5	+1,5	–0,1	+1,1	+1,0	+0,6	–0,3	+1,7	+0,4	+0,7

2. Average precipitation for various periods based on data from the weather station at the Sarny Research Station of the IWPaLR, mm

Period	**Months**												**Spring–Fall (April–September) (average)**	**Year (average)**
	I	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**		
Before land reclamation, 1946–1961	25,6	25,2	25,3	30	47,2	73,3	76,4	64,7	40,4	49,2	46,1	34,6	332,0	538,0
Land reclamation period, 1962–1988	36,2	31,2	28,0	43,9	59,8	83,6	79,8	59,4	54,1	40,5	39,2	39,4	380,5	595,0
Winter-spring (I–III) warming period, 1989–1998	18,7	23,7	22,9	39,9	52,2	64,8	98,2	56,0	75,5	39,4	37,2	36,9	386,6	565,4
Period of steady increase in monthly and annual average daily air temperatures, 1999–2014	24,3	27,7	25,2	22,2	41,0	58,2	78,3	52,1	40,4	27,8	27,1	24,7	292,2	448,8
Current period, 2015–2024	29,0	23,4	25,9	26,0	50,6	42,5	69,1	39,2	31,3	39,5	29,6	42,0	258,7	448,1
Average annual values of average daily air temperatures for the observation period (normal), 1946–2024	28,5	27,3	26,0	33,9	51,3	68,8	79,8	56,0	48,4	39,4	36,7	35,5	338,1	531,5
Deviation from long-term averages (+ increase, – decrease)														
1946–1961	–2,9	–2,1	–0,7	–3,9	–4,1	4,5	–3,4	8,7	–8,0	9,8	9,4	–0,9	–6,1	6,5
1962–1988	+7,7	+3,9	+2,0	+10,0	+8,5	+14,8	0,0	+3,4	+5,7	+1,1	+2,5	+3,9	+42,4	+63,5
1989–1998	–9,8	–3,6	–3,1	+6,0	+0,9	–4,0	+18,4	0,0	+27,1	0,0	+0,5	+1,4	+48,5	+33,9
1999–2014	–4,2	–0,4	–0,8	–11,7	–10,3	–10,6	–1,5	–3,9	–8,0	–11,6	–9,6	–10,8	–45,9	–82,7
2015–2024	0,5	–3,9	–0,7	–7,9	–0,7	–26,3	–10,7	–16,8	–17,1	0,1	–7,1	6,5	–79,5	–83,5
Changes in precipitation levels since 1999														
2015–2024 compared to 1999–2014	4,7	–3,6	0,1	3,8	9,6	–15,7	–9,2	–12,9	–9,1	11,7	2,5	17,3	–33,6	–0,8

An analysis of data on average daily air temperature for the time periods specified above shows that during the period of large-scale land reclamation (1962–1988), there was a slight (0,1 (°C)) decrease in this value compared to its average (both for the annual period and the April–September period) during the period prior to large-scale land reclamation (1946–1961).

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The average precipitation totals for various periods, based on data from the weather station at the Sarny Experimental Station of the Institute of Water Problems and Land Reclamation of the National Academy of Agrarian Sciences, are presented in Table 2.

The period 1989–1998 was characterized by winter-spring (January–March) warming, while since 1999, warming has occurred throughout the entire calendar year. The highest precipitation occurs in July–74,8 mm.

Based on data from the last decade (2015–2024), annual precipitation has decreased by 83,5 mm compared to the long-term average and by 79,5 mm for the April–September period. The average daily air temperature for the annual period and the April–September period has increased by an average of 1,1 (°C) and 1,3 (°C), respectively, which is a very significant indicator.

The increase in the area of the evaporating surface, caused by land reclamation, led to an increase in the intensity of total evaporation and, consequently, to a decrease in air temperature. The increase in total evaporation during the period of large-scale land reclamation led to an increase in total precipitation during the growing season by 48,5 mm compared to the amount that fell before reclamation, and by 57 mm per year. An analysis of the research data suggests that large-scale land reclamation on drained lands resulted in positive climatic changes, and the current climate warming in the Polissya region is not associated with these reclamation efforts. Regarding climate changes after 2000, the average

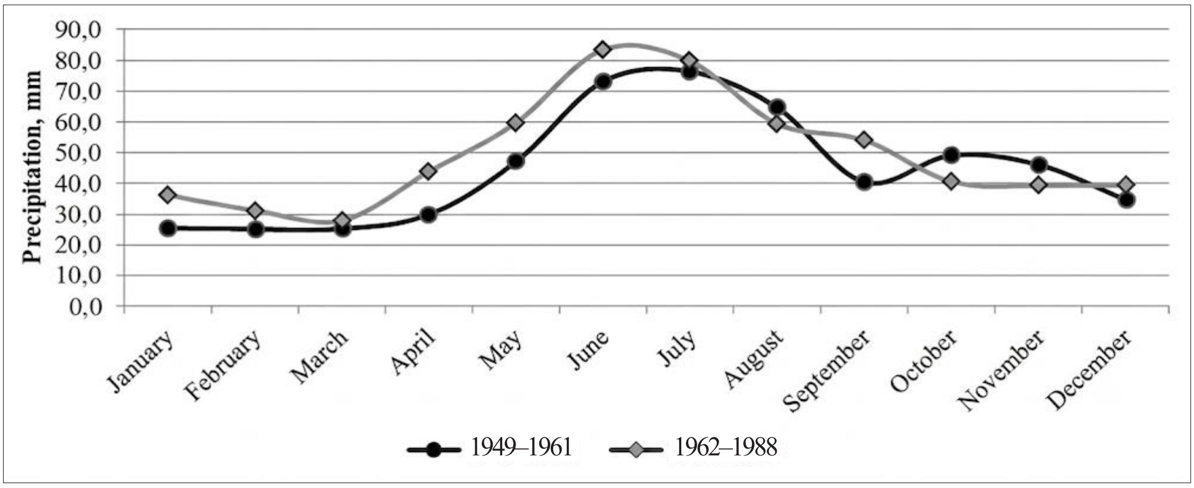

Fig. 1. Precipitation trends for the periods 1946–1961 and 1962–1988, "Chemerne" peat bog complex, Sarny Experimental Station of the IWPaLR

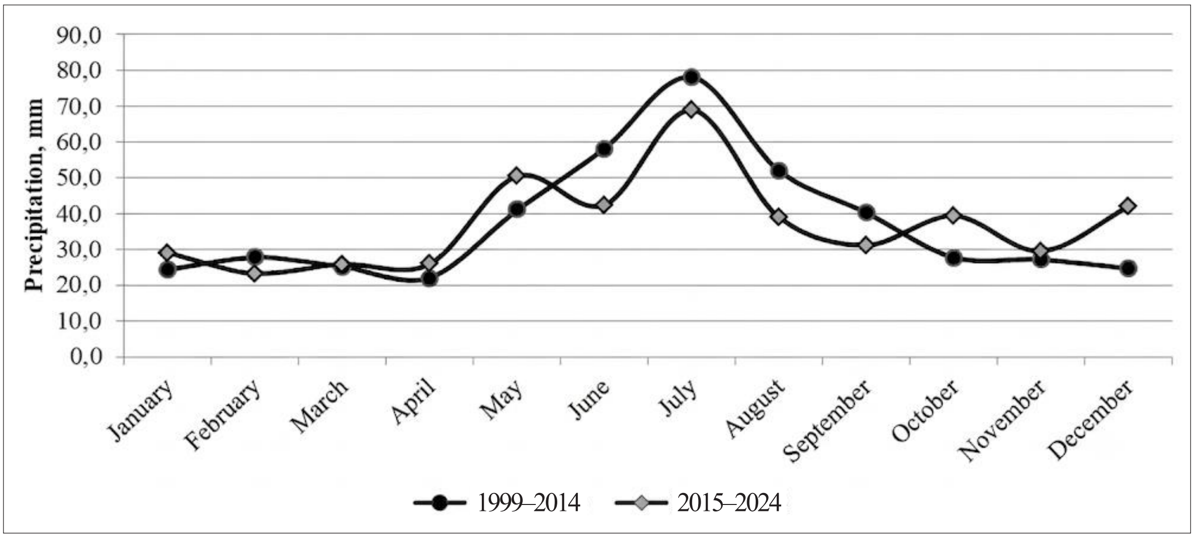

Fig. 2. Precipitation trends for the periods 1999–2014 and 2015–2024, "Chemerne" peat bog complex, Sarny Experimental Station of the IWPaLR

precipitation for the April–September period during 2015–2024, as recorded at the Sarnensk Research Station weather station, decreased by 33,6 mm compared to the 1999–2014 period. The decrease in precipitation during the 2015–2024 period, compared to the 1999–2014 period, was observed during the active growing season–June through September–which, overall, is an unfavorable factor for agricultural production against the backdrop of rising average daily temperatures. Regarding temperature patterns, the average monthly air temperature for the April–September period rose by +0,4 °C, and by +0,7 °C over the annual period, which is a fairly significant increase.

Thus, based on data from the weather station at the Sarnensk Research Station of the IWPaLR, climate changes in the "Chemerne" peat bog complex over the past decade are due to a significant decrease in precipitation during April–September against the backdrop of a general increase in average monthly air temperatures. The results obtained from instrumental observations are fully consistent with the general trends of climate change in the иelarusian Pollsya region.

The data in Figures 3–4, based on observations from the Sarnenskaya Research Station weather station, show that air temperatures have been rising most rapidly since the beginning of 2000, and this process continues to the present day; furthermore, the increase in average daily temperature is occurring against a backdrop of decreasing precipitation.

Overall, climate change is moving toward aridification, and based on key climate indicators, the Polissya region now more closely resembles–in the classical sense–the Forest-Steppe zone.

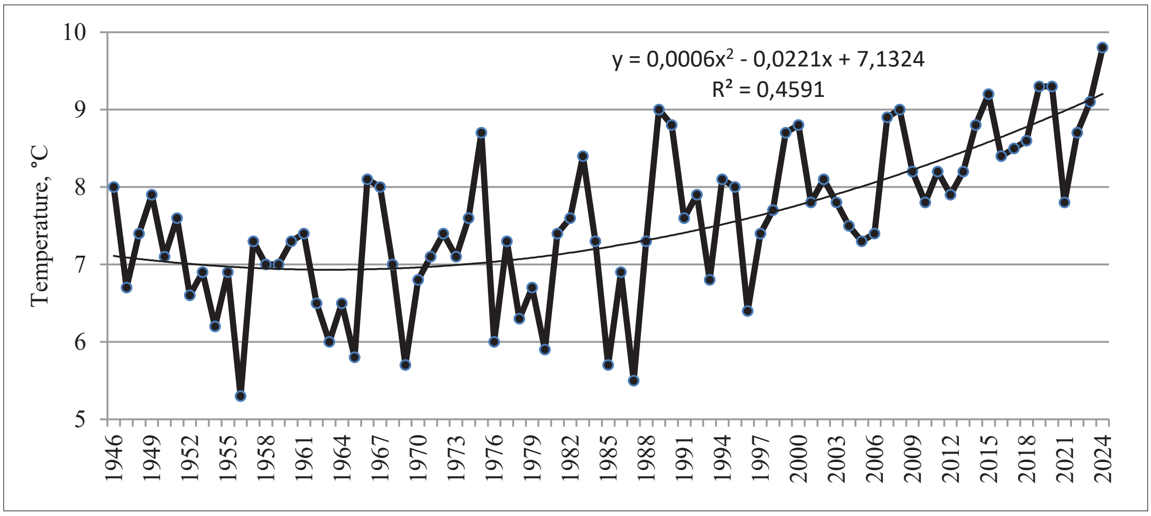

Fig. 3. Trends in average annual air temperature for 1946–2024

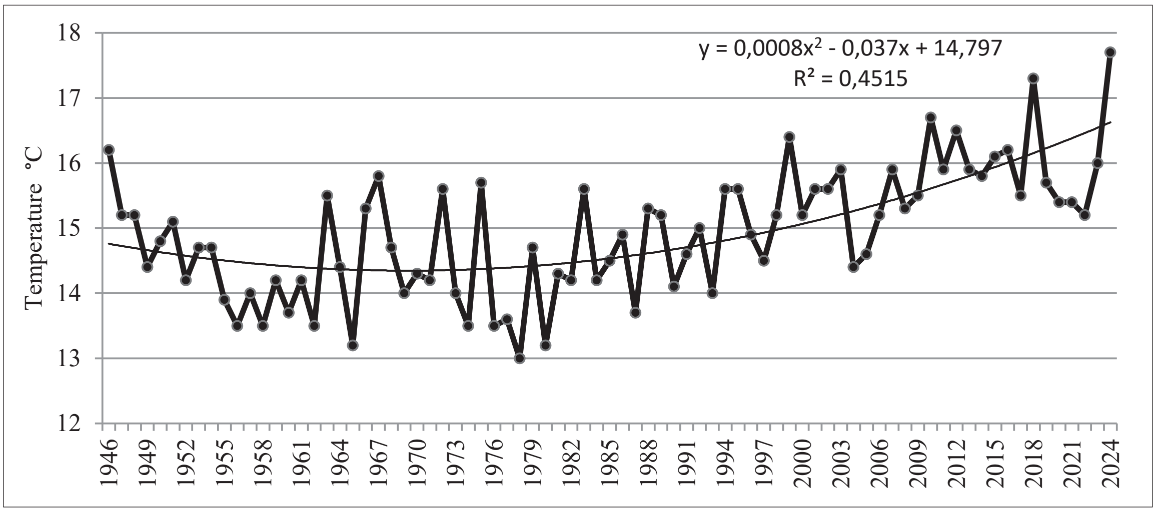

Fig. 4. Trends in average monthly air temperature for April–September, 1946–2024

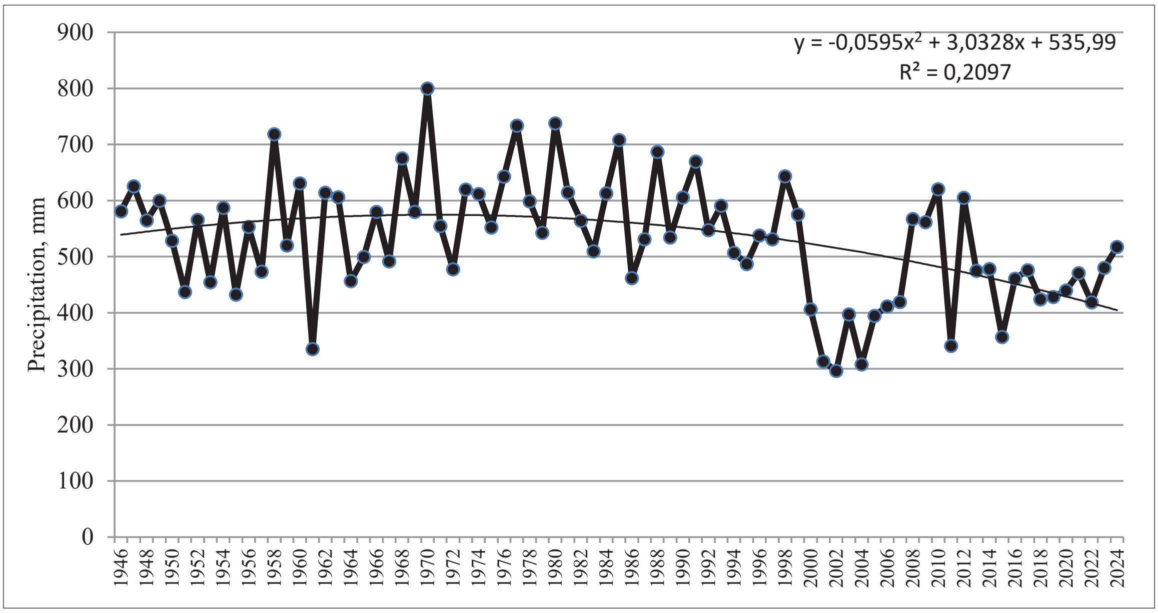

Fig. 5. Trends in annual precipitation for 1946–2024

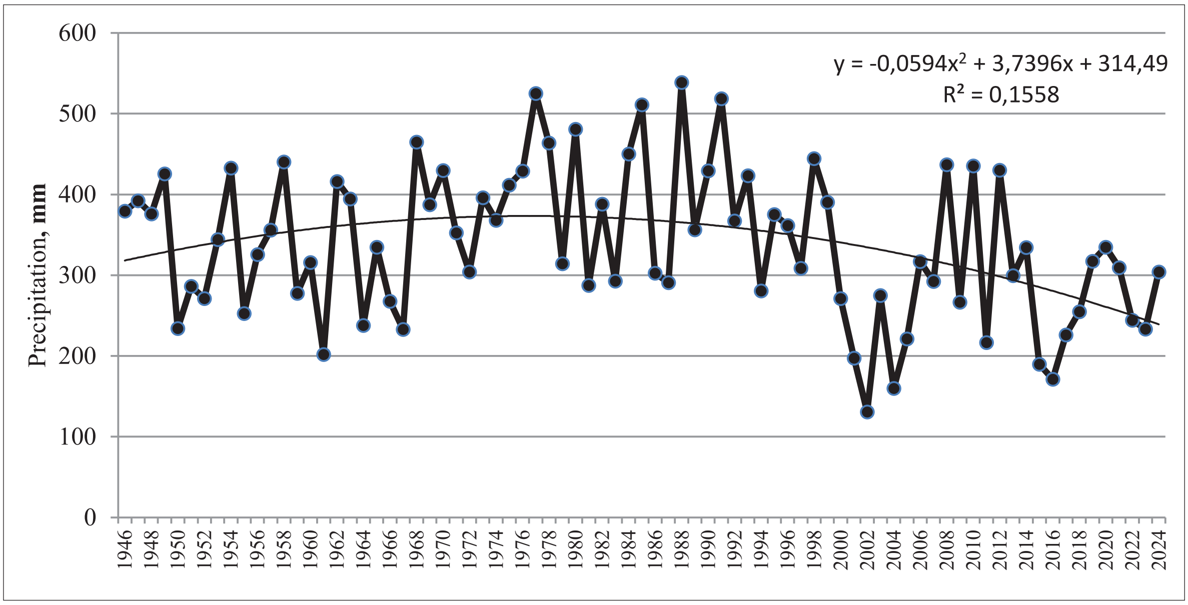

Fig. 6. Trends in precipitation for April–September during 1946–2024

As for the impact of current climate change on agro-industrial production, thanks to a significant increase in heat availability during the growing season, it is already possible to successfully grow crops that are non-traditional for the Polissya region – economically attractive agricultural crops typical of the forest-steppe and steppe zones, such as grain corn, soybeans, and sunflowers–which are rapidly replacing crops previously typical of this region, such as winter rye, buckwheat, oats, perennial grasses, and others.

However, a very cautious approach is needed when cultivating these crops in the Polissya region. In many cases, crop cultivation technologies are mechanically transferred from the Steppe and Forest-Steppe zones without taking into account the region's soil and climatic characteristics, which often leads to a decrease in their yield. First and foremost, a particularly careful approach is required when selecting varieties and hybrids best adapted to the specific soil and climatic conditions of the Polissya region. In the Polissya region, given the less favorable hydrothermal conditions, preference should be given to early-maturing hybrids of corn, sunflower, and soybeans. As recent studies show, the difference in yield between individual hybrids of corn, sunflower, and soybeans can be as high as 2–3 times.

At the same time, economically attractive crops such as corn, soybeans, and sunflowers are demanding in terms of soil moisture, so given the trend toward decreasing precipitation in the Polissya region, their cultivation on large areas will inevitably require the restoration of irrigation systems, a significant portion of which are currently not functioning properly.

Thus, based on data from the weather station at the Sarny Experimental Station of the IWPaLR, climate changes in the "Chemerne" peat bog complex over the past decade have been caused by a significant decrease in precipitation during the growing season against the backdrop of a general increase in average monthly air temperatures. The results obtained from instrumental observations are fully consistent with the general trends in climate change documented in Ukraine and in the belarusian Pollisya region.

Conclusions. Analysis of data on average daily air temperature shows that during the period of large-scale land reclamation–1962–1988– there was a decrease in this value, both compared to the long-term average for 1946–2024 as well as compared to the average for the period prior to large-scale land reclamation (1946–1961). The increase in the area of the evaporating surface caused by land reclamation led to an increase in the intensity of total evaporation and, consequently, to a decrease in air temperature. The average decrease in the mean daily air temperature during the growing season and over the year is, in both cases, 0,5 (°C). The increase in total evaporation during the period of large-scale land reclamation led to a 48,5 mm increase in total precipitation during the growing season compared to the amount that fell prior to reclamation. On an annual basis, this figure amounts to 57,0 mm.

An analysis of meteorological data for the last decade (2015–2024) shows that annual precipitation decreased by 83,5 mm compared to the long-term average and by 79,6 mm during the growing season. The average daily air temperature during the growing season has increased by an average of 1,2 °C and 1,4 °C, respectively, which is a significant indicator.

Conflicts of interest: the authors declare no conflict of interest.

Use of artificial intelligence: the authors confirm that they did not use artificial intelligence technologies during the creation of this work.

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КЛІМАТИЧНІ ЗМІНИ НА ТОРФОБОЛОТНИХ МАСИВАХ ЗАХІДНОГО ПОЛІССЯ НА ПРИКЛАДІ МЕТЕОПОСТУ САРНЕНСЬКОЇ ДОСЛІДНОЇ СТАНЦІЇ

М.Д. Зосимчук[1], канд. с.-г. наук, М.Г. Стецюк[2], О.А. Зосимчук[3], канд. с.-г. наук, О.А. Данилицький[4], О.С. Поліщук[5]

[1] Сарненська дослідна станція ІВПіМ НААН, Сарни, Україна;
https://orcid.org/0000-0002-7162-8300; e-mail: zosimchykm@gmail.com
[2] Сарненська дослідна станція ІВПіМ НААН, Сарни, Україна;
https://orcid.org/0000-0001-6773-2546; e-mail: nick.stetsiuk@gmail.com[2]
[3] Сарненська дослідна станція ІВПіМ НААН, Сарни, Україна;
https://orcid.org/ 0000-0001-9556-0181; e-mail: oksana.zosimchyk@gmail.com
[4] Сарненська дослідна станція ІВПіМ НААН, Сарни, Україна;
https://orcid.org/0000-0002-0772-0516; e-mail: tsigan770@gmail.com
[5] Інститут водних проблем і меліорації НААН, Київ, Україна
https://orcid.org/0009-0002-8831-0662; oleksii.polishchuk.mail@gmail.com

Анотація. *Аналіз багаторічних даних по середньодобовій температурі повітря показує, що в період проведення широкомасштабної меліорації – 1962–1988 рр., спостерігалось зниження її величини, як порівняно з середньобагаторіними показниками – 1946–2024 рр., так і з середньою її величиною за період до широкомасштабної меліорації – 1946-1961 рр.*

Викликане проведенням меліорації збільшення площі випаровуваної поверхні призвело до підвищення інтенсивності сумарного випаровування і відповідно до зниження температури повітря. Середня величина зниження середньодобової температури повітря за період вегетації і за рік складала в обох випадках в середньому 0,1 оС. В свою чергу збільшення сумарного випаровування в період широкомасштабної меліорації привело до збільшення суми випадання опадів за вегетаційний період на 48,5 мм порівняно з їх кількістю, що випадали в період до меліорації, в річному розрізі ця величина складає 57,0 мм. Отже вцілому в результаті проведення широкомасштабної меліорації на осушуваних землях відбулись позитивні кліматичні зміни, і сучасне потепління клімату в зоні Полісся не повязане з її проведенням.

Аналіз сучасних кліматичних змін показує, що середня кількість опадів за вегетаційний періоди 2015–2024 рр. порівняно з 1999-2014 рр. є меншою на 33,6 мм. Слід зазначити про доволі істотне зменшення кількості опадів у період активної вегетації сільськогосподарських культур – червень-вересень, що вцілому є негативним явищем для ведення сільскогосподарського виробництва. Середньомісячна температура повітря за вегетаційний період протягом 2015–2024 рр. порівняно з 1999–2014 рр. підвищилась на 0,5 оС та на 0,8 оС за рік.

Кліматичні зміни в останні десялиліття, які полягають у істотному збільшенні теплозабезпеченості вегетаційного періоду дають можливість вирощувати нетрадиційні для зони Полісся – Лісостепові та Степові економічно-привабливі сільськогосподарські культури, такі як – кукурудза на зерно, соя, соняшник, що останнім часом стрімко витісняють раніше традиційні для даного регіону культури – озиме жито, гречка, овес, багаторічні трави та ін.

Ключові слова: *Західне Полісся, зміни клімату, широкомасштабна меліорація, режим атмосферних опадів, температура повітря, гідротермічні умови*

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HYDRAULIC STRUCTURES AND INNOVATIVE TECHNOLOGIES FOR MANAGING THE HYDROLOGICAL REGIME OF SMALL RIVERS IN THE STEPPE ZONE OF UKRAINE

H. V. Hapich[1], Ph.D. in Engineering, V. V. Kovalenko[2], Ph.D. in Agricultural Sciences

[1] Dnipro State Agrarian and Economic University, Dnipro, Ukraine;
https://orcid.org/0000-0001-5617-3566, e-mail:hapich.h.v@dsau.dp.ua ;
[2] Dnipro State Agrarian and Economic University, Dnipro, Ukraine;
https://orcid.org/0000-0003-3865-597X, e-mail: kovalenko.v.v@dsau.dp.ua

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Abstract. *Small rivers in the steppe zone of Ukraine are the most vulnerable link in the hydrographic network, reacting acutely to climate change and anthropogenic pressure. The current trend toward their shallowing and loss of flow during the low-water period is caused by excessive regulation of river channels by ponds and reservoirs, which transforms rivers into stagnant bodies of water. Using the Dnipropetrovsk region as an example, it has been established that over the past 40 years, the number of ponds has increased 2,7-fold, and their total capacity has exceeded the volume of local runoff, posing a threat to the ecological safety of aquatic ecosystems. Traditional dams block the flow after a flood, so it is essential to develop solutions for water storage that do not disrupt the hydrological regime. The research methodology is based on the analysis of hydrological data and engineering modeling of gravity-fed flow regulation systems using algorithms from the QGIS geographic information system. The first proposed option involves modernizing channel ponds by separating the river channel from the pond basin using a retaining dam and creating a bypass channel. An open regulator is installed at the headwaters, allowing the pond to fill during periods of high water without interrupting the transit flow at all. To improve water quality, the hydraulic structure incorporates a rock-filled connecting structure that ensures intensive aeration and self-purification of the flow. The second option involves creating autonomous floodplain complexes with artificial basins. This technology allows not only for the accumulation of floodwater but also for its active discharge back into the river channel during dry periods to maintain ecological flow. A comparative analysis confirms that the river channel option is optimal for restoring flow in already regulated rivers, while floodplain reservoirs are effective for sustainable water supply without interfering with the river channel. The practical implementation of the proposed solutions was tested at a site in the Lower Tersa River basin (catchment area of 85,1 km^2). Simulation results confirmed the system's operational effectiveness: at a normal water table (NWT) of 108,0–108,5 m BS and during a 1 % return period design flood (water level of 109,50 m in Baltic Normal Height System (BS), 560 thous.m^3 of water while fully preserving the ecological flow in the bypass channel. The implementation of such complexes enables the principles of the EU Water Framework Directive regarding river revitalization to be realized, ensuring a "living flow" even in low-water years and creating conditions for the restoration of biodiversity in steppe ecosystems amid post-war recovery and rapid climate change.*

Keywords: *hydraulic structure; water body; river; water engineering; water technologies; hydrological regime; environmental safety*

Introduction. Small rivers in the steppe zone of Ukraine are the most vulnerable link in the hydrographic network, being the first to respond to anthropogenic pressure and climate change [1, 2]. Currently, there is a persistent trend toward their shallowing, intensive siltation, and complete loss of flow during the low-water period. One of the key factors contributing to the degradation of these waterways is the excessive and often irrational regulation of their channels by ponds and reservoirs [3, 4]. This leads to the cessation of natural self-purification processes, a deterioration in water quality, and the transformation of rivers into a cascade of ecologically unstable, stagnant bodies of water [5, 6]. For the most part, such water bodies lack hydraulic connectivity with one another for a significant portion of the year.

An analysis of trends in hydraulic engineering construction reveals the critical scale of this problem, particularly in the arid southeastern regions of the country. Using the Dnipropetrovsk Oblast as an example, it has been established that over the past 30–40 years, the number of ponds has increased 2,7-fold–from 1,239 to 3,292 [4]. Currently, the total capacity of the region's artificial reservoirs exceeds 1 billion $^{m^3}$, while local runoff does not exceed 0,825 billion m^3. This ratio poses a direct threat to environmental safety and significantly worsens water use conditions.

Analysis of recent studies and publications. Traditional engineering approaches based on the construction of transverse dams have a significant drawback: they halt the flow after the end of the hydrological period of high water levels, which stimulates wetland formation and negatively affects the ecological condition of water bodies [7]. Due to this situation, a movement to dismantle barriers (hydraulic structures) on rivers is gaining momentum worldwide, and particularly in Europe. As of 2025 (https://damremoval.eu/), more than 9,000 barriers (weirs, dams, locks, and obsolete rapids) have been dismantled in Europe. Most of the removed structures (over 65%) are small hydraulic engineering structures several meters high (Fig. 1). These are precisely the types of structures most commonly found on the small rivers of the Ukrainian Steppe, which lead to siltation and the cessation of their flow. According to the EU Biodiversity Recovery Strategy, the restoration of at least 25,000 km of free-flowing rivers is planned by 2030 [8]. It is worth noting that as part of the implementation of the Association Agreement with the EU and the provisions of the Water Framework Directive 2000/60/EC, Ukraine has committed to achieving "good ecological status" for its water bodies, which underscores the urgency of addressing the aforementioned problem.

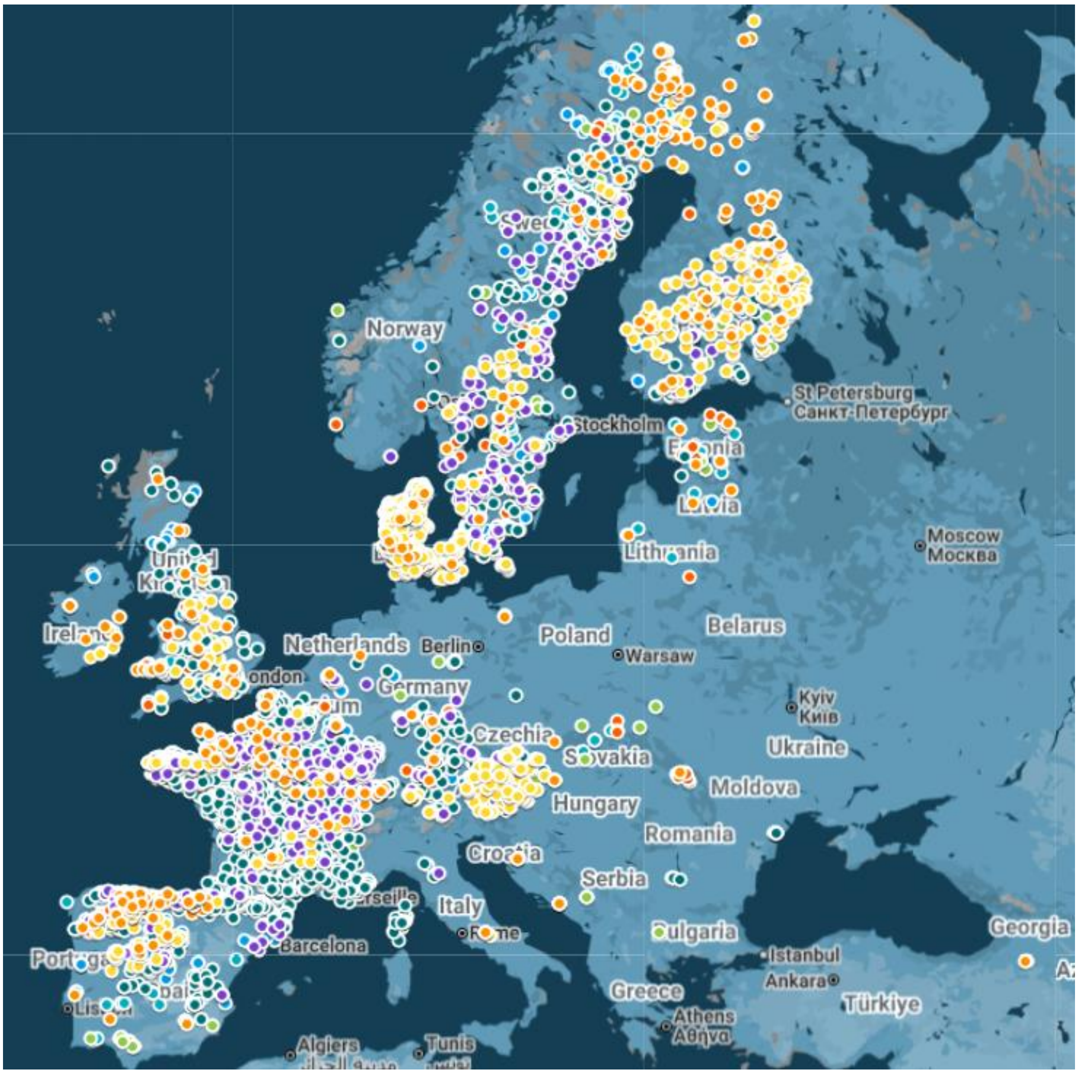

Fig. 1. Interactive map of dam (barrier) removal on European rivers (source: https://damremoval.eu/)

On the other hand, the situation has significantly worsened as a result of full-scale military aggression, due to which Ukraine has lost about one-third of its available (engineered) water reserves [9, 10]. Widespread destruction of hydraulic infrastructure–in particular, the catastrophic destruction of the Kakhovka Reservoir–has led to the destabilization of water supply and irrigation systems across a significant portion of the country's southeastern regions [11]. Under these conditions, further economic development and the full-scale recovery of the agricultural sector are impossible without a fundamental overhaul of the water resources management strategy [12, 13]. Addressing the issue of water scarcity requires the implementation of effective methods for accumulating and conserving runoff in volumes sufficient to sustain regional livelihoods, but without repeating past mistakes associated with the excessive regulation of river channels.

In this regard, there is an urgent need for non-standard solutions–the development of simple and effective methods for managing the hydrological regime [14]–that would simultaneously allow for water storage and ensure the ecological protection of small rivers by maintaining their natural flow [15, 16]. In our opinion, the solution to this challenging problem lies in the implementation of innovative complexes of hydraulic structures in river floodplains, which allow for the rational use of floodwater resources without causing destructive impacts on the river ecosystem.

It is worth noting that the works of leading Ukrainian scientists (S.O. Afanasyev, V.I. Vyshnevsky, I.V. Voitovich, I.V. Gopchak, E.D. Gopchenko, V.V. Hrebin, N.S. Loboda, V.B. Mokin, V.I. Osadchiy, V.I. Pichura, V.M. Popov, A.M. Rokochynskyi, M.I. Romashchenko, S.I. Snizhko, V.M. Starodubtsev, V.A. Stashuk, A.M. Shevchenko, V.K. Khilchevskyi, A.V. Yatsyk, M.V. Yatsyuk and many others).

Research Methods. The research methodology is based on a comprehensive approach that combines an analysis of modern foreign and domestic innovative solutions for managing the hydrological regime of watercourses [17, 18], statistical data, known hydrological design characteristics of river ecosystems in the steppe zone of Ukraine, and methods of engineering modeling of hydraulic structures.

The hydrographic network of small rivers in the steppe zone of Ukraine was chosen as the object of study and the basis for theoretical generalization and typification [3, 19, 20]. The analysis was based on data on the dynamics of pond and reservoir construction over the past 50 years, as well as a comparison of the volumes of accumulated water with local runoff volumes.

To substantiate the general parameters of hydraulic structures and their operational technologies, evaluation and comparison methods were applied, in particular, well-known data on water inflow during flood periods and the spring flood season. Prospects for incorporating new technologies and methods of managing hydraulic structures took into account current and projected climate changes, as well as the actual state of river channel regulation and the level of technical operation of existing water management structures.

The methodology for developing technical solutions included the development and justification of two options [21, 22]:

1) for channel ponds–simulation of the physical separation of the channel using embankments to ensure a free-flowing (unobstructed) current.

2) for floodplain complexes–justification of the standardization of artificial excavation parameters (depth and volume) in accordance with water consumption needs and local hydrological and hydrogeological conditions.

A comparative analysis of the overall effectiveness of the proposed solutions was evaluated by comparing the technical and technological parameters of the various options.

The methodology for managing the hydrological regime is based on the principles of gravity-fed flow regulation. It involves establishing algorithms (protocols) for the operation of control structures (opening/closing of gates) depending on the phase of the river's hydrological regime; the use of artificial aeration via rock-fill connecting structures to enhance the water's self-purification capacity; modeling the processes of reverse discharge of water from reservoirs into the river channel during the low-flow period to maintain ecological flow. To implement the proposed approach at a real-world study site, we used standard methods for calculating maximum discharge (peak discharge rate) for rain-induced floods and snowmelt.

In the absence of direct hydrometric observations of maximum storm runoff in the Steppe Zone of Ukraine, the most reasonable approach is to apply the calculation models proposed by P. F. Vyshnevsky [23]. Specifically, for a storm flood:

$$Q_p = 1.67 \cdot h_m \cdot F \cdot \varphi \cdot n \cdot r \cdot r_1 \cdot \lambda, \qquad (1)$$

where Q_p is the maximum instantaneous discharge (m³/s) with a probability of exceedance of $P\%$;

1,67 is the measurement factor; h_m – maximum storm runoff yield with a 1% probability of exceedance, determined from a map and equal to 5,5 mm/10 min for the center of the watershed; φ – the reduction factor for maximum storm runoff, which depends on the slope run-off time and is determined as $\varphi = (2.26)/(1+6{,}3n_1)$ when $n < 1$; $-\varphi = 0{,}626/(1+1{,}02n_1)$ when $n > 1$; F – the catchment area of the river basin upstream of the design cross-section, km^2; n – a coefficient accounting for the influence of forests and wetlands on runoff from the basin, which is slightly less than 1; r – a coefficient accounting for the retention of runoff by pond and reservoir systems; in the calculation, the areas of all ponds and the depth of the regulating reservoir were determined; r_1 – a coefficient for natural regulation of discharge by wetland floodplains, depending on the floodplain's shape, type of wetland coverage (proportion), and wetland areas; λ – a transition coefficient from a 1% probability of exceeding maximum water discharge to the design discharge.

The following formula was used to estimate the parameters of the maximum snowmelt runoff:

$$Q_p = 0{,}28 \cdot \alpha_m \cdot \varphi \cdot F \cdot \rho \cdot r \cdot \lambda, \qquad (2)$$

where Q_p is the maximum instantaneous discharge (m^3/s) with a probability of exceedance *of* P%; a_m is the maximum intensity of meltwater runoff (mm/hour). In this study, a 1% confidence level (probability of exceedance) is adopted based on reference data, and for the design watershed, it equals 4,3 mm/hour; φ is the reduction factor for the maximum discharge modulus, which is determined separately for each designated cross-section; F – the area of the watershed upstream of the design section, km^2; ρ – a coefficient that modifies runoff discharge from the basin due to the influence of forest cover and wetland areas; r – a coefficient accounting for the influence of the reservoir system; λ – a transition coefficient from a 1% probability of exceeding maximum discharge to another probability; *0,28* – a measurement coefficient.

The determination of minimum runoff characteristics [q, L/(sec·km^2)] was based on the methodological approach proposed by V.K. Khilchevsky [24]. Data on regional average monthly runoff modules were used for the calculations. The lowest value of the runoff module with a 75% probability of occurrence was adopted as a representative indicator of the minimum 30-day water discharge.

The QGIS toolkit was used for the morphometric analysis and spatial modeling of the Nizhnya Tersa River watershed. A 3D terrain model was created based on USGS digital elevation models (DEMs) through geospatial processing (constructing continuous surfaces by interpolation). Using terrain analysis algorithms, a hydrological correction of the DTM was performed, which made it possible to accurately determine the boundaries of the catchment area of the studied pond, calculate the water surface areas at various water levels, and derive the topographic characteristics of the pond basin $W = f(H)$.

Research Results. During the study, two promising technical solutions were developed and analyzed, aimed at restoring the hydrological regime of small rivers in the steppe zone of Ukraine. Both options are based on the principle of rational use of runoff during the flood season; however, they differ in their engineering design and functional purpose, which allows the water infrastructure to be adapted to modern operating conditions.

Option 1) *A method for constructing a complex of hydraulic structures based on existing channel ponds.* This option involves transforming the existing hydraulic complex by introducing a set of structures that separate the functions of water storage and ensuring a continuous river flow. The main idea is to physically separate the river channel from the reservoir's regulating capacity. The technical details of the construction are as follows (Fig. 2). Along one of the reservoir's banks, a coffer dam is built using local soil materials, forming a bypass channel (the river channel). This structure bounds the channel on one side, while the natural shoreline serves as the other barrier. The embankment is designed such that its crest elevation prevents any interaction (overflow) between the regulating reservoir and the river channel during all phases of the river's flow regime. An open control gate is installed at the head of the reservoir (upstream). The reservoir's filling regime is controlled either manually or automatically–by installing a simple automated system to monitor water levels upstream and downstream of the regulating structure. This ensures unimpeded flow of domestic water through the river channel. The construction of additional structures (regulatory, control, connecting, and spillway structures) as part of the hydraulic complex and the achievement of the specified hydrological regime of the river are carried out under conditions of gravity-fed flow regulation, taking into account the river's current water availability. To increase the efficiency of water intake during reservoir filling, a backwater structure–a stone weir combined with a flow-directing intake spur–is constructed next to the

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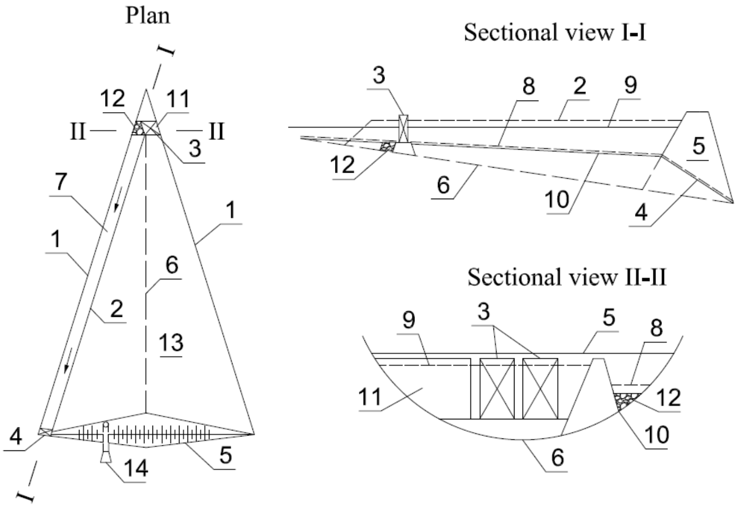
regulator. This allows water to be directed into the reservoir even at low water levels. Once the reservoir is filled to the normal backwater level (NBL) or to the lowest hydrologically feasible level, the regulator gate is closed, and all domestic wastewater is diverted through a bypass channel. An additional water discharge structure is installed in the existing dam to allow water to flow into the lower reach. It is constructed as a rock-fill connecting water-passage structure (a rapid with artificial roughness or a drop). This solution ensures intensive aeration of the flow, which is a key factor in enhancing the river's self-purification capacity. The spillway, which is typically part of the hydropower complex, will perform its function during years of high water levels. This technology allows the reservoir to be used as a regulating capacity without interrupting the river's transit flow, thereby minimizing environmental risks.

Option 2) *Technology for creating autonomous floodplain complexes with artificial basins.* The second technological option involves creating new storage basins in the river floodplain at a certain distance from its natural channel (Fig. 3). This solution is most effective for flat terrain, where it is necessary to ensure a guaranteed water supply for agriculture without blocking the river channel. The key components of this complex of hydraulic structures are constructed in the following sequence. First, during the low-water period, an excavation pit for an artificial reservoir is formed in the floodplain of a small river. Its depth and volume are calculated based on water consumption needs, local hydrogeological conditions, and the river's guaranteed water flow or the characteristics of its hydrological regime.

To prevent water loss, the bottom and walls of the excavation on the river side are lined with protective screens made of clayey rock. The connection to the river is established via a special channel equipped with a control structure at its mouth. The technology provides not only for water intake during floods (passive accumulation) but also for the active discharge of water from the excavation back into the river channel during dry periods via a water outlet. This allows for the artificial regulation of the river's flow, prevents it from drying up, and maintains an ecologically safe natural state (discharge) of its floodplain during the dry season. Under these technical and technological conditions for the construction of the water management system complex, the method of managing the hydrological regime of small rivers is carried out in such a way that during a flood, water from the river flows through a control structure located at the mouth of the intake channel into the excavation pit and into the artificial reservoir. In this case, the regulator's shut-off device remains open until the pit is filled or until a hydrologically justified level is reached under the conditions of a specific high-water phase. When the water level in the river channel drops, the regulator's shut-off device is closed to prevent reverse outflow of water from the pit. During the dry season, when the river


Plan

Sectional view I-I

Sectional view II-II

Fig. 2. Schematic diagram of the construction of hydraulic structures on existing channel ponds [21]: 1 – pond shoreline; 2 – embankment; 3 – open regulator; 4 – water passage structure; 5 – existing weir; 6 – pool thalweg; 7 – bypass channel; 8 – low-water level of the watercourse; 9 – normal backwater level of the pool; 10 – bottom of the bypass channel; 11 – flow-directing (water-intake) spur; 12 – retaining structure–rap; 13 – pond; 14 – spillway

water level drops below its minimum value, water is discharged from the artificial reservoir back into the river channel by opening the control structure's shut-off device and/or the spillway to prevent the river from drying up. Thus, managing the volumes and timing of river water intake and discharge using a complex of hydraulic structures ensures flow regulation and the achievement of a predetermined, ecologically safe hydrological regime for small rivers.

Based on the presented results of the technological methods for constructing hydraulic structures, a comparative analysis of these methods has been compiled (Table 1).

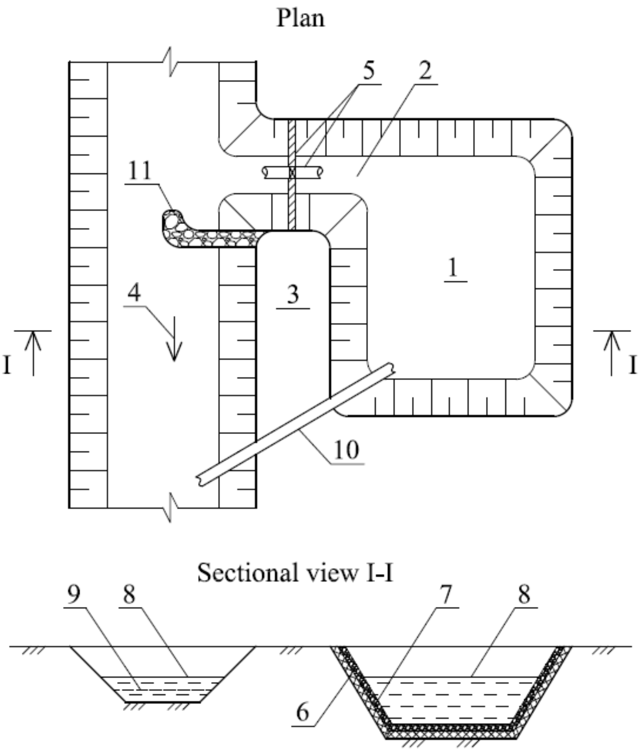


Fig. 3. Schematic diagram of the creation of autonomous floodplain complexes with artificial basins [22]:

1 – basin for an artificial reservoir; 2 – intake channel; 3 – embankment; 4 – river channel; 5 – control structure; 6 – anti-filtration screen; 7 – protective layer of bedrock; 8 – maximum and 9 – minimum water levels in the river; 10 – water outlet; 11 – water intake spur to increase the water intake coefficient

1. Comparative characteristics of the proposed technical solutions

Comparison parameter	Option 1: channel pond	Option 2: floodplain reservoir
Main objective	✓ Restoration of a natural river flow within the pond basin with the ability to store runoff	✓ Accumulation of runoff and replenishment during the low-flow period
Key technological element	✓ Bypass channel and distribution regulator	✓ Excavation with an anti-filtration screen
Environmental impact	✓ Aeration and self-purification of the flow, restoration of free flow	✓ Prevention of riverbed drying
Advantages	✓ Ensures continuous transit of water and sediment through the riverbed; ✓ Improves oxygen levels (aeration); ✓ Does not require the acquisition of new land parcels	✓ Minimal impact on the natural river channel; ✓ Eliminates the risk of silting in the main channel during floods; ✓ Allows for precise control of water discharge during low-water periods.
Disadvantages/ Risks	✓ Technical complexity of constructing a spillway dam within an existing reservoir; ✓ The need for constant monitoring of the technical condition of the bypass channel;	✓ Significant earthwork is required to excavate the foundation pit; ✓ Risk of localized flooding if the integrity of the screen is compromised.

The presented and substantiated technological methods for managing the hydrological regime of small rivers allow us to move from theoretical analysis to practical modeling of the operation of hydraulic structures. To verify the proposed technical solutions and assess their effectiveness under real-world conditions in the Steppe Zone, a typical site was selected–a channel pond (Fig. 4)–located in the basin of the Nyzhnia Tersa River (Dnipropetrovskyi region). This site was chosen for its representativeness: the morphometric characteristics of the watershed and the degree of anthropogenic transformation of the river channel correspond to general regional trends. Based on a digital elevation model (DEM) created using the QGIS GIS toolkit, a detailed alignment of the calculated water levels with the actual topographic base was performed, which made it possible to substantiate the design parameters of the innovative hydraulic structure.

To determine the hydrological parameters of maximum discharge at the actual study site, calculations were performed for storm floods and spring floods (Equations 1 and 2; Table 2).

Based on the results of these calculations, it was determined that for the studied watershed, the zoned value of the minimum runoff coefficient is 0,07 L/(sec·km²). Accordingly, the calculated minimum (30-day) water discharge with a 75% probability of occurrence is 660 L/sec. The obtained results correlate with regional patterns of runoff formation within the selected physiographic zone.

To perform further water management calculations and justify the design parameters of hydraulic structures at this site, a spatial analysis and modeling algorithm was used in the QGIS environment. A 3D model (Fig. 5) was created, and the topographic characteristics (Fig. 6) of the pond's floodplain were determined.

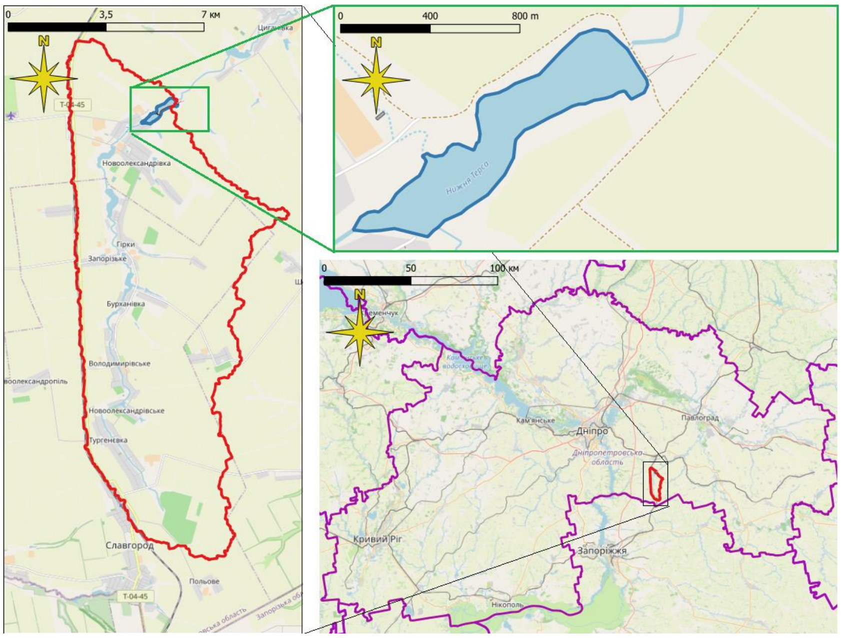


Fig. 4. Study site for substantiating the proposed engineering solutions (ponds near the village of Novooleksandrivka on the Nyzhnia Tersa River, Dnipropetrovsk Oblast)

2. Calculations of maximum discharge during spring floods and rain-induced floods on the Nyzhnia Tersa River at the pond site near the village of Novooleksandrivka

Site characteristics: Nyzhnia Tersa River; cross-section of the studied reservoir, F_{bas}= 85,1 km²		**Confidence level P, %**					
		0.5	**1**	**2**	**5**	**10**	**25**
Spring Flood							
Maximum instantaneous flow rate	m³/s	35	31	26	21	17	11
Maximum average daily flow rate	m³/s	19	17	15	12	9	6
Flood discharge volume	million m³	7,8	6,9	6,1	5,0	4,1	3,0
Rain-induced flooding							
Maximum flow rate	m³/s	40	33	27	17	12	4
Flood discharge volume	million m³	3,4	2,9	2,4	1,7	1,1	0,6

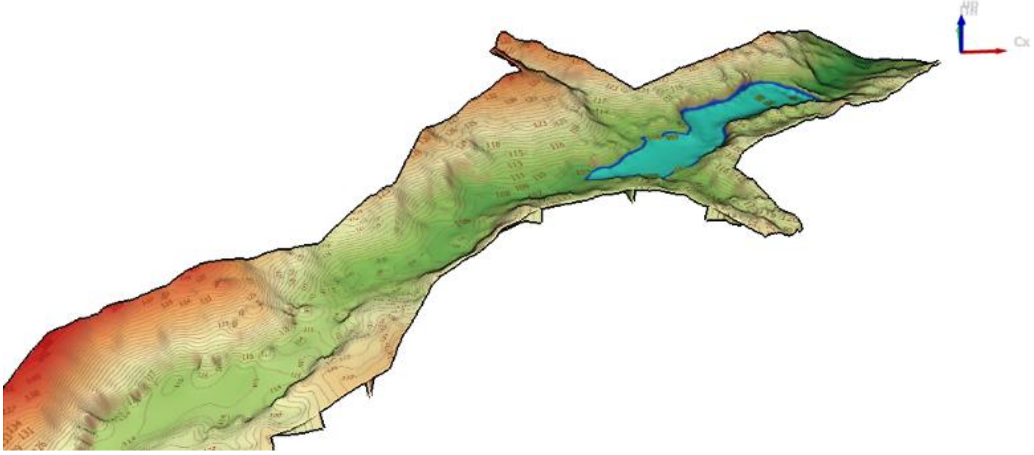
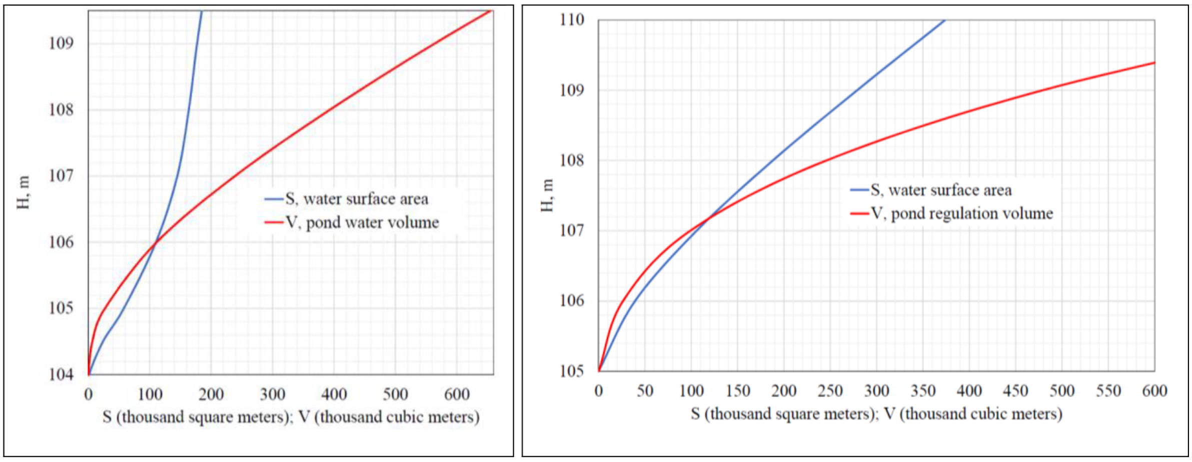


Fig. 5. 3D model of a section of the pond's floodplain in the upper reach



a) b)

Fig. 6. Topographic characteristics: a) the pond, b) the regulating capacity of the upper reach

As can be seen in Figure 6, the curve representing the pond area shows a marked upward trend. This is explained by the erosion of the banks by water at levels close to the normal (NPG) and forced (FPG) water tables, as confirmed by the topography. At the same time, in the upper reach– which is almost always a marshy area with dense vegetation and shallow depths–such erosion was simply impossible, so the curve showing changes in area exhibits a classic pattern.

An example of implementing this approach to river water regime management and the construction of hydraulic structures based on the first design option is shown in Figures 7 and 8. It is worth noting that the dimensions of the regulator and the weir can be varied to achieve an optimal hydrological regime for the watercourse, based on hydrological calculations and specific management objectives.

The next step in justifying the operating parameters of the hydraulic structures is to perform hydraulic calculations for the water-passage structures. Such a flow balance calculation was performed for floods with 1%, 10%, and 25% return periods (Figures 9, 10, and 11, respectively) and to determine the conditions for filling the reservoir's useful capacity.

The initial conditions for the calculation are as follows: the minimum water level in the upper reach is close to the domestic water level during the inter-flood period and is 106 m BS. This level is taken as the bottom of the weir channel. The water level in the lower reach of the reservoir is close to the dead storage level (DSL) and is 105,0 m BS.

It should be noted that the presence of a spillway ensures the simultaneous discharge of excess water; therefore, the FPG will be slightly lower than the value calculated in the balance calculation and will subsequently drop to the NPG level. The symbols used in Figures 9–11 share the following characteristics: Q% – hydrograph

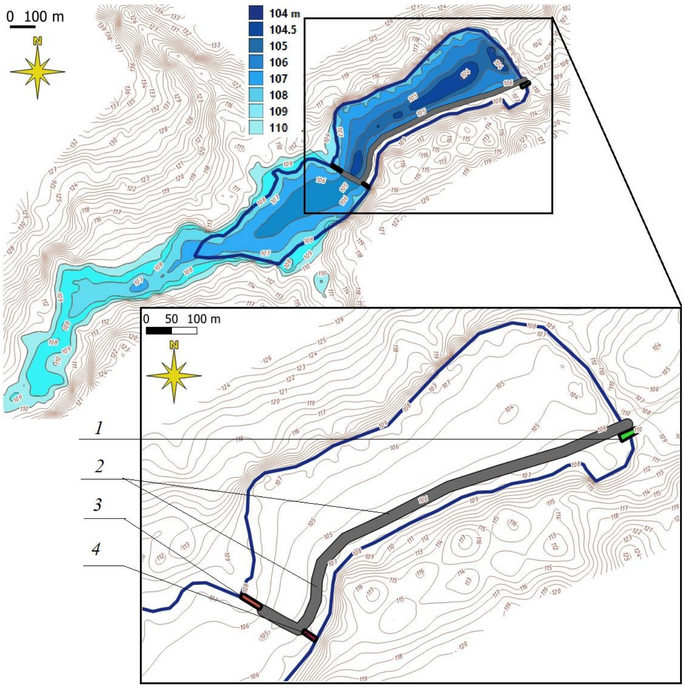


Fig. 7. Determination of topographic characteristics (water surface area) in QGIS using a 3D digital elevation model and an example of the practical implementation of a technical approach to the construction of hydraulic structures for river water regime management:

1 – connecting (water-passing) structure; 2 – embankment dam; 3 – regulator (open regulator); 4 – channel weir

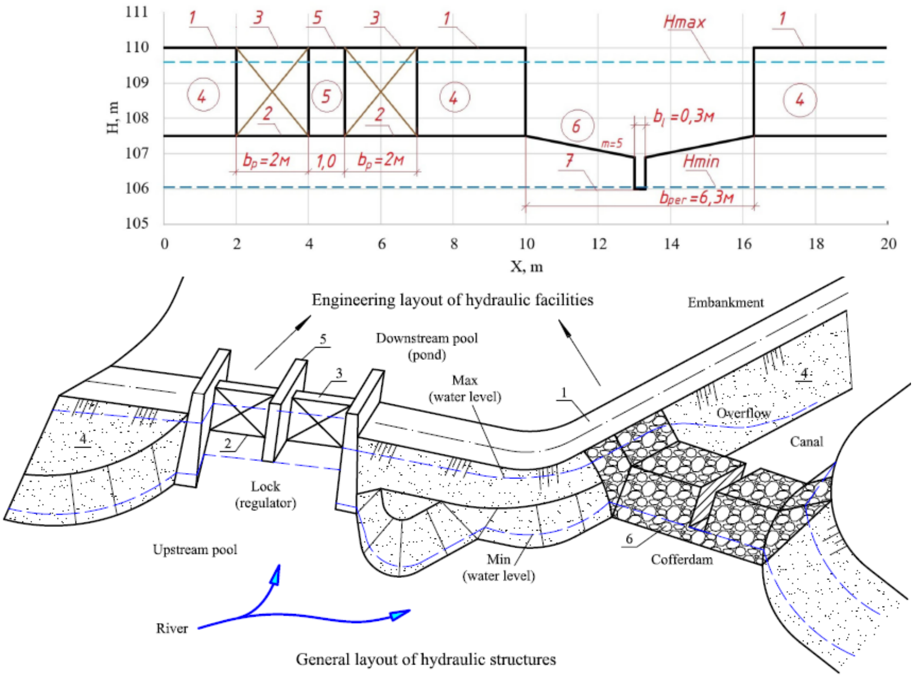


Fig. 8. General view of the hydraulic structures at a channel-type reservoir for managing the river's hydrological regime:

1 – crest of the spillway dam; 2 – weir of the regulating intake; 3 – upper edge of the flat gate; 4 – embankment; 5 – regulator weir; 6 – channel cross-connection; $H_{max(min)}$ – water level limits in the upper reach (H_{min} corresponds to the passage of the minimum flow through the cross-connection channel; H_{max}corresponds to the discharge of the 1% flood flow, thereby determining the structural dimensions of the complex of structures)

of the % probability of occurrence, accounting for flow transformation by the upper reservoirs; Q_{per} – water flow through the spillway; Q_{st} – flow rate for filling the reservoir through the control gate; T_{close} – gate closure time (optimal condition: equalization of levels in the reservoir and the upper reach; in practice, for any probability of occurrence, this corresponds to the period when the hydrograph begins to decline); T_{open} – start of reservoir filling; dH – difference in levels between the flood control basin and the reservoir; H_{flood} – the level regime in the flood basin during a flood of a given probability – determined under conditions of hydraulic equilibrium, i.e., the continuity equation ($Q_{inlet(flood)} = Q_{outlet(overflow\ through\ the\ control\ structure\ and\ spillway)}$); $H_{reservoir}$ – the reservoir filling regime.

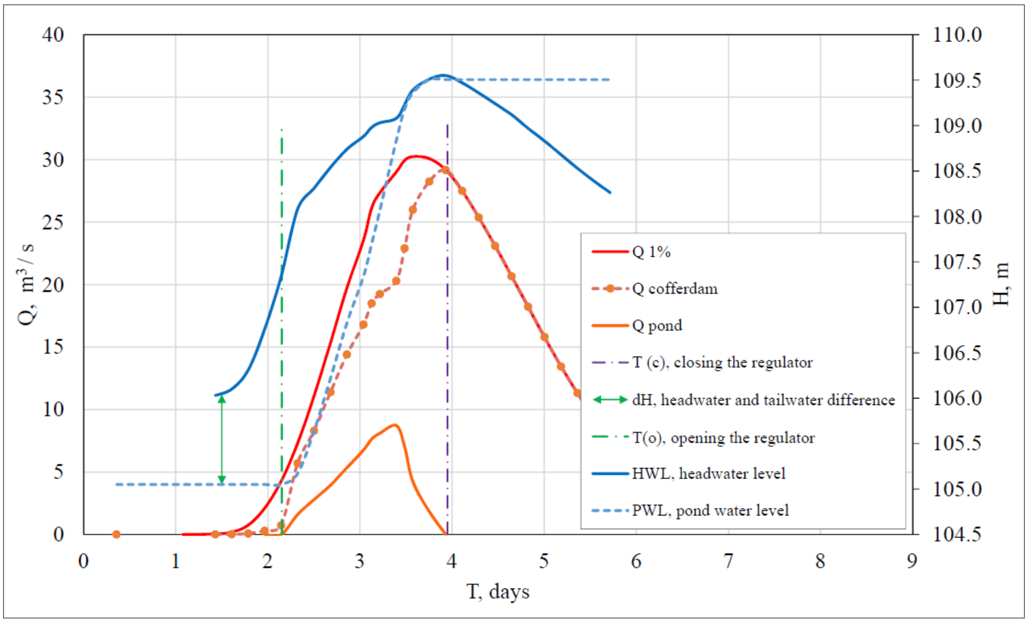


Fig. 9. Balance calculation for the discharge of a 1% probability flood and the filling of the reservoir's usable capacity

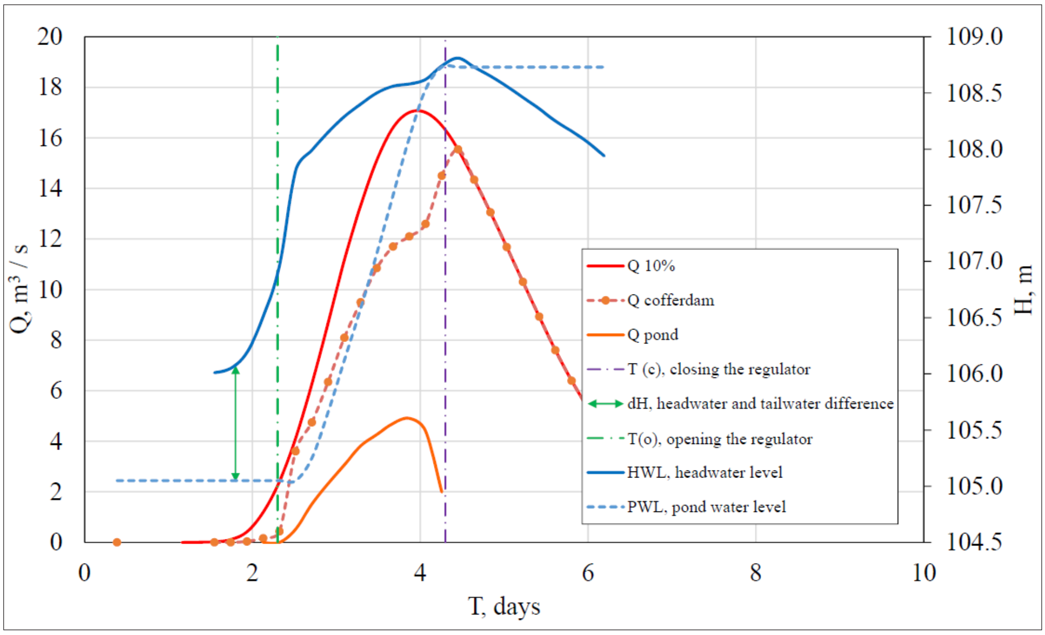


Fig. 10. Balance calculation for flood discharge with a 10% probability and filling of the reservoir's usable capacity

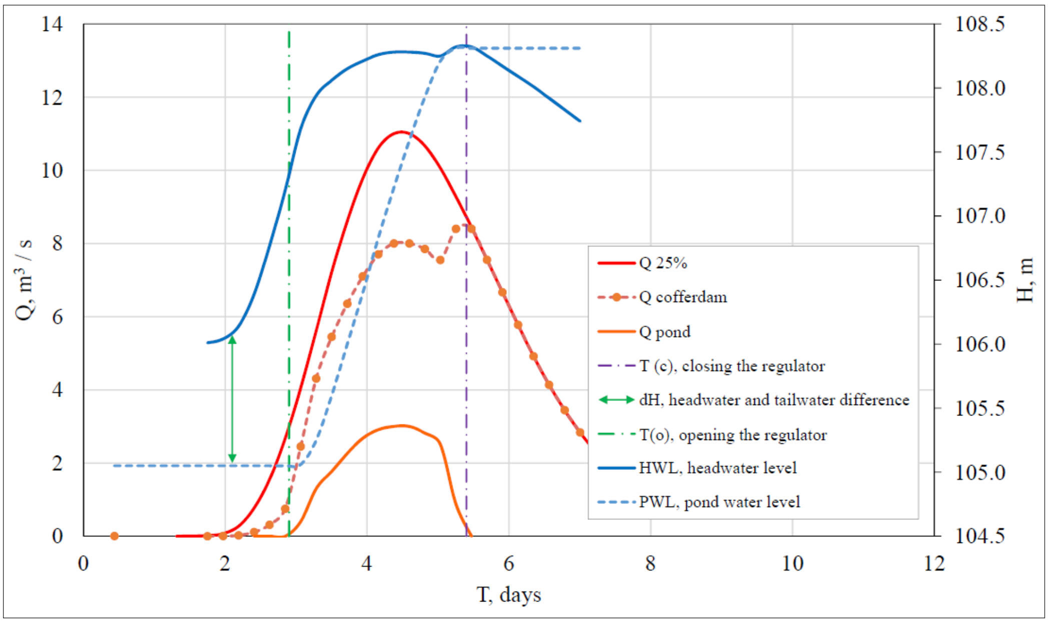


Fig. 11. Balance calculation for flood discharge with a 25% probability and filling of the reservoir's usable capacity

An analysis of the hydraulic operating regime of the hydraulic structure revealed characteristic fluctuations in water discharge at the spillway, which are caused by the regulator operating in a submerged mode. A decrease in the regulator's discharge capacity under such conditions leads to a redistribution of flow toward the spillway. This process is described by the continuity equation for water flow, according to which the total discharge of a 1% probability flood is equal to the sum of the discharges through the spillway: $Q_{i\%}= Q_{max}+ Q_{spillway}$. It has been established that when critical flooding levels are reached, the main hydraulic head is transferred to the bridge, which must be taken into account when calculating the static stability of the structure.

Based on the hydrological calculations and an analysis of high-water levels in the reservoir basin, it has been determined that the normal water level of the reservoir under study, assuming the presence of a spillway, is estimated at 108,0–108,5 m (in Baltic Normal Height System). At the same time, the minimum elevations of the dam crest are recorded at 110.0 m, which ensures the necessary safety margin. During a 1% probability design flood, the maximum possible water level in the reservoir reaches 109,50 m. According to the constructed storage capacity curve, at an elevation of 109,0 m, the reservoir's storage volume is approximately 560 thousand m^3. Analysis of the data indicates that floods with a probability of occurrence of 40–50% or higher ensure stable filling of the reservoir basin to the design water level.

Environmental and economic assessment of the proposed solutions. The practical implementation of the proposed innovative technology for managing the hydrological regime of a water body involves a number of engineering, hydrotechnical, and financial and economic challenges. For channel ponds in the steppe zone of Ukraine with an area of 10–50 hectares, the scale of such work is significant, since the length of the distribution embankment, depending on the geometry of the reservoir basin, can range from 500 to 1,000 meters. Depending on hydrological conditions, the thickness of bottom sediments, the availability of specialized equipment, and environmental requirements for the conservation of biota, we have identified and analyzed two main technical options for constructing the distribution dam. For the conditions of the site under study, a comparative analysis of the technical, economic, and environmental indicators of both options was conducted (Table 3).

The comparative analysis presented in Table 3 illustrates the dilemma between technological simplicity and environmental responsibility. International practices are clearly focused on minimizing environmental risks. As a result, Option 1 (with dewatering) is considered economically unfeasible in developed countries due to the enormous associated costs and environmental compensation requirements.

3. Comparative analysis of technical and economic options for constructing a partition dam for a pond with an area of 10–50 hectares

Indicator / Evaluation criterion	**Option 1 (full or partial draining)**	**Option 2 (without draining the reservoir)**
Work Procedure	This approach involves draining water through the existing spillway during the summer-fall low-water period. After the pond bed has been drained (or temporary drainage channels have been constructed to dewater the construction site), the dam is built using traditional mechanized methods with bulldozers and excavators, with layer-by-layer soil compaction.	The work is carried out directly in the aquatic environment. To prevent the displacement of weak silty soils in the foundation and the erosion of the dam body, modern geosynthetic materials are to be used; these are laid on the bottom before backfilling with rock or sandy-clay soil. In global lake restoration practice [25, 26], the most effective variation of this method involves the use of geotextile tubes, which are filled with bottom sediment using dredgers.
Capital expenditures for earthworks	Base (100%)	Increased (125–150%) due to geomaterials and soil loss in water
Need for special materials	Minimal (local soil)	High (geotextiles, geogrids, crushed stone)
Project Duration	Long (depend on the rate of bed drying)	Short (not dependent on the water level in the reservoir)
Environmental damage and penalties	High (loss of water resources, riverbed desiccation, destruction of the biocenosis)	Minimal (local impact in the backfill area)
Economic losses to the water user	Significant (loss of water management functions and fish productivity for 1–2 seasons)	None or minimal (the pond remains fully operational)
Environmental impact assessment procedure and environmental approvals	Complex and time-consuming	Simplified (equivalent to revitalization measures)
Advantages	High-quality compaction of the dam body, minimal material loss due to scouring, ability to precisely profile the transit channel “on dry land”	Preservation of the water volume and ecological balance of the reservoir during construction; no need to drain the water; simplified environmental compliance procedure.
Disadvantages	Temporary suspension of the pond’s operation leads to significant environmental damage (death of aquaculture, ecosystem degradation) and a loss of revenue for water users for at least 1–2 seasons. In domestic practice, the direct cost of earthworks using this method is considered the baseline. However, when evaluating similar projects in the EU and the U.S. (https://ascelibrary.org/), this method is regarded as the most expensive. The direct cost of excavating and compacting soil “dry” abroad is approximately \$20–45 per m^3, while associated compensation payments for the destruction of wetlands can reach \$25,000–100,000 per hectare of drained land. Furthermore, obtaining permits to completely drain large water bodies (50 hectares or more) in Western practice takes years and costs between \$20,000 and \$100,000. Thus, the total estimated cost of implementing Option 1 for a 1,000-meter-long dam, based on European prices, may exceed \$1,0–1,5 million.	The technology requires increased soil consumption (by 20–30% due to silt absorption and initial underwater erosion) and the use of specialized materials. Heavy woven geotextiles cost between \$5 and \$50 per m^2 on the global market, depending on their strength. The average cost of constructing underwater barriers and dams using geotextile tubes is \$600–750 per meter. Thus, the total estimated cost of constructing a 1,000-meter dam without draining the water, based on global benchmarks, is approximately \$600,000–850,000. Despite the higher direct material costs, this option offsets, to some extent, environmental fines and losses resulting from the cessation of the reservoir’s operation.

At the same time, given current domestic realities, the most technologically feasible and engineering-wise approach remains the “dry” embankment construction–provided the reservoir is completely drained or during its summer-autumn low-water period (Option 1). This is due to the availability of traditional equipment and the lack of a need for expensive imported geosynthetic materials.

The situation is complicated by institutional factors. Under current conditions, which are burdened by a deep economic crisis, the consequences of military operations, and the inadequacy of domestic environmental legislation, the actual completion of environmental impact assessment (EIA) and strategic environmental assessment (SEA) procedures for projects of this scale is quite complex and atypical for Ukrainian practice. Due to excessive bureaucracy or, conversely, a purely formal approach to oversight, these tools often fail to fulfill their regulatory function. In light of this, in our opinion, under current development conditions, the likelihood of the first option being implemented–albeit without a proper and comprehensive environmental review–is the highest.

Thus, a comprehensive analysis shows that although, from the perspective of balanced natural resource use and European experience in water resource management, Option 2 (or a combined method involving a partial reduction in water level by 30–40%) is significantly safer, the actual economic and geopolitical context in Ukraine forces water users to choose simpler, albeit more environmentally destructive, engineering solutions.

Conclusions:

1. It has been proven that the critical degradation of small rivers in the Ukrainian Steppe is caused by a disruption of the hydrological integrity of watercourses due to the cascade regulation of their channels. It has been established that the existing model of reservoir operation, where the storage volume exceeds the volume of local runoff, leads to the cessation of “living flow” during the low-water period, which requires the implementation of new technological schemes for runoff management [27].

2. The use of GIS tools (QGIS) and the analysis of digital elevation models have improved the accuracy of morphometric calculations for watersheds. The reservoir capacity curves constructed using GIS algorithms served as the basis for accurately predicting flood discharge transformation, which is an essential step in designing innovative hydraulic structures under complex physical and geographical conditions.

3. It has been scientifically demonstrated that separating the river channel from the reservoir’s storage capacity using a bypass channel and control structures (the authors’ Ukrainian utility model patents No. 154298 and No. 156105) is a promising and effective method for river revitalization. The proposed technology for equipping existing ponds with bypass channels and distribution regulators allows for the separation of water storage and flow transit functions. This ensures a continuous river flow throughout the year, activates self-purification processes through aeration on rocky rapids, and promotes the restoration of the watercourse’s ecosystem functions. The creation of artificial basins in floodplains with protective anti-filtration screens is an effective method for ensuring a reliable water supply without blocking the river channel. Such a system allows not only for the accumulation of water during floods but also for the replenishment of the river during dry periods of the year.

4. Calculations and modeling of the implementation of the proposed approaches at a real-world site in the Lower Tersa River basin confirmed the feasibility of these solutions. It has been established that at a normal water level of 108,0–108,5 m BS and during a 1% probability flood (maximum level of 109,50 m BS), the system provides for the accumulation of 560,000 $m^3$of water. At the same time, a continuous transit flow through the bypass channel is maintained, which eliminates the risk of overflow over the dam (elevation 110,0 m BS) and sustains the hydrological regime of the river downstream. Filling the reservoir basin to the design water level is ensured with a 40–50% probability of flooding and a higher level of reliability.

5. The proposed technologies are consistent with the strategic objectives of the EU Water Framework Directive and can be used as model solutions for the post-war restoration of Ukraine’s hydraulic infrastructure. This will help balance the interests of the agricultural sector and ensure compliance with environmental requirements for the conservation of biodiversity in small rivers amid global climate change.

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ГІДРОТЕХНІЧНІ СПОРУДИ ТА ІННОВАЦІЙНІ ТЕХНОЛОГІЇ УПРАВЛІННЯ ГІДРОЛОГІЧНИМ РЕЖИМОМ МАЛИХ РІЧОК СТЕПОВОЇ ЗОНИ УКРАЇНИ

Г.В. Гапіч[1], канд. тех. наук, В.В. Коваленко[2], канд. с.-г. наук

[1] Дніпровський державний аграрно-економічний університет, м. Дніпро, Україна;
https://orcid.org/0000-0001-5617-3566, e-mail: hapich.h.v@dsau.dp.ua;
[2] Дніпровський державний аграрно-економічний університет, м. Дніпро, Україна;
https://orcid.org/0000-0003-3865-597X, e-mail: kovalenko.v.v@dsau.dp.ua

Анотація. *Малі річки степової зони України є найбільш вразливою ланкою гідрографічної мережі, що гостро реагує на кліматичні зміни та антропогенний тиск. Сучасна тенденція до їх обміління та втрати течії в меженний період зумовлена надмірним зарегулюванням русел ставками і водосховищами, що перетворює річки на застійні водойми. На прикладі Дніпропетровської області встановлено, що за період останніх 40 років кількість ставків зросла у 2,7 рази, а їхня загальна місткість перевищила об'єм місцевого стоку, що створює загрозу екологічній безпеці водних екосистем. Традиційні греблі зупиняють потік після паводку, тому актуальним є розробка рішень* *для акумуляції води без порушення гідрологічного режиму. Методика дослідження базується на аналізі гідрологічних даних та інженерному моделюванні систем самопливного регулювання стоку із застосуванням алгоритмів геоінформаційної системи QGIS. Перший розроблений варіант передбачає модернізацію руслових ставків шляхом відокремлення русла річки від ємності ставка за допомогою дамби обвалування та створення обвідного каналу. У верхів'ї встановлюється відкритий регулятор, що дозволяє наповнювати ставок у періоди високих вод, взагалі не припиняючи транзитну течію. Для підвищення якості води у складі гідровузла застосовується кам'яно-накидна сполучна споруда, що забезпечує інтенсивну аерацію та самоочищення потоку. Другий варіант полягає у створенні автономних заплавних комплексів із штучними котлованами. Ця технологія дозволяє не лише накопичувати паводкову воду, а й здійснювати її активний скид назад у русло в посушливий період для підтримки екологічного стоку. Порівняльний аналіз підтверджує, що русловий варіант оптимальний для відновлення проточності вже зарегульованих річок, тоді як заплавні водойми ефективні для сталого водозабезпечення без втручання в русло. Практична реалізація запропонованих рішень апробована на об'єкті в басейні річки Нижня Терса (площа водозбору 85,1 км^2). Результати моделювання підтвердили працездатність системи: при нормальному підпірному горизонті (НПГ) 108,0–108,5 м БС та проходженні розрахункового паводка 1 % забезпеченості (рівень наповнення 109,50 м БС) забезпечується акумуляція 560 тис. м^3 води при повному збереженні екологічного стоку в обвідному каналі. Впровадження таких комплексів дозволяє реалізувати принципи Водної рамкової директиви ЄС щодо ревіталізації річок, забезпечуючи «живу течію» навіть у маловодні роки та створюючи умови для відновлення біорізноманіття степових екосистем в умовах повоєнного відновлення та стрімких змін клімату.*

***Ключові слова:** гідротехнічна споруда; водний об'єкт, річка, водна інженерія, водні технології, гідрологічний режим, екологічна безпека*

RETRACTION NOTICE

The editorial board of the journal “Land Reclamation and Water Management” is retracting the article: P.I. Kovalchuk, O.S. Demchuk, V.P. Kovalchuk, & H. A. Balykhina “Combined system of extreme control of mineralized water dilution in river basins,” published № 2, 2021, pp. [33–44], DOI: 10.31073/mivg202102-296.

The article was retracted by decision of the editorial board based on COPE recommendations following consideration of a complaint by Vasylenko Y. The Committee’s investigation confirmed the unauthorized use of the complainant’s cartographic material in 2015 without attribution, as well as evidence of digital manipulation of a photograph of the site (removal of the copyright stamp).

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ПОВІДОМЛЕННЯ ПРО РЕТРАКЦІЮ

Редакція журналу «Меліорація і водне господарство» відкликає статтю: *Ковальчук П.І., Демчук О.С., Ковальчук В.П., Балихіна Г.А. «Комбінована система екстремального управління розбавленням мінералізованих вод у басейнах річок»*, опубліковану в № 2, 2021 р., стор. [33–44], DOI: 10.31073/mivg202102-296.

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CONTENTS

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WATER RESOURCES

AGRO RESOURCES

HYDRAULIC ENGINEERING

НОТАТКИ
NOTES

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Замовлення книг:
тел.: +38 (050) 915-34-54, +38 (068) 517-50-33
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