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"LAND RECLAMATION AND WATER MANAGEMENT"

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KYIV • 2024

МІЖНАРОДНИЙ ЖУРНАЛ

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POST-DESIGN MONITORING OF THE IRRIGATION IMPACT ON THE ENVIRONMENT

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Abstract. *Approaches to conducting post-design monitoring of the impact of irrigation on soil condition are highlighted on the example of an individual agricultural farm of LLC "Granex-Cherkasy". The results of the implementation of the five-year post-design monitoring program under the conditions of irrigation by groundwater using sprinkling and drip methods proved the need to develop both unified general approaches to the formation of monitoring programs, as well as the mandatory consideration of the peculiarities of its management under different irrigation methods and hydrogeological-ameliorative conditions on the irrigation sites. As a basis for the development of a system of post-design monitoring of the impact of irrigation on the state of environmental components, it is proposed to use approaches to the organization and performance of local (on-site) monitoring of irrigated lands based on the requirements of current regulatory and methodological documents. The observation system, formed on the basis of previous studies, included periodic determination of irrigation water quality indicators in storage ponds or in the places of watering and routine observations of soil conditions at permanent monitoring points (observation points), which are recommended to be taken as coordinate points of the previously conducted testing study (at the stage of the preparation of the environmental impact assessment report). The results of the post-design monitoring proved the ecological admissibility of the impact of irrigation within the farm with groundwater of I and II quality classes (suitable and limitedly suitable according to individual quality indicators). Based on the results of monitoring, it was established that the soils under irrigation did not undergo significant classification changes in terms of deterioration for 5 years. The lack of manifestations of secondary (irrigation) salinization, sodification, and alkalinization of soils under the influence of irrigation indicates the environmental safety of the latter in accordance with the accepted standards for indicators of the degree of development of the specified soil degradation processes.*

Key words: *soil, salinization, irrigation, irrigation water, sodification, post-design monitoring, water quality*

Relevance of research. During the last decade, the process of restoring irrigation on existing irrigation systems in the regions of traditional irrigated agriculture, as well as the construction of the new irrigation networks in almost all the regions of the country, due to the progressive increase in the aridity of the climate and the significant deterioration of the conditions of natural moisture sufficiency for the cultivation of agricultural crops has begun in Ukraine [1−3]. The need to restore and increase the areas of actual irrigation is also emphasized in the "Irrigation and Drainage Strategy in Ukraine for the period until 2030" [4] and the Action Plan for its implementation [5].

The full-scale military aggression of the Russian Federation against Ukraine, the partial occupation of the territories, the destruction of the Kakhovska HPP dam and the emptying of the Kakhovska Reservoir led to a 70 % reduction in the irrigated area (Kherson, Mykolaiv, Zaporizhzhya, and Dnipropetrovsk regions), actually leaving almost 95 % of irrigation systems without a source of water in Kherson, 74 % – in Zaporizhia, and 30 % – in Dnipropetrovsk regions [6]. Such circumstances encourage farmers in other regions to increase the area under vegetables and other crops that were previously grown on the occupied territories or affected by the military invasion of the Russian Federation, and to use irrigation more widely to obtain guaranteed yields.

The experience of irrigation in different natural and climatic zones of Ukraine shows both the increase in the productivity of irrigated lands and certain negative ecological consequences of irrigated agriculture, in particular the development of soil degradation processes (flooding, irrigation erosion, secondary salinization and alkalinization of soils, pollution of soils and groundwater etc.) [7−9]. Therefore, obviously, and because of this, land reclamation, in particular, irrigation, on territories with an area of 20 hectares or more along with the construction of reclamation systems and specific facilities of the engineering infrastructure of reclamation systems are classified in the second category of types of planned activities and objects that can have a significant environmental impact and are subject to the environmental impact assessment (EIA) procedure in accordance with the Law of Ukraine “On Environmental Impact Assessment” adopted in 2017 [10].

According to the Article 13 of the aforementioned law, in order to identify any discrepancies and deviations in the predicted levels of impact on the effectiveness of measures to prevent environmental pollution and its reduction, the conclusion of the environmental impact assessment may provide for the implementation of post-design monitoring (PDM) by the business entity. In such a case, the order, terms and requirements for monitoring the impact of such activity on individual components of the environment, in particular on the soil cover, groundwater, etc., must be determined in the conclusion of the EIA of the planned activity related to irrigation. According to the results of the post-design monitoring, if necessary, the business entity and the relevant authorized authorities agree on taking additional measures to prevent, minimize, or eliminate the adverse consequences of the influence of irrigation on the condition of soils, groundwater, etc.

However, there are currently no unified approaches to the organization and implementation of such monitoring, requirements for reporting materials, and the implementation of necessary environmental protection measures. Only recently, the Ministry of Environmental Protection and Natural Resources of Ukraine approved the Methodological Recommendations for post-design monitoring, which contain general recommendations on the structure, content, and drawing up of the post-design monitoring report, on data and evaluation of PDM results [11].

The analysis of the available EIA conclusions confirms that most of them do not contain clear requirements for conducting monitoring, the terms and procedure for its implementation. During the practical implementation of monitoring, there may be problems related to the methodical provision of monitoring works, the composition and periodicity of certain types of observations, evaluation of their results, in particular, the admissibility and ecological safety of changes in soil fertility indicators and other environmental elements caused by irrigation.

In the context of the regulation of the latter and the impact of irrigation, the role of environmental standards established by the Resolution of the Cabinet of Ministers of Ukraine dated September 2, 2020 No. 766 “On the standards of environmentally safe irrigation, drainage, watering, and water disposal management” should be decisive [12]. However, some aforementioned indicators and their norms raise certain doubts and cannot be used for correct assessment of irrigation safety (norms of indicators relating to irrigation water, salinity, and alkalinity of soil, “ameliorative plantation plowing according to the depth of groundwater with mineralization of more than 5 g/dm^3» and “fractional composition of soils by susceptibility to wind erosion” indicators, etc.).

An urgent issue is taking into account the specifics of irrigation methods in monitoring observations. The problem of assessing the ecological and reclamation state of irrigated lands and the irrigation water quality for the Polissia zone needs to be solved.

Solving the vast majority of problematic issues and increasing the effectiveness and role of post-design monitoring of the irrigation systems impact can be ensured by involving in its organization and performance of the specialists with relevant experience in scientific and methodological support and implementation of ecological and remedial monitoring of irrigated lands. It is optimal to involve such specialists at the stage of preparation of the EIA Report.

Analysis of recent research and publications. Ecological and remedial monitoring is an important component of the information provision of control, primarily of the State, of the conditions of irrigated lands to substantiate measures for their rational and ecologically safe use, prevent or minimize soil degradation processes [13]. In Ukraine, irrigated lands monitoring (ILM) is carried out in accordance with the Law of Ukraine “On Land Reclamation”, Resolution of the Cabinet of Ministers of Ukraine dated March 30, 1998 No. 391 “On Approval of the Regulation on the State Environmental Monitoring System” as a branch component of state environmental monitoring.

Starting from the second half of the 90s of the last century, the hydrogeological and land reclamation service (expeditions and parties) of the State Water Administration (later State Water Agency) of Ukraine has been providing practical ecological and reclamation monitoring on irrigated lands of Ukraine. However, in the absence of sufficient funding, reduction of irrigation areas, optimization of the structure of organizations subordinate to the State Water Agency (reorganization and, essentially, semi-liquidation of the specialized hydrogeological and melioration service), annexation by the

Russian Federation of the Autonomous Republic of Crimea, partial occupation of Donetsk and Luhansk regions, cancellation of statistical reporting on irrigated lands according to form 1-OVG, in the last 10–15 years, there has been a decrease in the actual areas of reclaimed land under control, the volume of monitoring works, the number of observation networks, as well as a partial decrease in the informativeness of certain obtained results of the ILM [14].

New challenges and threats for the irrigated lands monitoring are associated both with the full-scale armed aggression of the Russian Federation against Ukraine, and with the declared and to some extent semi-spontaneously initiated institutional reform of the organizational structure of water resources management and land reclamation with the need to separate water resources management functions from water infrastructure management functions and provision of services. The transfer of powers related to hydrotechnical reclamation from the State Water Agency to the State Agency of Reclamation and Fisheries and their partial reorganization have led to the fact that, in practice, the implementation of the ILM by water management organizations of the State Water Agency has mostly been suspended.

A similar situation is observed with the publications in the sphere of irrigated lands monitoring, although in previous years sufficient attention was paid to the coverage of certain aspects of scientific and methodological support of the conduct of the sectoral ILM, methods for processing of its data, analysis of the results of assessment of the ecological and reclamation conditions of irrigated lands, etc, both by the scientists and the specialists of water management organizations [7, 15−17].

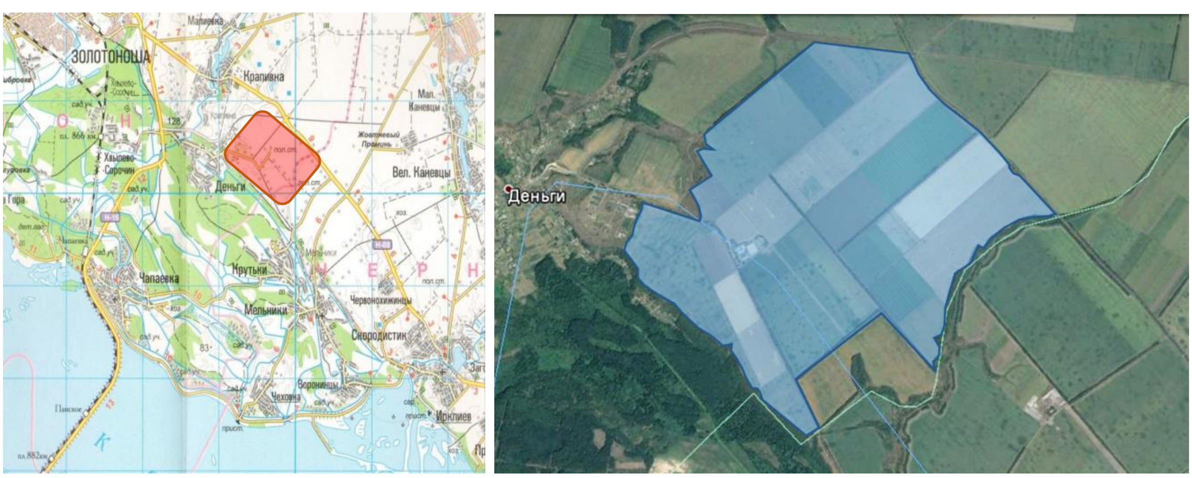
There are almost no freely available reports on post-design monitoring of newly created or reconstructed irrigation systems.

In general, the issue of methodical and information provision of post-design monitoring of the irrigation impact on the components of the environment, in particular on drip irrigation systems, with the use of groundwater for irrigation, primarily in the forest-steppe and Polissia zone, is poorly studied, and there are almost no publications on the results of its conduct [18, 19], which indicates the relevance of research and highlighting of possible changes in the environment associated with the irrigation systems functioning.

The experience of substantiating the post-design monitoring of the irrigation impact on environmental components and its conduct is considered on the example of planning and implementation of activities to ensure the irrigation of lands with underground water by sprinkling and drip methods in the agricultural farm LLC "Granex-Cherkasy", Zolotonosha district, Cherkasy region.

The purpose of the research is to assess changes in the quality of irrigation water and the conditions of irrigated soils on the lands of LLC "Granex-Cherkasy".

Research materials and methods. The post-design monitoring studies of soil conditions and irrigation water quality, which were carried out during 2019−2023, are territorially limited to the land plot, which is in use under the lease rights of LLC "Granex-Cherkasy" and is located northeast of the village Denhy in the administrative boundaries of Denhy starosta okruh (eldership) of the Zolotosha territorial community, Zolotonosha district, Cherkasy region (Fig. 1).



a b

Fig. 1. Overview map (a) and situational scheme (b) of the location of the research plot for post-design monitoring of irrigated lands of LLC "Granex-Cherkasy"

In terms of geomorphology, the territory of the research plot belongs to the orographic region of the Dnipro lowland, represented on the left bank of the Dnipro river by the Middle Dnipro terrace plain. Directly, the land plot of LLC "Granex-Cherkasy", within which monitoring studies of the irrigation influence were carried out, is located within the boundaries of the ancient fourth supraflood (moraine) terrace of the Dnipro River. The surface of the plot is mainly characterized by a flat relief with the presence of micro depressions.

Within the research area, the first from the surface is an aquifer complex in unbounded Lower Neopleistocene alluvial and fluvioglacial sediments and Middle Neopleistocene water-glacial sediments. The most water sufficient part of this complex is an aquifer tied to the alluvial Lower Neopleistocene deposits of the fourth supraflood terrace of the Dnipro River.

The soil cover on the plot is represented mainly by typical zonal black soils, low-humus, light- and medium-loamy, and low-humus black soils in a complex with sweetened light-loamy soils, as well as regraded black soils with slightly and medium-washed and alluvial light-loamy, sod clay, and sodic (deeply leached) medium-loamy soils (in closed depressions-saucers).

Irrigation on the plot began in 2013–2014. Irrigation in LLC "Granex-Cherkasy" is based on the use of Lower Neopleistocene alluvial and fluvioglacial deposits for groundwater. As of 2023, 15 water intake wells are used for agricultural crops irrigation. Water from the wells is supplied to the storage pool, and from it by a container-type pumping station to a hydrant for watering agricultural crops with sprinkler machines. Currently, the farm uses three frontal machines for irrigation: Valley and Otech, as well as sprinklers of the hose drum type. In addition, since 2019, drip irrigation systems have been used on areas from 5.0 to 38.5 hectares.

Various grain, oil, and vegetable crops are grown on the farm's land: wheat, barley, soybeans, millet, rapeseed, potatoes, corn, beets, onions, etc, with unequal water demand and irrigation regime, as well as the requirements for soil environment.

The development of the program (plan) of post-design monitoring (for 5 years) stipulated by the conclusion on environmental impact assessment provided by the Ministry of Natural Resources of Ukraine was based on the requirements of current regulatory and methodological documents on the irrigated lands monitoring organization [13, 20–23]. According to them, monitoring should be carried out through the periodic determination of indicators of the ecological and reclamation conditions of lands based on the results of routine observations at designated monitoring points and planar surveys. Based on the tasks and features of the post-design monitoring of the irrigation impact on soil conditions, the soil-ameliorative indicators and the indicators of irrigation water quality (in the storage basin of underground water or in the watering places) were primarily subject to control. At the same time, the system of local (objective) monitoring of irrigated lands of the farm (existing and prospective) was created on the basis of studies previously carried out in 2018 on the assessment of the quality of groundwater for irrigation and its possible impact on soil conditions, taking the determined indicators as the baseline for further comparisons and changes detection in soil fertility and the ecological and reclamation conditions of lands, as well as the quality of water used for irrigation.

The specific work program, primarily in the part of soil sampling, was formed taking into account the actual use of irrigation in a certain plot, as well as the initial conditions of soil salinity or alkalinity.

In order to provide determination, based on the monitoring studies results, the changes in soil conditions on the plot under the influence of long-term, in particular, periodic, irrigation, the work program included the implementation of a complex of field, laboratory, and analytical studies.

Field work included carrying out an annual (at the end of an irrigation season) field survey of the land with the soil samples collection down to a depth of 100 cm (next to the wells – down to 200 cm) and water sampling. Analyzing samples from soil surface and subsoil, the salt composition and pH, the composition of exchangeable cations, the content of carbonates, humus and nutrients content, soils granulometric composition, and soil density were determined.

For the irrigation water (groundwater) samples the chemical composition, basic cations and anions, dry residue, pH, and individual microcomponents were determined.

The classification of soils by the degree of salinity by the total amount of salts and by the content of toxic salts in the water extract was carried out in accordance with [13, 20], the classification of the soil by the degree of alkalinity, in particular secondary – by [13, 24], the grouping of soils by the degree of acidity and alkalinity, content of humus, mobile forms of nitrogen, phosphorus, potassium, mobile compounds of trace elements and heavy metals, etc, according to [25]. Assessment of water quality according to agronomic criteria was carried out in accordance with the provisions of DSTU 2730:2015 [26].

In the context of regulating the irrigation impact, the standards of environmentally safe irrigation and irrigation management established by the Resolution of the Cabinet of Ministers of Ukraine dated September 2, 2020 No. 766 were taken into account [12].

The data recorded by observations and laboratory analyzes are components of the information base of local monitoring, based on which the directions, nature, and degree of irrigation transformation of the conditions of irrigated soils are estimated taking into account specific factors of influence during the period of monitoring studies conduct.

Research results and their discussion. During monitoring observations, in certain years, irrigation was carried out within different fields depending on the agricultural crops grown on them. The total irrigated area ranged from 132 ha in 2021 to 471 ha in 2022. So, in 2023, irrigation was carried out on fields with potatoes (field 1–11) on an area of 72,2 ha, with soybeans (fields 1–10, 1–15) on a total area of 206,9 ha, winter wheat on an area of 87,8 ha (fields 1–14a and 1–11), and onions on an area of 44,0 ha within the boundaries of a part of the field 1–10 – with frontal sprinklers, as well as on a site with a drip irrigation system installed within the boundaries of the field 1–17 on an area of 5,2 ha with potatoes (Fig. 2). In general, the vast majority of the land was covered by irrigation – 416,1 ha, 410,9 ha of which were sprinkled and 5,2 ha were under drip irrigation.

During the irrigation season of 2021 308 thousand m^3 of irrigation water was supplied. In 2022 this volume was 516,0 thousand m^3. So, in 2023, irrigation on the farm started in June and ended in September. During the irrigation season, 413,324 m^3 of water was poured onto irrigated land, in particular, 172,352 m^3 in June, 144,496 m^3 in July, 66,183 m^3 in August, and 30,293 m^3 in September. In May, due to a significant amount of precipitation, irrigation was not carried out, which led to a generally lower total irrigation rate. Sprinklers of frontal action supplied 400,824 m^3 of water to fields 1–10, 1–11, 1–14a, and 1–15, i.e. the average total irrigation rate was 975 m^3/ha, although it was slightly higher for potatoes. The water supply to the drip irrigation system was 12,500 m^3 for the potato with total irrigation area of 5,2 ha (about 2,400 m^3/ha). In some years, the total irrigation rate for sprinkler irrigation reached 2200–2500 m^3/ha.

The plot is characterized by a deep (over 10 m) groundwater table, which indicates a good ecological and reclamation conditions of the land according to this indicator.

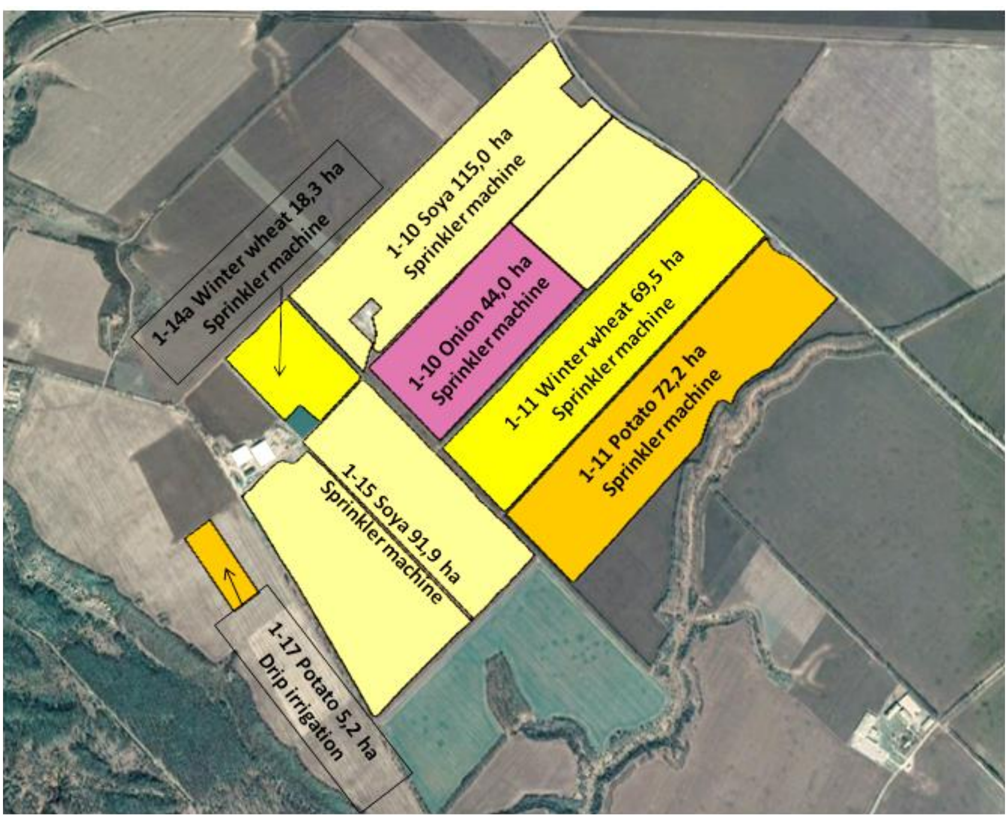


Fig. 2. Contours of irrigated fields at LLC Granex-Cherkasy LLC in 2023

Assessment of irrigation water quality. Assessment of the quality of water used by LLC "Granex-Cherkasy" for agricultural crops irrigation was carried out on the basis of the results of chemical analysis of groundwater samples taken during irrigation periods (from the storage pool).

During the entire period of research (2019–2023), the mineralization of irrigation water was on average 500 mg/dm^3 for the hydrogen carbonate magnesium-calcium, less often calcium, type of chemistry. The reaction of water is mainly slightly alkaline (pH – from 7,2 to 7,7). According to the indicator of total hardness, the water belonged to both moderately hard and hard classes.

During water evaluation, it was taken into account that the soil cover within the irrigated plots is mainly represented by typical, low-humus, light- and medium-loamy black soils in a complex with solodic soils with a mostly neutral reaction (at the time of the surveys), medium-buffering with respect to salinization (by $CaCO_3$ content).

Regarding the danger of irrigation salinization of the soil based on the calculated indicator of the sum of toxic salts in equivalents of chloride ions (eCl^-), the value of which for water in the storage pool during the irrigation season of 2023 was 2.1 and 1.6 meq/dm^3, water according to DSTU 2730:2015 [26] belongs to the Ist class (suitable) for all groups of soils according to their granulometric composition in the 0–100 cm soil layer. It is worth to mention that during the entire period of monitoring observations of the irrigation water quality, the amount of toxic salts (in equivalents of chloride ions) in it fluctuated between 1.6–2.4 meq/dm^3, that is, it was low enough and did not cause a threat of irrigation salinization of the soil.

The assessment of water quality regarding the danger of soil alkalinization was based on taking into account pH indicators, the content of CO_3^{2-}, and toxic alkalinity (HCO_3^- – Ca_2^{2+}) with differentiation by soil groups and the reaction of the environment according to [26] (Table 1).

Therefore, according to the danger of soil alkalization due to increased values of toxic alkalinity indicators (from 3,1 to 4,3 meq/dm^3) and pH (for alkaline soils), the water belongs to the IInd class, both in previous years and in 2023 ("limited use").

Assessment of the irrigation water quality regarding on the risk of soil sodification gives reason to assign it to the Ist class (Table 2). The amount of alkaline cations of sodium and potassium in the water was from 9 to 14 % of the amount of all cations, which is much lower than the threshold value (45 %) of this indicator for loamy medium-buffer black soils, even for the IInd water class according to the alkalization danger.

According to the risk of toxic effects on plants during sprinkler irrigation, irrigation water from water intake wells (from the pool) in 2023, in general, according to a set of evaluation indicators, belongs to the IInd class as of July due to increased pH values (over 7,5) and to the Ist class as of August, which confirms a certain constancy of water quality indicators in the time dimension (Table 3).

1. Assessment of the irrigation water quality according to the risk of soil alkalinization on the lands of LLC "Granex-Cherkasy"

Sampling date from the storage pool	Water quality indicators			Water quality class according to individual indicators			Water quality class
	pH	content CO_3^{2-}	content of toxic alkalinity (HCO_3^- – Ca^{2+})	pH*	CO_3^{2-}	toxic alkalinity	
		meq/dm^3					
25.06.2019	7,7	0,0	4,0	I/II	I	II	II
20.09.2019	7,5	0,0	3,8	I/I	I	II	II
24.06.2020	7,4	0,0	4,0	I/I	I	II	II
22.09.2020	7,6	0,0	3,8	I/II	I	II	II
03.07.2021	7,6	0,0	3,2	I/II	I	II	II
22.09.2021	7,6	0,0	4,3	I/II	I	II	II
22.06.2022	7,7	0,0	3,7	I/II	I	II	II
29.09.2022	7,7	0,0	3,9	I/II	I	II	II
12.07.2023	7,6	0,0	3,3	I/II	I	II	II
10.08.2023	7,2	0,0	3,1	I	I	II	II

*Before a slash – for acidic and neutral soils, after a slash – for alkaline soils.

2. Assessment of the irrigation water quality according to the risk of sodification of the soil on the lands of LLC "Granex-Cherkasy" near the village Denhy, Zolotonosha district, Cherkasy region (the storage pool)

Sampling date from the storage pool	Irrigation water class according to the risk of alkalinity	The ratio of the sum of alkaline cations to the sum of all cations, %*	Water quality class
25.06.2019	II	14,3	I
20.09.2019	II	12,6	I
24.06.2020	II	11,4	I
22.09.2020	II	9,3	I
03.07.2021	II	12,3	I
22.09.2021	II	9,6	I
22.06.2022	II	9,5	I
29.09.2022	II	14,3	I
12.07.2023	II	11,3	I
10.08.2023	II	7,7	I

* Threshold value for water of the Ist class is 45 %.

3. Assessment of the irrigation water quality from the storage pool according to the risk of toxic effects on plants during sprinkler irrigation (LLC "Granex-Cherkasy")

Sampling date from the storage pool	Water quality indicators			Toxic ions, equivalents Cl	Water quality class
	pH	CO_3^{2-}	Cl^-		
		meq/dm^3			
25.06.2019	7,72	Absent	0,4	2,0	II
20.09.2019	7,48	The same	0,6	2,2	I
24.06.2020	7,36	» »	0,6	2,2	I
22.09.2020	7,63	» »	0,6	2,1	II
03.07.2021	7,58	» »	1,1	2,4	II
22.09.2021	7,58	» »	0,5	2,2	II
22.06.2022	7,72	» »	0,4	1,9	II
29.09.2022	7,67	» »	0,4	2,0	II
12.07.2023	7,65	» »	0,1	2,1	II
10.08.2023	7,16	» »	0,4	1,6	I

We can conclude, that from the point of view of assessing the irrigation water quality of water according to agronomic criteria provided by DSTU 2730:2015, the underground water withdrawn from wells to irrigate the lands of LLC "Granex-Cherkasy" near the village of Denhy, belongs to the Ist class ("suitable") with respect to irrigation salinization and sodification danger for the soils and to the IInd class ("limitedly suitable") with respect to alkalinization danger for soils (according to the indicators of pH and toxic alkalinity) and toxic effect on plants in case of direct ingress of water on the leaves, fruits, etc (in specific periods according to the pH indicator), that, as a whole, means that it is a water of the IInd class. According to [12], watering with such water is possible if restorative measures are applied.

Groundwater in the study area, due to its use for drip irrigation systems, belongs to the Ist class with respect to the danger of irrigation salinization and sodification of soils and to the IInd class with respect to the danger of soil alkalization (exceeding the threshold values of pH and toxic alkalinity).

Assessment of soil condition by individual indicators. The main attention during monitoring studies of the irrigated soils' condition was devoted to the study of possible changes in their salt characteristics due to irrigation water influence, i.e., the income of an additional amount of salts with it, taking into account their qualitative composition. Thus, based on the average values of water mineralization and average irrigation rates, approximately from 0,49 to 1,25 t/ha of salts were added to the fields with irrigation water during the irrigation period. In addition, every year, during the works, some indicators of soil fertility (pH, content of $CaCO_3$, microelements, and heavy metals) were determined at individual points.

In 2023, during continuous testing of all fields, soil samples were extracted in order to determine in laboratory conditions the values of agrophysical and agrochemical indicators (granulometric and aggregate composition of soils, their density, humus and nutrients content, salt and exchangeable cations compositions).

The study of the soil condition in 2023 was carried out both at the designated monitoring points as well as at the additional test points for soil and salt survey, the layout of which is shown in Fig. 3.

Research results on secondary soil salinity. In 2023, according to research results of the easily soluble salts content in the soil layer (down to 1.0–2.0 m) based on the analysis of water extracts, both irrigated and non-irrigated soils within the examined farm fields were classified as non-saline. At the same time, the soils are non-saline both by the sum of all easily soluble salts and by the content of a part of these salts that in certain concentrations have a toxic effect on plants, inhibiting their growth and development, i.e. toxic salts, according to their division by the degree of salinity according to the current regulatory documents [13, 23]. A similar situation was observed in all previous years of study.

The total weighted average content of easily soluble salts in the upper 1 m soil layer in 2023 on the examined fields was quite low and was within 0,043–0,084 % of dry soil (according to the data of the continuous survey of 2018 – 0,040–0,062 %). The toxic salts content in the one-meter layer of soil ranges from 0,013 to 0,036 %, which is 17,2-47,1 % of the total amount of salts. In some years, the value of the easily soluble salts content increased up to 0,062-0,192 %, of toxic ones – up to 0,014-0,061 % (2021).

At the same time, the main types of soil salinization in the upper 1 m layer in 2023 were hydrocarbonate and sulfate-hydrocarbonate, in 2022 – sulfate-hydrocarbonate; in 2021 – sulfate-hydrocarbonate, hydrocarbonate-sulfate; in 2020 – hydrocarbonate, in 2019 – hydrocarbonate

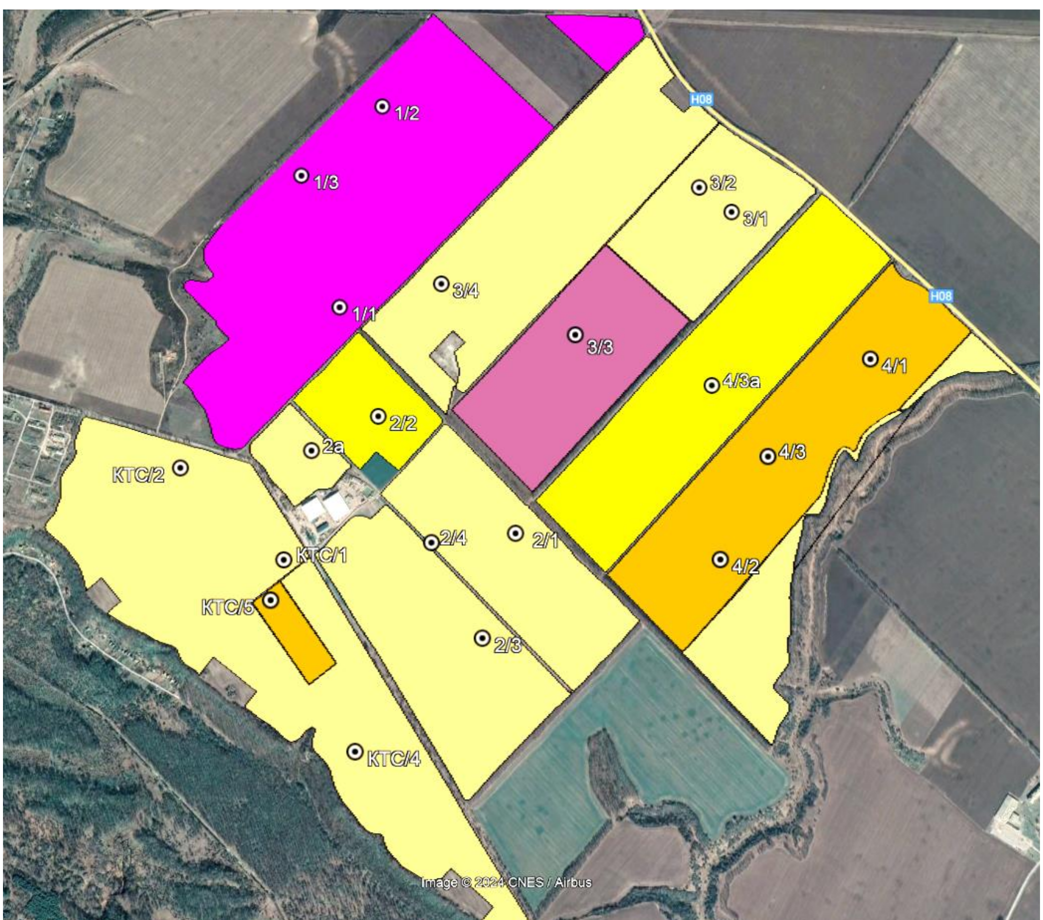


Fig. 3. Layout of soil sampling points in the area of monitoring studies

and sulfate-hydrocarbonate – by anionic composition, magnesium-calcium and calcium – by cationic composition.

It is worth noting that the heterogeneity of the salinity chemistry and the salts content is observed within individual layers of 1 m thickness and deeper, although in terms of the total salts content and their toxic part, the studied sediments in the test intervals are everywhere non-saline. Maximum salinity in the soil profile was noted at different depths (Fig. 4).

The weighted average total content of water-soluble salts in the interval of 100–200 cm at individual monitoring points tested in 2023 is 0,079–0,116 %, and toxic salts – 0,017–0,077 %, that means that the share of the latter is from 25,9 to 51,0 % of the total amount of easily soluble salts. According to the type of salinity, the soils of this interval are hydrocarbonate and sulfate-hydrocarbonate (by anions) and mainly magnesium-calcium by cation composition. Therefore, in this layer, the soil is also non-saline, although compared to the 2018 survey, slightly higher values of both the total content of easily soluble salts and their toxic part were recorded, which previously amounted to 0,058−0,070 % and 0,018−0,029 %, respectively.

Attention should also be paid to certain differentiation in area and profile at the individual test points (wells) of salinization chemistry, especially in terms of anionic composition, although the predominant types of salinization are associated with the predominance of hydrocarbonate and sulfate ions along with

2a

2/4

3/3

Fig. 4. Typical salt profiles of the distribution of the ions and salts content in the water extract (2023)

calcium and magnesium cations. At the same time, an unfavorable trend is a certain increase in the amount of chlorine salts and sodium ions at certain points.

Over the years of monitoring studies, the ranges of the content of easily soluble salts in the arable layer (0−25 cm) were 0,040−0,079 % (2018), 0,023−0,073 (2019), 0,032−0,058 (2020), 0,046−0,091 (2021), and 0,024−0,084 % (2022).

The arable layer at the time of the survey in August 2023 was distinguished by a generally low salts content (from 0,022 to 0,081 %), in particular, toxic ones (from 0,004 to 0,044 %, that is below the toxicity threshold) and heterogeneous types of salinity by anions: bicarbonate-sulfate, sulfate- hydrocarbonate, hydrocarbonate, calcium, calcium-magnesium and magnesium-calcium types according to the cationic composition, that means that it is considered as non-saline.

In general, the monitoring studies results and soil-salt survey provide grounds for assigning all lands on the site to the non-saline category throughout the entire observation period, i.e. 2019−2023, which indicates, according to [12], the environmental safety of the performed irrigation.

Determination of soils sodification. The sum of exchangeable cations in the 0−25 cm soil layer varies on the farm plot from 12,5 to 27,5 meq/100 g of soil, and in the 25−50 cm layer – from 16,3 to 28,8 meq/100 g of soil, which corresponds to the optimal parameters of fertility indicators of typical black soils [27].

Among the exchangeable cations of the examined soils in the 0−50 cm layer, absorbed calcium dominates in most points, the share of which is from 43,4 to 94,5 % of the sum of all cations. The content of absorbed magnesium ranges from 5,3 to 56,4 %. In the test points 3/3, KTS/4 (layer 25−50 cm), and KTS/5 (layer 0−25 cm) the magnesium content is close to the calcium content with a slight excess over the latter at points on the field 1−17 (KTS).

The content of absorbed sodium at all test points and all investigated fields in the intervals of 0−25 and 25−50 cm during the post-design monitoring does not exceed 0,5−1,7 % of the absorption capacity, which is typical for zonal forest-steppe soils. *Therefore, according to the content of absorbed sodium, the main types of soils on the research area are non-saline* (less than 3 % of Na for low-humus soils). The same applies to the possible secondary (irrigation) salinity of irrigated soils, especially since the light soils on the site in the 0−50 cm layer are mostly medium buffering with respect to sodification (in terms of $CaCO_3$ content – 6−10 %), for which the sodification threshold (transition to slightly saline) is the content of exchangeable alkaline cations (Na+K) equal to 5 % of the absorption capacity (Na+K+Mg+Ca) [13, 23, 24].

At the same time, it should be taken into account that the increased content of exchangeable magnesium (more than 20 % of the soil absorption complex capacity or the sum of all exchangeable cations), what is noted at most points of soil testing, according to separate approaches [13], can adversely affect soil fertility (20-30 % – weak impact, 30-40 % – medium impact, over 40 % – critical impact) and should be interpreted as magnesium sodification, especially since magnesium is one of the main cations in groundwater used for irrigation (up to 30-40 % of the total cations, according to the data of 2019−2021 and 2023), although, according to the research data of 2022, its content did not exceed 0,4−0,8 meq/dm^3 or 8−15 % of the sum of cations.

Evaluation of soils by the degree of their alkalization by the pH indicator, the content of CO_3^{2-}, and toxic alkalinity (HCO_3^{-}-Ca^{2+}) in accordance with the current classification [13] indicates the absence of this unfavorable soil degradation process in the soil of the tests sites (pH less than 8 units; CO_3^{2-} is absent; the content of toxic alkalinity is less than 0,5 meq/100g of soil).

However, the fact that groundwater, from the point of view of assessing its suitability for irrigation, is limitedly suitable for irrigation due to the danger of soil alkalinization, and the pH of the water in some points at depths of 25–75 cm reach 7,5–7,8 units, indicates the need for further monitoring of this indicator as a component of the assessment of the ecological and reclamation state of irrigated lands.

In general, the results of monitoring studies indicate the absence of processes of secondary (irrigation) salinization, sodification, and alkalinization of soils as a result of lands irrigation in LLC “Granex-Cherkasy”.

Agrophysical and agrochemical indicators of soil fertility. The results of soils granulometric composition determination in 2023 give reasons to classify them as light loams (field 1–14 – wells 2a, 2/1; field 1–15 – well 2/4; field 1–10 – well 3/4; field 1–11 – well 4/3, thickness 0−50 cm; field 1–17 – wells KTS/1, KTS/2, KTS/4) or as medium loams (field 1–9 – well 1/2; field 1–10 – wells 3/1, 3/2, 3/3; field 1–11 – well 4/3a). A certain heaving of the soil granulometric composition compared to the base values of 2018 is associated with an increase in the content of the smallest fraction (diameter less than 0,001 mm).

The determination of the soil density indicator during the on-site survey of the lands of LLC "Granex-Cherkasy" in August 2023 confirmed the presence of over-compacted soils in almost all fields that were the monitoring was carry out. Thus, the arable layer density (0−25 cm) generally fluctuated within the range of 1,26−1,53 g/cm^3, which exceeds the optimal parameters of this indicator for typical black soils (1,1−1,3 g/cm^3) and characterizes the soil as dense or very dense. This, under irrigation conditions, worsens the permeability of irrigation water into the soil and its moistening. The density in the soil layer of 25–50 cm is 1,36–1,62 g/cm^3, which are the typical values for subarable horizons. Therefore, in fields where increased values of the arable layer density are recorded, special attention should be paid to monitoring the compliance with the optimal parameters of this indicator through appropriate soil cultivation, the application of organic fertilizers and meliorants.

The content of humus in farm's soils, according to the study, is mainly in the range of 2,1–3,8 % (average level). To a lesser extent (test points 3/1, 3/2, 4/3a, KTS/2, KTS/4) the humus content values are 3.1–4.0 % (increased content). In most soil samples, the humus content gradually decreases with depth, which is natural, but at points 2/1, 2/2, 2/4, 3/1 the humus content in the soil layer 0−25 cm is lower than in the layer 25−50 cm by 0,21−0,35 in absolute percent. Compared to the survey of 2018, a certain increase in humus content is observed over the territory of most fields. In general, the humus content corresponds to the optimum for typical black soils with light loam granulometric composition.

The reaction of the soil solution of the studied fields is mostly neutral (pHsol 6,1−7,0), as well as slightly alkaline (pHsol 7,1−7,5), in some cases slightly acidic (pHsol 5,1−5,6), but generally acceptable for growing most crops.

Conclusions. Post-design local monitoring of the irrigated lands of LLC "Granex-Cherkasy" through the periodic determination of water quality indicators in the storage pool and soil reclamative indicators, primarily salt characteristics, at the monitoring points specified in the program, as well as the final soil and salt survey, provided an opportunity to assess the impact of the planned activities related to agricultural lands irrigation near the village Denhy, Zolotonosha district, Cherkasy region, on the soils and groundwater condition, which was provided by the conclusion of the environmental impact assessment provided by the Ministry of Natural Resources of Ukraine.

According to the results of the assessment in 2019−2023, we found that groundwater, which is taken from wells and supplied for irrigation, according to agronomic criteria can be classified to the Ist class (suitable) with respect to the danger of irrigation salinization and sodification of soils, and as limited suitable (the IInd class) with respect to the danger of soil alkalinization (according to pH and toxic alkalinity) and the danger of toxic effects on plants during sprinkler irrigation (according to pH).

According to the results of monitoring studies, we found that the soils under irrigation conditions did not undergo changes significant for their classification. According to the total easily soluble salts content and the toxic salts content in the upper 1 m layer, both irrigated and non-irrigated soils are classified as non-saline, mainly hydrocarbonate and sulfate-hydrocarbonate by anion composition and magnesium-calcium and calcium by cation types.

It was determined that the main types of soils on the investigated plot are non-saline based on the absorbed sodium and potassium alkaline cations content. A specific soils feature is the increased exchangeable magnesium content, which requires, after watering them with water of magnesium-calcium type, the control of the content of this indicator with, if necessary, application of calcium-containing meliorants.

The absence of manifestations of secondary (irrigation) salinization, sodification, and alkalinization of soils under the influence of irrigation indicates its environmental safety in accordance with the accepted norms for the indicators of the degree of specified soil degradation processes development.

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ПІСЛЯПРОЄКТНИЙ МОНІТОРИНГ ВПЛИВУ ЗРОШЕННЯ НА ДОВКІЛЛЯ

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Анотація. *На прикладі окремого агрогосподарства ТОВ «Гранекс-Черкаси» висвітлено підходи до ведення післяпроєктного моніторингу впливу зрошення на стан ґрунтів. Результати виконання п'ятирічної програми післяпроєктного моніторингу за умов зрошення земель підземними водами дощуванням і краплинним способом засвідчили необхідність напрацювання як єдиних загальних підходів до формування програм моніторингу, так і обов'язкового врахування особливостей його ведення за різних способів поливу та гідрогеолого-меліоративних умов на ділянках зрошення. В основу розроблення системи післяпроєктного моніторингу впливу зрошення на стан складових довкілля запропоновано використовувати підходи до організації та ведення локального (об'єктового) моніторингу зрошуваних земель на основі вимог чинних нормативних і методичних документів. Сформована на підставі попередніх досліджень система спостережень включала періодичне визначення показників якості зрошувальної води у ставку-накопичувачі або у місцях поливу та режимні спостереження за станом ґрунтів на постійних моніторингових точках (пунктах спостережень), які рекомендують приймати як координатно прив'язані точки випробування проведеного раніше (на стадії підготовки звіту з оцінки впливу на довкілля) дослідження. Результати післяпроєктного моніторингу засвідчили екологічну допустимість впливу проведення зрошення земель у господарстві підземними водами І та ІІ класів якості (придатними та обмежено придатними за окремими показниками якості). За результатами моніторингу встановлено, що ґрунти в умовах зрошення впродовж 5 років не зазнали класифікаційно значних змін щодо погіршення стану. Відсутність прояву процесів вторинного (іригаційного) засолення, осолонцювання та підлуження ґрунтів під впливом зрошення свідчить про екологічну безпечність останнього згідно з прийнятими нормативами за показниками ступеня розвитку зазначених ґрунтово-деградаційних процесів.*

Ключові слова: *ґрунти, засолення, зрошення, зрошувальна вода, осолонцювання, післяпроєктний моніторинг, якість води*

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INFORMATION MATERIALS FOR ASSESSING THE IMPACT OF CLIMATE FACTORS ON FORMING SOIL WATER REGIME ON DRAINED LANDS

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Abstract. *The research results on creating information materials for assessing the impact of modern climatic factors on the formation of soil water regimes on drained lands are presented. By the results of the research, carried out at the «Romen» drainage and irrigation system (Sumy region), it was established that over the past 34 years, the average air temperature during the growing season has varied from 14,2 to 19,4 °C. In general, there is a trend for its slight decrease (almost by 0,2 °C). The highest average monthly air temperatures are recorded in July and August, and the lowest ones – in April. It was specified that the water regime of the active soil layer during the growing season is formed mainly due to moderate (4–14 mm – 44 %) and significant (15–49 mm – 40 %) precipitation, the total share of which in water reserves is 84 %. There is a trend towards an increase in the share of significant precipitation (on average, up to 46–60 % of the total amount during the growing season) in years with high-water growing seasons, and its predominant amount falls in the range of 15–29 mm. There is also an increase in the share of moderate precipitation (up to 49 % of the total amount during the growing season) in years with low-water growing seasons.*

Information materials on the distribution of atmospheric precipitation by year in quantitative and percentage indicators, their recurrence in the growing seasons of 1990–2022 ("Romen" DIS, Sumy region), presented as an interactive visual report with graphic materials (dashboard) have been created. Informational materials in the form of dashboards enable us to monitor changes in climatic conditions, promptly providing up-to-date data when forecasting future trends in changes in the water supply of agricultural territories, in particular, the formation of the soil water regime on drained lands and addressing the challenges related to climate change.

Key words: *climate change, drained lands, precipitation, air temperature, information materials, soil water regime*

Relevance of research. Global climate change is a modern challenge for the world, as it significantly affects agricultural production – one of the most climate-dependent sectors of the economy, and endangers food production [1–3]. Climate change can cost the world about 5 % of GDP every year, and if the most pessimistic forecasts are implemented, this figure can grow to 20 % [4]. The consequences of climate change are becoming more and more noticeable in Ukraine as well. Today, Ukraine is one of the leading producers and exporters of food in the world. Therefore innovative and investment development of the domestic agro-industrial complex is very relevant. At the same time, our country is already trying to implement its competitive advantages and consider its national interests. Therefore, despite all the existing risks and challenges under climate change and Russian military aggression, domestic agricultural production has to meet the requirements of national security [4, 5].

Modern climate change significantly affects agricultural production since it leads to a lack of available moisture on agricultural lands, which is the main limiting factor for the sustainable functioning of agriculture [6, 7]. The impact of weather conditions on yield productivity is about 52 % [8].

Therefore, in modern conditions, agriculture needs the development and implementation of adaptive measures, which will enable us to reduce the negative effects of climate change and ensure the competitiveness and sustainable development of the agricultural sector.

Given that agriculture is one of the main branches of the Ukrainian economy, the share of which is 10 % of GDP, there is a need to improve existing agricultural production models and optimize the management technologies in agriculture given modern climate change [5].

Analysis of the latest research and publications shows that the impact of climate change on the production of agricultural products will have a mostly negative effect. With a global warming of 2 °C, many countries will lose up to 20 % of crop yields [3].

Climate changes in Ukraine are happening faster than global ones. Since 1991, each decade has been warmer than the previous one. The average annual temperature in Ukraine from 1961 to 1990 was +7,8 °C, and from 2010 to 2019 it has already reached +9,6 °C. The absolute maxima of air temperature have increased by 1–4 °C, and temperature indices are becoming more equal across the country's territory [3]. At the same time, in the drainage zone, the increase in average annual air temperature is quite significant: in the western regions – by 1,2–1,3 °C, in the northern and central regions – by 1,4–1,5 °C [9, 10].

According to the estimates of world and domestic climatologists, in the future, there is a high probability of a further increase in air temperature both on a global scale and in various natural and climatic regions of Ukraine [11, 12].

Atmospheric precipitation is one of the main factors determining the features of the regional climate. The amount and seasonal precipitation distribution are key factors in forming a water regime on agricultural lands.

Literary sources indicate that current fluctuations in average annual precipitation are within the climatic norm (5–10 %). With a slight change in the precipitation amount, its nature and intensity have changed noticeably for the territory of Ukraine [13]. The number of cases when half or a monthly precipitation norm falls in a few hours has increased [14].

The study of precipitation in modern climate change conditions is relevant for adapting the economy, especially the agricultural sector [15]. A significant amount of scientific research, which uses various methods, databases, and scientific approaches, is devoted to studying the processes of precipitation formation and its structural features. The dynamics of precipitation, its spatial distribution, duration, and repeatability in different regions are evaluated [16, 17]. Domestic scientists mostly study the formation conditions and statistical characteristics of heavy rains and downpours and assess their impact on the natural environment [18,19].

Literary sources indicate that at the beginning of the XXI century, in Ukraine in general and in the drainage zone, there was a tendency to increase the number of heavy downpours (precipitation of 30 mm or more that falls in 1 hour or less). Heavy downpours from 1986 to 2015 were observed in Ivano-Frankivsk and Transcarpathian regions, slightly less in Kyiv, Cherkasy, Chernivtsi, and Lviv regions. From 2001 to 2010, the amount of heavy downpours increased more than twice compared to 1991–2000. And from 2011 to 2015, the amount of heavy downpours in Kyiv and Chernihiv regions increased significantly [20, 21].

Precipitation is one of the most variable meteorological factors in time and space. There are very few detailed studies today on the features of its structure, formation, and fluctuations. The reasons for precipitation fluctuations are also insufficiently studied, although some connections with solar activity and the rhythmicity of macro-scale synoptic processes have been identified. The reasons for cyclicity have not been definitively elucidated; there are only hypotheses about their origin [14, 16].

Despite the wide range of possible future changes in the average amount of atmospheric precipitation, it is predicted that extreme precipitation in all seasons may become more intense, which will cause an increase in the number of wettest days of the year by 10–25 % as well as surface runoff and rain floods by the end of the century [10, 22].

Therefore, an increase in air temperature and uneven distribution, change in the nature, intensity, and structure of precipitation, as well as an increase in the number of heavy downpours, which have a local character in the warm period of the year, do not make it possible to ensure the effective accumulation of moisture in the soil. Given modern changes in natural moisture supply, an important limiting factor in efficiently managing agricultural production is moisture reserves in the active soil layer, the necessary amount of which is not provided during the growing season [6, 9].

It is necessary to obtain improved parameters of water regulation technologies that take into account the entire complex of factors affecting the formation of the moisture regime in the aeration zone to solve the modern problems of managing agricultural systems, namely, the water regime of the soil on drained lands in the conditions of climate change.

Given the results of analytical studies, the research of climate change at both the regional and local levels and the creation of informational materials for assessing the impact of modern climatic factors on the formation of soil water regimes are relevant today.

The purpose of the research is to create informational materials for assessing the impact of climatic factors on the formation of soil water regimes on drained lands.

Methods and objects of the research. Informational materials for assessing the impact of modern climatic factors on the formation of soil water regime were created, based on the results of meteorological measurements in the growing seasons of 1990–2023 on reclaimed lands of the drainage and irrigation system (DIS) "Romen" (Sumy region).

The basis of methodological approaches to field studies is applying generally accepted methods of conducting meteorological observations of air temperature and atmospheric precipitation during the growing season.

The values of average daily, decadal, and monthly air temperatures and daily, monthly, and yearly atmospheric precipitation were determined to obtain information materials on the impact of climatic factors on the formation of soil water regimes. Calculations, creation of smart tables, and interactive graphical and visual reports (dashboards) were made using the Microsoft Office Excel program.

Research results and discussion. To analyze the impact of climatic factors on the formation of soil water regimes, such meteorological factors as air temperature and atmospheric precipitation were considered.

Informational materials on air temperature values during the growing season of 1990–2023 on reclaimed lands of the "Romen" DIS are presented in Table 1 and Fig. 1.

1. Average monthly air temperature (°C) for the growing season of 1990–2023 («Romen» DIS)

Year	**Month**						**Average for a growing season**
	April	**May**	**June**	**July**	**August**	**September**	
1	2	3	4	5	6	7	8
1990	9.6	14.7	17.3	19.1	18.0	12.6	15.2
1991	9.0	14.0	20.3	21.9	19.0	17.8	17.0
1992	6.5	13.8	19.1	20.4	21.9	13.1	15.8
1993	7.4	16.1	16.6	18.1	17.0	9.7	14.2
1994	10.7	13.4	16.7	21.1	19.2	18.5	16.6
1995	9.2	14.2	21.5	21.7	19.2	14.2	16.7
1996	8.6	19.4	19.9	20.8	19.9	15.7	17.4
1997	6.8	16.6	20.3	19.4	18.3	10.4	15.3
1998	-	14.1	19.2	20.1	17.2	12.5	16.6
1999	10.7	15.7	22.1	22.1	19.1	12.6	17.1
2000	11.8	12.5	16.7	20.1	24.6	13.2	16.5
2001	10.7	13.2	16.0	23.6	20.2	12.8	16.1
2002	8.4	13.3	19.4	23.8	18.6	13.7	16.2
2003	4.8	17.6	17.5	21.0	18.3	12.9	15.4
2004	8.0	12.3	17.1	19.5	20.4	13.7	15.2
2005	9.8	17.0	17.3	21.6	19.7	14.3	16.6
2006	8.4	13.5	18.7	19.9	20.3	15.1	16.0
2007	7.3	18.4	20.4	21.2	21.7	14.5	17.3
2008	10.4	13.2	19.7	20.9	21.4	13.1	16.5
2009	7.5	13.2	20.6	21.9	18.9	16.3	16.4
2010	9.7	16.6	20.7	25.1	25.0	-	19.4
2011	8.1	17.5	22.5	24.2	21.3	15.4	18.2
2012	12.6	18.9	19.6	21.9	19.7	14.5	17.9
2013	7.1	18.9	20.3	20.1	18.1	8.2	15.5
2014	9.7	16.5	19.0	20.3	20.1	13.2	16.5
2015	9.2	15.3	18.4	19.7	21.1	17.2	16.8
2016	10.4	13.5	18.7	20.8	18.8	12.5	15.8

Table 1 (ending)

1	2	3	4	5	6	7	8
2017	7.8	11.1	16.4	19.5	20.2	13.7	14.8
2018	8.8	16.4	17.9	19.4	20.2	16.1	16.5
2019	8.8	14.6	20.4	17.4	17.5	12.8	15.3
2020	7.1	11.6	21.2	19.8	18.6	16.5	15.8
2021	6.3	13.1	19.4	23.9	21.3	11.2	15.9
2022	6.5	11.7	19.3	19.3	19.7	10.8	14.6
2023	9.1	13.8	17.8	19.7	21.6	16.5	16.4
Average	8.7	14.9	19.1	20.9	19.9	13.8	16.3

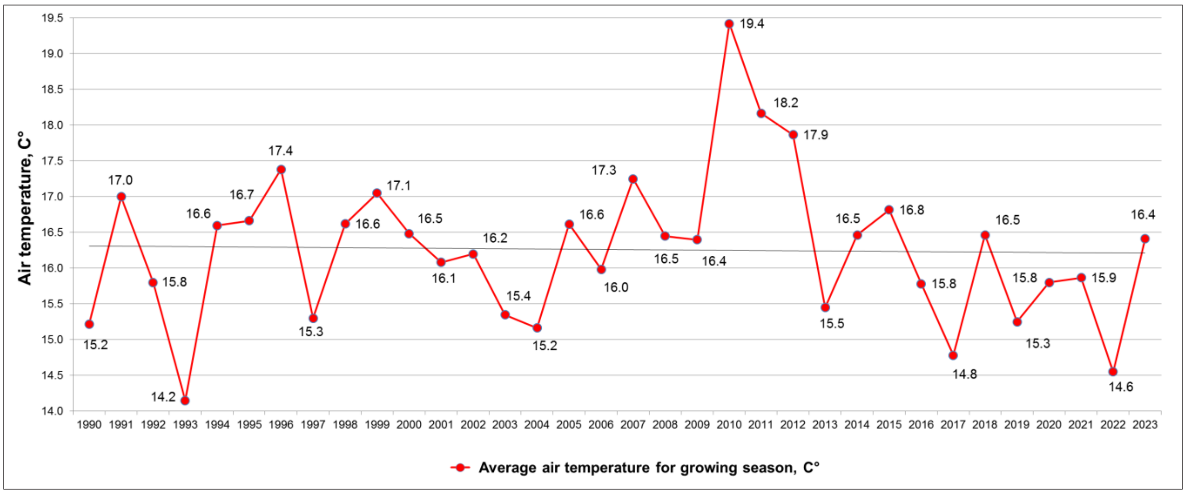

Fig. 1. Dynamics of the average monthly air temperature for the growing season of 1990–2023 (“Romen” DIS)

According to the results of analyzing the given materials, it was established that the average air temperature during the growing season over the past 34 years varied from 14.2 to 19.4 °C. There is a general trend towards a slight decrease (by almost 0.2 °C) in the average air temperature during the growing season. The highest average monthly air temperature values were recorded in July and August, and the lowest in April.

Atmospheric precipitation is one of the main factors that determines the features of regional climate, so their amount and distribution are determining indicators in the formation of the territory’s moisture regime [23].

Informational materials on the distribution of atmospheric precipitation by months of the growing seasons of 1990–2023 on the reclaimed lands of the “Romen” DIS are given in the Table. 2.

The dynamics of atmospheric precipitation in the growing seasons of 1990–2023 on the reclaimed lands of the “Romen” DIS is shown in Fig. 2. The results of the analysis show the presence of a tendency to a slight decrease in the total amount of precipitation during the growing seasons. During the studied period, 2006, 1995, 2022, and 1990 years were the wettest with the precipitation amount for a growing season, 584,8, 540,5, 493,6, and 435,6 mm, respectively. The lowest precipitation for a growing season was recorded in 2011, 2017, and 2002, with the values 202.1, 209,7, and 210,1 mm, respectively.

Atmospheric precipitation is one of the main factors that determines the features of regional climate, so their amount and distribution are determining indicators in the formation of the territory’s moisture regime [23].

The categorization of precipitation amounts was made by the instruction on meteorological forecasting following the gradation: light (<3 mm), moderate (4–14 mm), significant (15–29 mm, 30–39 mm and 40–49 mm), heavy (50–59 mm, 60–69 mm and 70–79 mm) and extreme precipitation (80–89 mm and 90–100 mm) [24].

It was determined that the water regime of the active soil layer during the growing season is formed mainly due to moderate (4–14 mm – 44 %) and significant (15–49 mm – 40 %) precipitation, the total share of which is 84 %.

The distribution of precipitation (by repetition and average intensity) by months of the growing season (1990–2022) is shown in Fig. 3.

2. Atmospheric precipitation (mm) for the growing season of 1990–2023 («Romen» DIS)

Year	Month						In total for a growing season
	April	May	June	July	August	September	
1990	92.5	63.3	70.9	87.6	70.8	50.5	435.6
1991	42.0	63.7	35.7	57.6	30.6	15.9	245.5
1992	38.1	38.7	21.8	58.6	14.2	65.1	236.5
1993	51.5	24.8	70.9	103.1	44.2	88.0	382.5
1994	31.3	61.2	51.4	23.8	46.4	23.4	237.5
1995	81.8	52.1	138.6	27.3	68.1	172.6	540.5
1996	16.8	48.0	76.2	36.7	78.1	84.0	339.8
1997	47.5	33.1	56.2	76.9	25.7	62.3	301.7
1998	-	53.4	9.9	144.8	134.4	57.7	400.2
1999	17.4	67.3	16.6	64.3	34.3	22.6	222.5
2000	40.6	34.4	42.4	97.0	12.0	136.7	363.1
2001	31.6	54.5	173.2	74.2	18.2	56.2	407.9
2002	22.9	74.5	23.6	6.2	31.7	51.2	210.1
2003	43.0	18.9	15.2	162.9	95.2	50.8	386.0
2004	22.3	68.9	49.2	102.6	16.3	61.2	320.5
2005	33.2	30.4	139.8	28.0	25.0	8.3	264.7
2006	35.7	152.1	95.1	117.6	108.3	76.0	584.8
2007	18.1	38.9	106.2	52.2	38.0	58.4	311.8
2008	49.7	37.5	93.8	119.8	9.3	51.3	361.4
2009	2.8	43.3	30.7	107.0	6.8	51.1	241.7
2010	18.3	32.8	27.5	114.5	19.7	39.8	252.6
2011	14.0	14.9	40.5	87.2	38.5	7.0	202.1
2012	53.7	14.7	33.5	21.2	67.6	45.4	236.1
2013	16.5	62.8	50.2	41.9	102.6	111.0	385.0
2014	35.7	105.5	51.3	98.6	14.2	39.9	345.2
2015	25.7	108.2	83.1	63.0	1.8	47.7	329.5
2016	52.3	145.4	87.1	77.5	46.1	4.3	412.7
2017	27.2	20.2	56.4	72.8	6.9	26.2	209.7
2018	11.3	28.1	123.1	78.9	7.0	55.5	303.9
2019	33.7	72.1	26.6	36.9	17.2	33.4	219.9
2020	37.1	148.8	73.4	71.9	12.4	17.2	360.8
2021	75.3	52.3	118.5	39.3	46.0	83.0	414.4
2022	89.5	32.3	69.8	106.1	55.3	140.6	493.6
2023	46.3	8.4	60.9	51.4	56.6	11.0	232.9
Average	36.9	56.0	65.3	73.8	41.2	56.0	329.2
%	11.2	17.0	19.8	22.4	12.5	17.0	100.0

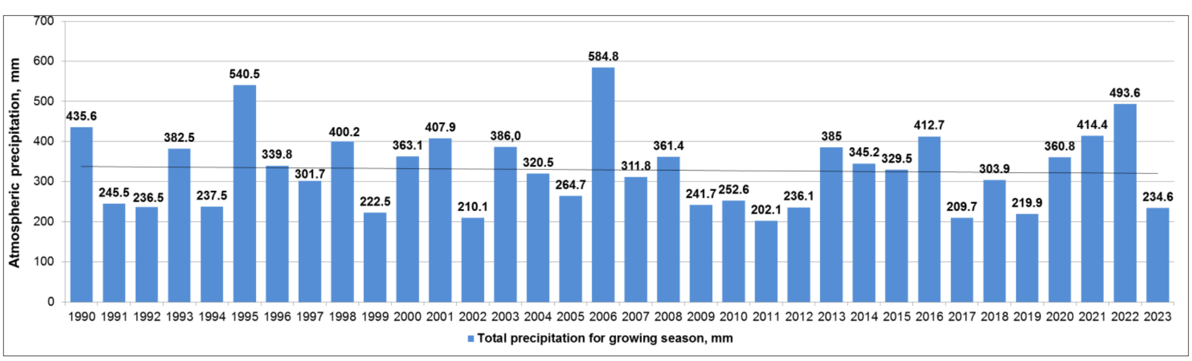

Fig. 2. Dynamics of atmospheric precipitation for the growing season of 1990–2023 («Romen» DIS)

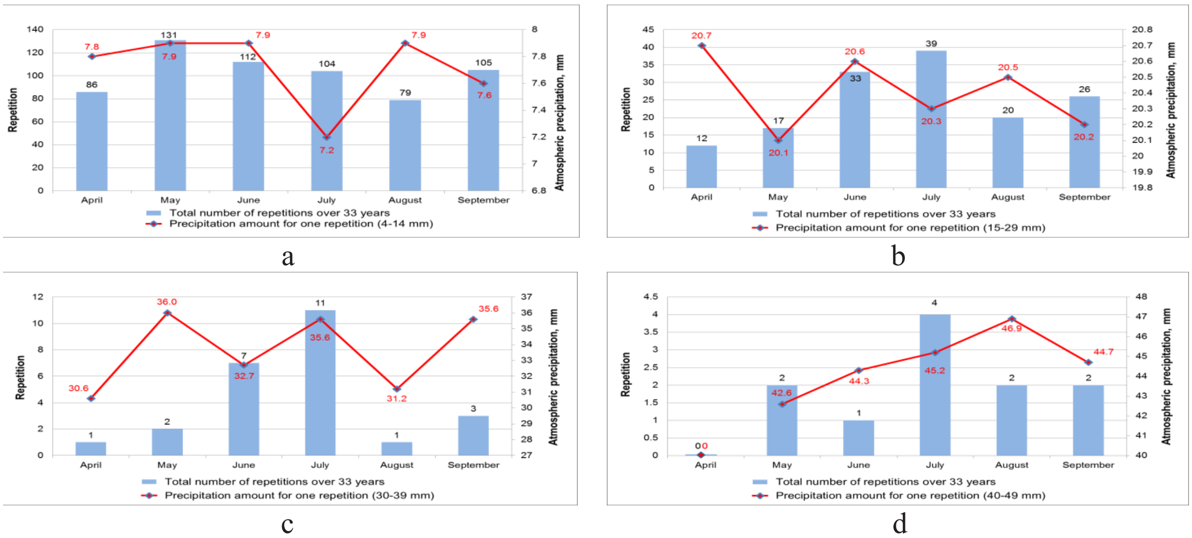

Fig. 3. Distribution of moderate and significant precipitation (by repetition and average intensity) for the growing season of 1990–2022 («Romen» DIS):
a – moderate (4–14 mm); b – significant (15–29 mm); c – significant (30–39 mm); d – significant (40–49 mm)

The trend towards an increase in the share of significant precipitation can be traced in years with high-water growing seasons. Thus, in 2006, the total amount of precipitation for the growing season was 584,8 mm. At the same time, the share of moderate precipitation was 33,4 % (195,4 mm), and significant – 59,7 % (349,3 mm) for the growing season (Fig. 4). The predominant amount (221,1 mm) of significant precipitation falls in the range of 15–29 mm. The largest amount of precipitation for the growing season was recorded in May (152,1 mm) and July (117,6 mm) (Table 2).

In 2022, the total amount of precipitation for the growing season was 493.6 mm. At the same time, the share of moderate precipitation was 39,7 % (196,1 mm), and significant – 49,6 % (244,6 mm) for the growing season (Fig. 5). The predominant amount (111.4 mm) of significant precipitation falls in the range of 15–29 mm. The largest amount of precipitation for the growing season was recorded in September (140,6 mm) and July (106,1 mm) (see Table 2).

In 1990, the total precipitation amount for the growing season was 435.6 mm. The growing season of the year was characterized by an increase in the share of significant precipitation, which amounted to 46,0 % (200,3 mm) compared to the average values for the studied period (1990–2023). The share of moderate precipitation was 39,3 % (171,3 mm) (Fig. 6). Most significant

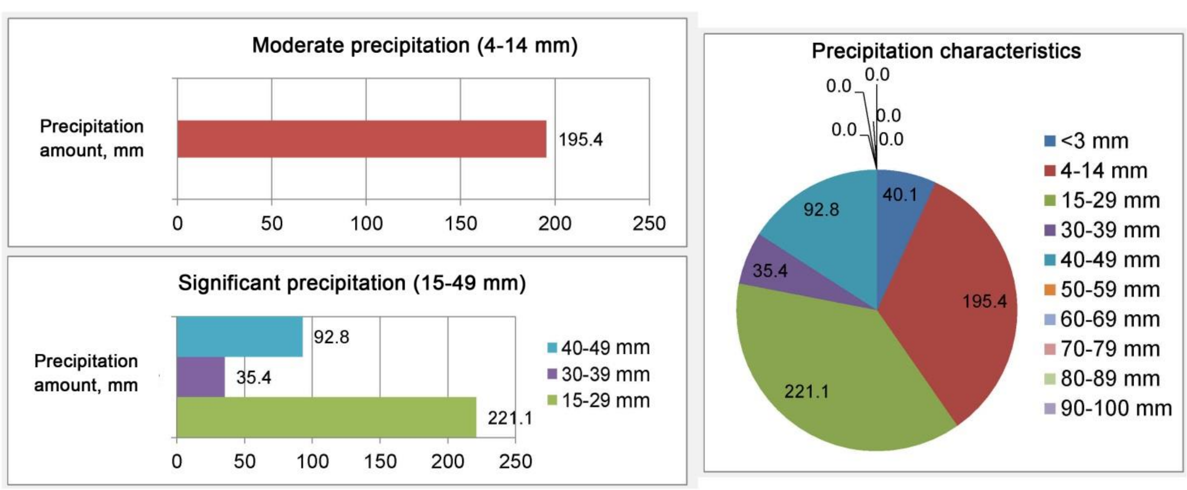

Fig. 4. Distribution of precipitation for the growing season of 2006 (following the gradation by [25]), "Romen" DIS

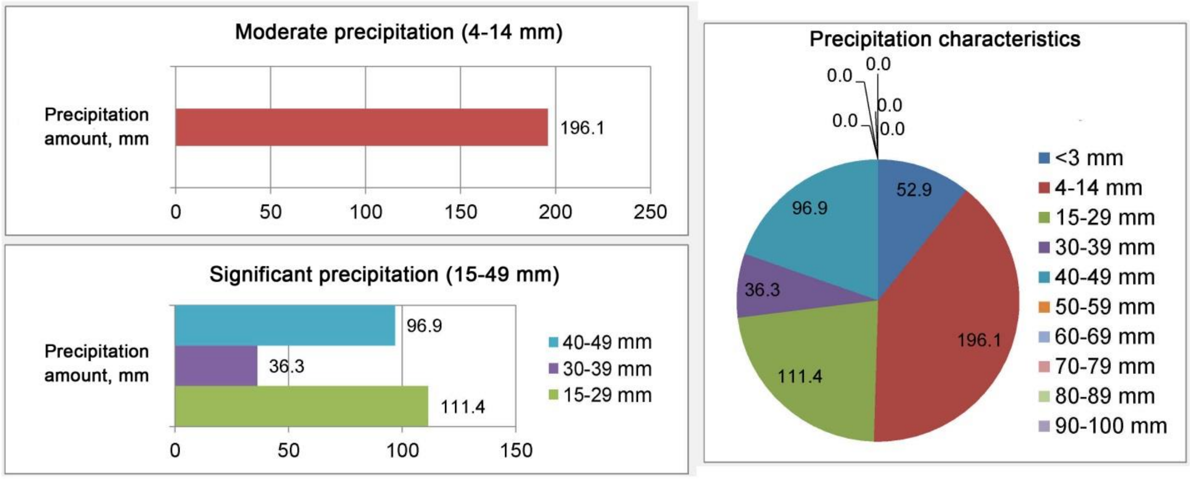

Fig. 5. Distribution of precipitation for the growing season of 2022 (following the gradation by [25]), "Romen" DIS

precipitation (165,0 mm) fell in the range of 15–29 mm. The largest precipitation amount during the growing season was recorded in April (92,5 mm) and July (87,6 mm) (see Table 2).

At the same time, there is a trend towards an increase in the share of moderate precipitation in years with low-water growing seasons.

Thus, in 2011, the total precipitation amount for the growing season was 202.1 mm. At the same time, the share of moderate precipitation was 48.9 % (98,6 mm), and significant – 30,1 % (61,0 mm) (Fig. 7). Significant precipitation fell in the range of 15–29 mm. The largest precipitation amount for the growing season was recorded in July (87,2 mm) and June (40,5 mm) (see Table 2).

Similarly, in 2017, the total precipitation amount for the growing season was 209,7 mm. At the same time, the share of moderate precipitation was 49,0 % (102,9 mm), and significant – 33,0 % (69,0 mm) (Fig. 8). Significant precipitation in almost the same amount (33,8 and 35,2 mm) fell on the ranges of 15–29 and 30–39 mm. The largest precipitation amount for the growing season was recorded in July (72,8 mm) and June (56,4 mm) (see Table 2).

Information materials on the distribution of atmospheric precipitation by year in quantitative and percentage values, its repetitions for the growing seasons of 1990–2022 («Romen» DIS, Sumy region) are presented as interactive visual reports (dashboards) with graphic materials that can be the basis of forming an assessment system for soil water regime. Dashboards enable us to visualize data and metrics in a convenient and understandable format, which makes it possible to quickly analyze and make decisions.

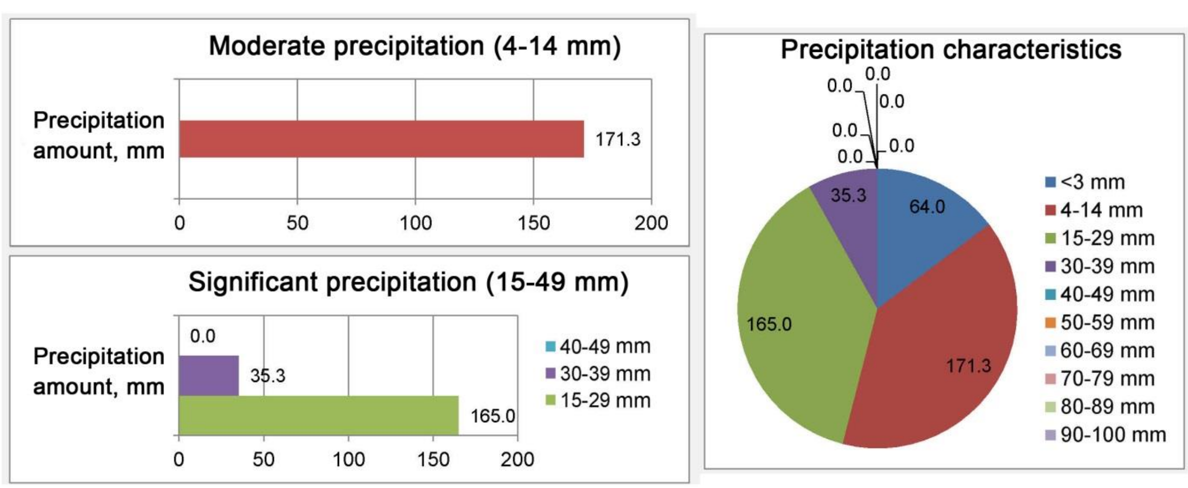

Fig. 6. Distribution of precipitation for the growing season of 1990 (following the gradation by [25]), «Romen» DIS

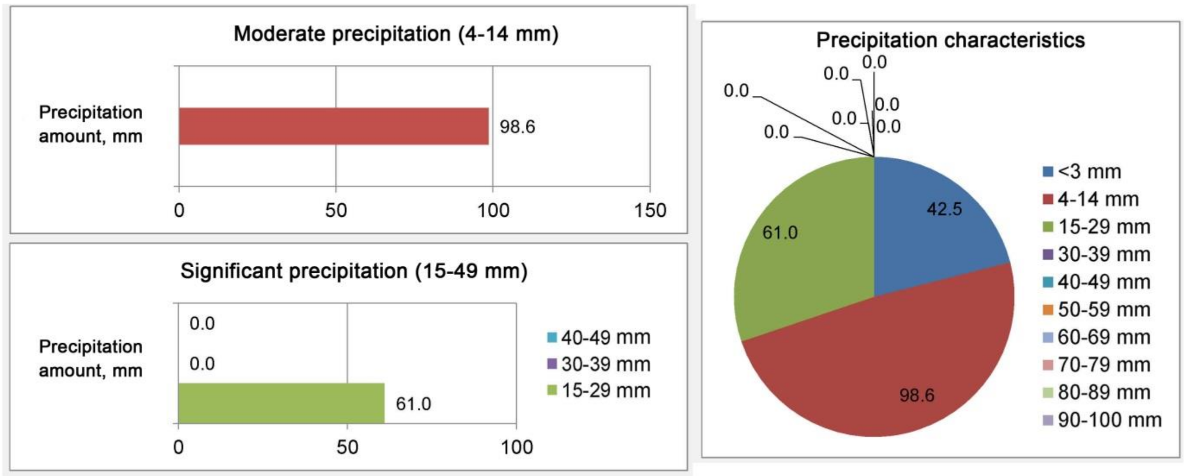

Fig. 7. Distribution of precipitation for the growing season of 2011
(following the gradation by [25]), "Romen" DIS

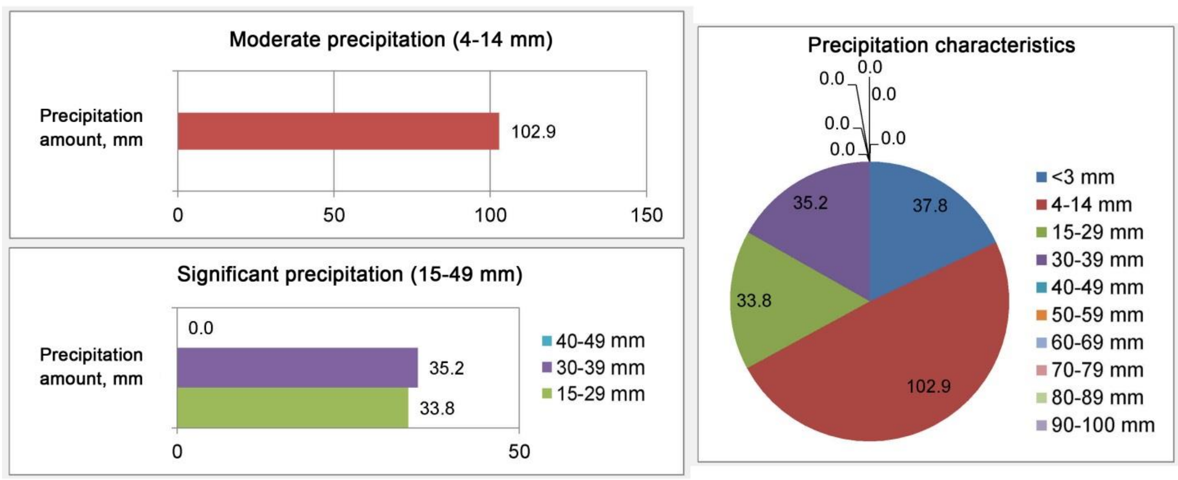

Fig. 8. Distribution of precipitation for the growing season of 2017
(following the gradation by [25]), «Romen» DIS

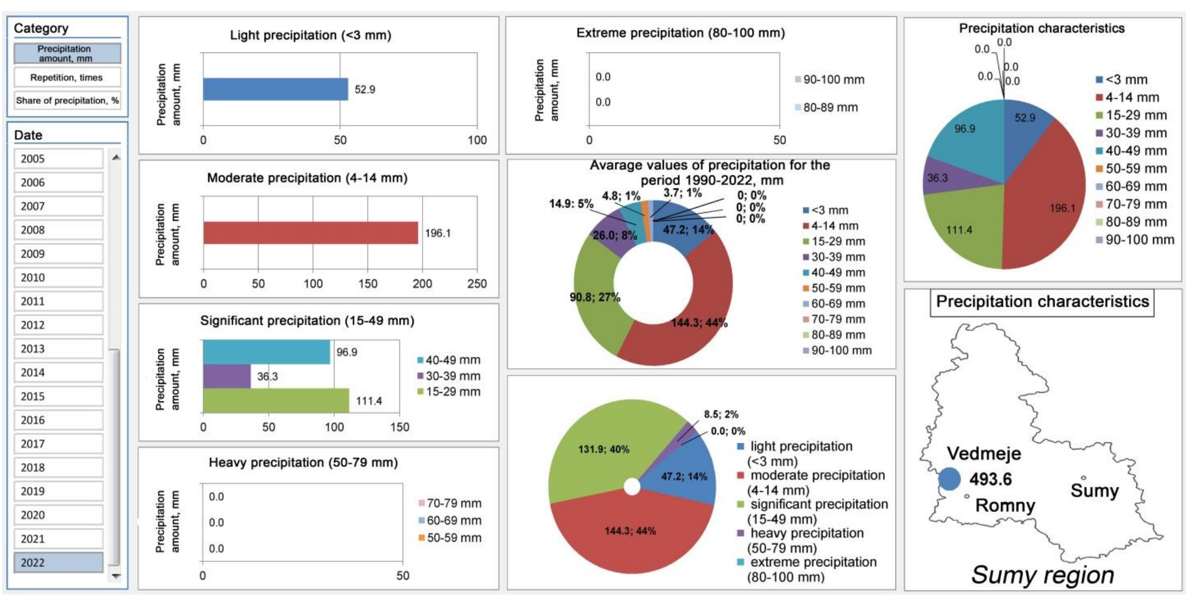

Fig. 9. Fragment of the dashboard for the growing season of 2022 («Romen» DIS)

A fragment of the developed dashboard is shown in Fig. 9.

The created dashboard consists of graphic materials that display all necessary metrics of precipitation distribution in quantitative and percentage values and its repetitions on one screen. It was made based on smart tables, where the AutoFilter function was added to each header column, which, in turn, determines what should be displayed or, conversely, not displayed at a specific time. Smart tables are a type of formatting, and after applying them to the specified range of data, their array acquires certain properties. First of all, after that, the program begins to consider it not as a range of cells but as a complete element. If an entry is made in any of the cells of a row or column, located directly near the boundaries of a "smart" table, this row or column will be automatically included in the table range [25, 26].

When using smart tables, the perception of an electronic worksheet improves, and data processing becomes easier, as they are adjusted to a certain system. Their use allows you to effectively use the time for data preparation by reducing manual operations, effectively making tables, and quickly using graphic elements.

This possibility proved its effectiveness in processing a large array of data, and the use of dashboards made it possible to display relevant information, form the necessary input data for making the right decision, and monitor the process of changing meteorological data [27, 28].

In general, the creation of information materials with the use of dashboards helps to monitor the changes in climatic conditions, promptly providing relevant data when forecasting future trends of changes in water availability of agricultural areas and solving challenges related to climate change.

Conclusions. To solve the modern problems of managing agricultural systems, namely soil water regime on drained lands in modern conditions of climate change, it is relevant today to study climate change both at the regional and local levels and to create informational materials for assessing the impact of modern climatic factors on forming soil water regime.

According to the results of research carried out at the «Romen» DIS (Sumy oblast), it was established that the average air temperature for the growing seasons over the past 34 years has varied from 14,2 to 19,4 °C. In general, there is a tendency to a slight decrease (almost by 0,2 °C) in the average air temperature for a growing season. The highest average monthly air temperatures were recorded in July and August, and the lowest in April.

It was determined that the water regime of the active soil layer during the growing season is formed mainly due to moderate (4–14 mm – 44 %) and significant (15–49 mm – 40 %) precipitation, the total share of which is 84 %. There is an increasing trend in the share of significant precipitation (on average, up to 46–60 % of the total amount for a growing season) in the years of high-water growing seasons, and most of it is in the range of 15–29 mm. There is also an increase in the share of moderate precipitation (up to 49 % of the total for a growing season) in the years of low-water growing seasons.

Information materials on the distribution of atmospheric precipitation by year in quantitative and percentage values, and their repetitions for the growing seasons of 1990–2022 («Romen» DIS, Sumy region) were made and presented as interactive visual reports (dashboards) with graphic materials. Dashboards enable us to visualize data and metrics in a convenient and understandable format, which makes it possible to quickly analyze and make decisions. They can be an important component of the information assessment system for forming soil water regimes, which makes it possible to monitor changes in climatic conditions and quickly provide relevant information for forecasting future trends in changing water availability of agricultural areas.

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ІНФОРМАЦІЙНІ МАТЕРІАЛИ ДЛЯ ОЦІНЮВАННЯ ВПЛИВУ КЛІМАТИЧНИХ ФАКТОРІВ НА ФОРМУВАННЯ ВОДНОГО РЕЖИМУ ҐРУНТУ НА ОСУШУВАНИХ ЗЕМЛЯХ

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Анотація. *Наведено результати досліджень щодо створення інформаційних матеріалів для оцінювання впливу сучасних кліматичних факторів на формування водного режиму ґрунту на осушуваних землях. За результатами досліджень на ОЗС «Ромен» (Сумська обл.) встановлено, що за останні 34 роки середня температура повітря у вегетаційний період змінювалася у межах від 14,2 до 19,4 °С, загалом відзначається тенденція до незначного її зниження (майже на 0,2 °С). Найвищі показники середньомісячної температури повітря припадають на липень та серпень, а мінімальні – на квітень. Визначено, що водний режим активного шару ґрунту у вегетаційний період формується, головним чином, за рахунок помірних (4–14 мм – 44 %) та значних (15–49 мм – 40 %) опадів, загальна частка яких становить 84 %. Простежується тенденція до зростання частки значних опадів (у середньому до 46–60 % загальної кількості у період вегетації) у роки з багатоводними вегетаційними періодами, а переважаюча їх кількість припадає на діапазон 15–29 мм. Відзначається також зростання частки помірних опадів (до 49 % загальної кількості за період вегетації) у роки з маловодними вегетаційними періодами. Створено інформаційні матеріли щодо розподілу атмосферних опадів за роками в кількісному та відсотковому показниках, їх повторюваності у вегетаційний період 1990–2022 рр. (ОЗС «Ромен», Сумська обл.), які подані у вигляді інтерактивного візуального звіту з графічними матеріалами (дашборду). Інформаційні матеріали у вигляді дашбордів дають змогу відстежувати зміни кліматичних умов, оперативно надаючи актуальні дані під час прогнозування майбутніх тенденцій зміни водозабезпеченості сільськогосподарських територій, зокрема і формування водного режиму ґрунту на осушуваних землях, та розв'язанні завдань відповідно до викликів, пов'язаних зі змінами клімату.*

Ключові слова: *зміни клімату, осушувані землі, атмосферні опади, температура повітря, інформаційні матеріали, водний режим ґрунту*

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REDUCING OF WATER AND ENERGY RESOURCES CONSUMPTION IN IRRIGATION BASED ON RESOURCE OPTIMISATION

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Abstract. *The need for further development of irrigation practices on the basis of nature oriented and ecologically efficient solutions is considered primarily regarding the saving of water and energy resources for the adaptation of irrigated agricultural production to the current global challenges and threats, the achievement of sustainable development goals. It is shown that there is an objective need to change methodological approaches to the assessment of overall efficiency and justification of optimal solutions in design, reconstruction, and operation projects of irrigation systems based on the principles of resource optimization. On the basis of the indicator of the level of irrigation sufficiency (introduced by the authors), which reflects the reduction of the studied watering and irrigation rates in relation to their design values, a study of the impact of reducing the use of water and energy resources under different modes of sprinkler irrigation on the corresponding decrease in the level of cultivated crops productivity was carried out. At the same time, it was experimentally determined that the intensity (rate) of the decrease in the cultivated crops productivity, which occurs due to the decrease in the usage of water and energy resources during the application of irrigation, is significantly lower than the intensity (rate) of the decrease in the usage of the resources themselves. The studied options for reducing the consumption on water and energy resources as a whole turned out to be economically profitable when with a decrease in water and electricity usage by 27–48 % there is more than two times lower decrease in the costs of gross products by 10,80–18,06 % with the achievement of a net income of 11,4 to 5,7 thousand UAH. The influence of various options of reducing water and electricity consumption on the discounted investment payback period shows that several options may be acceptable, for which the investment payback period does not exceed 10 years, and the choice of the optimal solution requires taking into account the conditions of a specific object, limitations of water resources, and the interests of investors and land users. At the same time, the ecological component of the overall efficiency of irrigation practices consists in the decrease in the use of water and energy resources that a priori reflects the decrease in the negative impact of irrigation on the environment. Thus, reducing the usage of water and energy resources is a fully justified decision on the way to adapt irrigated agriculture production to the modern conditions and requirements, and the presented results can be a scientific basis for the implementation of this approach while practically applying irrigation.*

Key words: *consumption reduction, water resources, energy resources, irrigation, resource-based optimization*

Relevance of research. Existing global problems related to climate changes, food, water, and energy crises confront the world community, including Ukraine, with the need to adapt to existing challenges and threats and to increase the overall efficiency of all sectors of economy, primarily agricultural production, in order to achieve the goals of sustainable development as the main modern concept of the further development of society with the aim of the safety for future generations, in particular, regarding the need for a safe and healthy environment [1–4].

The major part of territory of our country, and, accordingly, agricultural lands, are traditionally located in the zone of risky agriculture with insufficient level of natural moisture, and therefore their use for crop growing requires irrigation to a greater or lesser extent. In addition, in recent years, as a result of climate changes, the zone of risky agriculture in Ukraine has significantly expanded and, according to various estimates of scientists, reaches 18–20 million hectares [5]. At the same time, irrigated lands were, are, and remain a valuable production resource, which make it possible to obtain 2-3 times larger volumes of crop production compared to rainfed lands.

Under such conditions, irrigation is one of the most effective tools for reducing the negative impacts of climate changes on agricultural production, the implementation of which at the same time requires significant expenditures of water, energy, and other related resources. Therefore, the further restoration and development of irrigation require the implementation of natural based and ecologically sound solutions, which are an important condition for adapting agricultural production to existing global challenges and threats and for achieving the goals of sustainable development.

In addition, since the beginning of the full-scale war, the losses of cultivated areas in Ukraine caused by the temporary occupation and military actions amounted to more than 25 % of their total area, and the main part of these losses is the highly productive irrigated lands of the south and east of the country. After the terroristic attack of Russia at the Kakhovska HPP, which led to a further reduction of available arable land, the problem of the shortage of water resources for irrigation, [6] relevant both at the regional and planetary levels, reached the critical point, since the Kakhovska Reservoir itself was the source for irrigation of the lands of the south of Ukraine – the left bank of the Kherson region, partly in the Zaporizhzhia and Dnipropetrovsk regions. These are all consequences, the impact of which will be felt in the long term.

Analysis of recent studies and publications. Under the conditions of climate changes, aggravation of food, water, and energy crises, it is nature oriented and ecologically efficient solutions that can meet the needs of society and overcome social challenges in a natural sound way and in compliance with the principles of sustainable development based on more efficient use of natural resources, including water and energy [7].

In this regard, achieving and maintaining the country’s food security in conditions of necessary resources shortage requires the implementation of nature oriented and ecologically effective solutions to increase the efficiency of irrigation, in particular by developing regime-technological and technical resource-saving measures and means that should be based on saving water and energy resources to ensure the process of crops irrigation.

In recent years, the trend for purposeful reduction of water use in irrigation has been spreading in the USA, where farmers deliberately reduce the yield of cultivated crops in order to save scarce and expensive water and energy resources [8–10]. Similar practices are used in China by implementing the so-called “deficit irrigation” [11–14]. However, this is done without the scientifically based recommendations for the implementation of such an approach.

Considering the above-mentioned, in modern conditions for achieving the goals of sustainable development, extremely relevant are the studies aimed at scientific substantiation of such decisions and of the levels of involved resources saving in the context of the effectiveness of irrigation implementation and agricultural production as a whole.

Thus, the **purpose of the conducted research** is to substantiate the feasibility and optimal decisions regarding the level of usage reduction of water and energy resources on the basis of resource optimization utilizing the results of evaluating the overall resources (technological), economic, ecological, and investment efficiency of irrigation at different levels of its sufficiency.

Research methods and materials. Modern changes in the irrigation systems functioning lead to the need for changes in methodological approaches to their creation and design, which should be based on a resource approach. New methodological approaches to the creation and functioning of irrigation systems, improvement of regime and technological aspects of irrigation, types, facilities, and parameters of irrigation systems adapted to these changes should be based not only on the evaluation of the effectiveness of adopted technical and technological solutions, but also take into account real operating conditions of the object, the level and trends in agricultural production, as well as, first of all, the amount of resources spent for its provision.

In the development of our earlier studies [15], with this approach, the substantiation of optimal solutions in the projects of construction, reconstruction, and operation of irrigation systems, considered as complex natural, technical, ecological, and economic systems, can be performed using the following complex optimization model

$$\begin{cases} U_0 = \underset{\{i\}}{extr}\, U_i, i = \overline{1, n_i}; \\ R_{0j} = \underset{\{i\}}{\min} \left| R_{ji} - \widehat{R}_j \right|, j = \overline{1, n_j}; i = \overline{1, n_i} \end{cases} \quad (1)$$

where U_o is the extreme value according to the accepted condition of the selected criterion of economic optimality *U*, which corresponds to the optimal technical and technological solution according to the set of possible options $I = \{i\}$, $i = \overline{1, n_i}$;

R_{ji} is a set of $\{j\}$, $j = \overline{1, n_j}$ criteria for the use of water and energy resources primarily involved in irrigation for appropriate options of technical and technological solution;

$\widehat{R}_j$ are the appropriate justified indicators of the criteria for the use of the involved resources.

Such a system of equations in a general implicit form makes it possible, on the basis of resource optimization, to theoretically substantiate the possibility of setting a problem, research, and consistently determine the optimal regime, technological and technical solutions for heterogeneous constituent elements and the system as a whole in their relationships both on empirical and empirical-functional level of determining the dependency between them.

In turn, the implementation of this model requires the application of a complex of forecasting-simulation, optimization, and economic-mathematical methods and models, which is embodied in the "Software package for the justification of design solutions during the creation and functioning of water management and reclamation facilities" [16]. It is a set of computer programs that make it possible to perform predictive simulations based on a number of indicators that characterize various aspects of irrigation in relation to the technological, ecological, economic, and investment components of the results of its implementation under multiple variable natural-agro-ameliorative conditions both at the level of a field and the specific crop and the level of the system and the projected term of its functioning. Their use is regulated by relevant industry standards of the State Water Agency of Ukraine [17–19, 27].

On the basis of the software package [16] for researching the impact of water and energy resource usage on changes in the productivity of cultivated crops, a computational experiment was planned and carried out to assess the overall efficiency of irrigation [20] with different modes of resource usage. For its implementation, we used the data obtained by us during the evaluation of the effectiveness of the vibration filter of the settling tank for irrigation water cleaning with various degrees of pollution in LLC "S-Rostok", Kherson region [21, 22].

The agricultural enterprise LLC "S-Rostok" is located in the Kakhovka district of Kherson region, Ukraine. Agricultural lands are represented by southern low-humus black soils. The main directions of production activity of the agricultural enterprise are the cultivation of grain, including high-quality food grain, technical crops, and vegetables. Irrigation of cultivated crops is carried out by sprinkling using sprinkler machines DMF "Fregat" modification DMU-Bnm 463-57-01.

The initial conditions for the computational experiment are as follows: **region** – Kherson**; natural and climatic zone** – Steppe; **calculation groups of years according to the conditions of heat and moisture sufficiency during the vegetation seasons** (very wet (p = 10 %); wet (p = 30 %); average (p = 50 %); dry (p = 70 %); very dry (p = 90 %)); **soils** – southern chernozems with low humus contents; **the set of crops of the project crop rotation with a share of their content** (perennial grasses (green mass) – 0,4; winter wheat (grain) – 0,2; vegetables (tomatoes) – 0.2; corn (grain) – 0,2).

The initial data used for the computational experiment regarding the irrigation rates and the cost of electricity for their supply with different sprinkler irrigation modes for the crops of the project crop rotation in terms of the level of resource consumption are presented in Table 1. For their characterization, the indicator of the ***level of irrigation sufficiency (φ, %)*** was introduced, which in the percentage equivalent characterizes the level of compliance of the studied irrigation regimes with its design regime, i.e. what is the percentage for watering **(φ_m, %)** and irrigation **(φ_M, %)** rates of their values with a certain irrigation regime relative to the design values.

The data on the changing the watering rates of the crops of the project crop rotation presented in Table 1 were obtained using the dependency between water losses along with the reduction of watering rate comparing to the projected one and different levels of irrigation water pollution during sprinkler irrigation in the process of the evaluation of the effectiveness of the vibration filter of the sump for cleaning irrigation water of various degrees of pollution [21, 22]. At the same

1. The values of watering rates and electricity consumption for crops irrigation from the project crop rotation with sprinkler irrigation regimes of different levels of sufficiency

Crops of the project crop rotation and indicators of the sprinkler irrigation regime		The level of irrigation sufficiency (φ_M, %)					
		100 % (designed)	**73 %**	**70 %**	**67 %**	**62 %**	**52 %**
perennial grasses (green mass)	watering rate *(m, m^3/ha)*	600	440	420	400	360	300
	electricity consumption *(ω_m, kWh/ha)*	200	147	140	133	120	100
vegetables (tomatoes)	watering rate *(m, m^3/ha)*	540	400	380	360	350	300
	electricity consumption *(ω_m, kWh/ha)*	180	133	127	120	117	100
winter cereals (grain)	watering rate *(m, m^3/ha)*	380	270	260	250	240	200
	electricity consumption *(ω_m, kWh/ha)*	127	90	87	83	80	67
corn (grain)	watering rate *(m, m^3/ha)*	420	300	290	280	260	220
	electricity consumption *(ω_m, kWh/ha)*	140	100	97	93	87	73

time, these data adequately reflect the situation when there are different levels of deviation of watering rates from their design values. They are consistent with the accepted concept of research on the impact of different consumption of water and energy resources on the changes in the productivity of cultivated crops under different irrigation regimes that correspond to different levels of its sufficiency.

Corresponding data on electricity consumption for supplying watering rates, as well as for all subsequent calculations, were obtained taking into account the unit cost of electricity for irrigation water pumping, which for the studied conditions in the Kherson region is 333.9 kWh/thousand m^3.

As the main variants of the study, the following set of modes of sprinkler irrigation, differing in the level of irrigation sufficiency, was considered:

– **control** – sprinkler irrigation according to the design mode, $\varphi_M = 100\ \%$;

– **option 1** – sprinkler irrigation mode, which is corresponds to $\varphi_M = 73\ \%$;

– **option 2** – sprinkler irrigation mode, which is corresponds to $\varphi_M = 70\ \%$;

– **option 3** – sprinkler irrigation mode, which is corresponds to $\varphi_M = 67\ \%$;

– **option 4** – sprinkler irrigation mode, which is corresponds to $\varphi_M = 62\ \%$;

– **option 5** – sprinkler irrigation mode, which is corresponds to $\varphi_M = 52\ \%$.

At the initial stage of predictive simulations, the data on changing watering rates (Table 1) were used for predictive assessment, according to which at the field level for each of the crops from projected crop rotation, calculation groups of years typical with respect to the conditions of heat and moisture sufficiency, and different irrigation regimes that correspond to different levels of irrigation sufficiency we evaluated the value of a set of different data on the water regime of the soil, technological indicators of irrigation, including irrigation rates and the corresponding values of the effective yield of the cultivated crops from projected crop rotation.

The obtained values of the specific indicators of irrigation rates and yields of crops from the projected crop rotation in relation to multiple variable conditions served as the basis for determining a number of relevant indicators that characterize the technological, economic, ecological, and investment efficiency of the studied options of sprinkler irrigation, presented in the form of weighted averages of their values at the level of the system and the project term of its functioning.

Research results and their discussion. An important issue in assessing the overall technological, ecological, economic, and investment efficiency of different irrigation regimes, which correspond to different levels of its sufficiency, is the selection and justification of criteria as a set of indicators that reflect various aspects of the effectiveness of their implementation. In this regard, a matrix of pairwise correlation coefficients was created, as an integral and important component of multi-criteria regression analysis, between disparate indicators characterizing various aspects of irrigation efficiency during the application of different irrigation regimes, which correspond to different levels of irrigation sufficiency [23, 24]. The input data of the performed multi-criteria regression analysis are the weighted average values of multiple heterogeneous specific indicators, which describe different aspects of irrigation efficiency during the application of different irrigation regimes, which correspond to different levels of irrigation sufficiency, obtained according to the results of predictive simulation.

The generalized results of such an analysis showed a fairly high level of connectivity between the following disparate indicators, which describe various aspects of irrigation efficiency (Table 2). φ_M – the irrigation sufficiency level (according to the irrigation rate), *M* – the irrigation rate, *W* – the electricity consumption, *C* – the cost of the gross product of the crop rotation, *Ce* – the current operating costs for irrigation, NI – the net income.

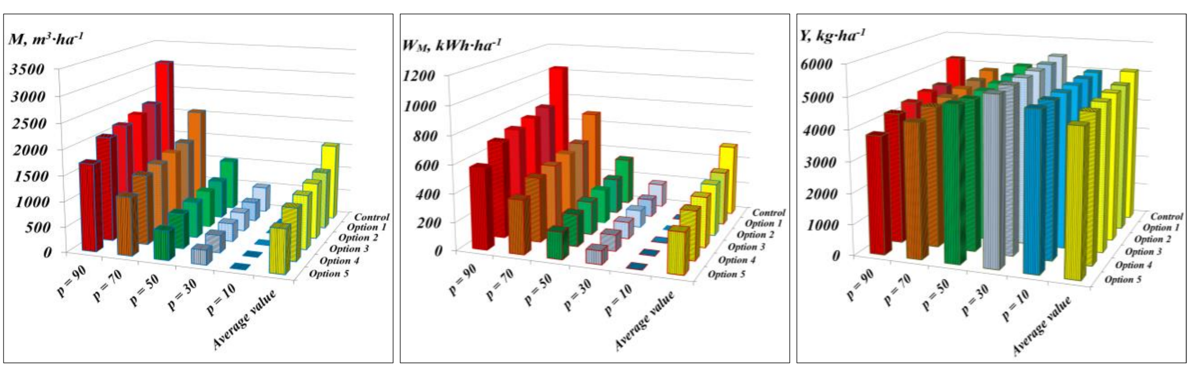
Based on the results of predictive simulations for the considered groups of years and crops from the projected crop rotation, changes in indicators of resource (technological) efficiency of irrigation were determined, namely, the values of irrigation rates and electricity consumption for sprinkler irrigation regimes with different levels of its sufficiency, and the resulting changes in the yield of cultivated crops as the main result of agricultural production, which directly determines the level of its economic efficiency.

A fragment of the obtained results, the case of the irrigation of winter wheat as the leading crop of the agricultural enterprise, which reflects the dynamics of changes in the values of the irrigation rate, electricity consumption, and yield of the cultivated crop according to the studied options at different levels of sprinkler irrigation sufficiency in relation to the calculation groups of years (very wet (p = 10 %) ; wet (p = 30 %); dry (p = 90 %); as well as their weighted average values are presented in Fig. 1.

The obtained results show that there is a clear dependency between the reduction of the irrigation rate, electricity consumption, and the decrease in the yield of cultivated crops. At the same time, the intensity of reducing the consumption of the relevant resources is significantly higher than the intensity of the decrease in the yield of cultivated crop. At the same time, under the conditions of the same level of irrigation sufficiency in relation to the calculation groups of years, and accordingly the level of reduction of water and energy resource consumption, the most significant reductions in the yield of winter wheat occur in drier years (under the conditions of medium (p = 50 %), dry (p = 70 %), and very dry (p = 90 %) years). The same conclusions are

2. Matrix of pairwise correlation coefficients between indicators characterizing the efficiency of irrigation implementation (R^2 = 0,8736)

Indicators	φ_M	***M***	***W***	***C***	C_e	***NI***
φ_M	1,0000	0,9153	0,8951	0,8758	–0,9061	0,8831
M	0,9153	1,0000	0,9523	0,8865	–0,9368	0,8803
W	0,8951	0,9523	1,0000	0,8853	–0,9145	0,8798
C	0,8758	0,8865	0,8853	1,0000	–0,8349	0,8721
C_e	–0,9061	–0,9368	–0,9145	–0,8349	1,0000	–0,8741
NI	0,8831	0,8803	0,8798	0,8721	–0,8741	1,0000



a *b* *c*

Fig. 1. Dynamics of changes in the values of the irrigation rate (*a*), electricity consumption (*b*) and the yield of the cultivated crop (*c*) according to the studied options at different levels of sprinkler irrigation sufficiency in accordance with the calculation groups of years in the case of the irrigation of winter wheat

typical for the rest of the cultivated crops.

Generalized among the set of crops from the projected crop rotation, the weighted average values of the indicators of the resource (technological) efficiency of sprinkler irrigation according to the studied options at different levels of its sufficiency for medium (p = 50 %), dry (p = 70 %), and very dry (p = 90 %) years, as those which are characterized by higher levels of expenditure of water and energy resources for irrigation from the entire set of calculation groups of years, are presented in Table 3.

A comparative assessment of the resource (technological) efficiency of sprinkler irrigation of the project crop rotation according to the studied options was carried out in relation to the weighted average values of the irrigation rate, electricity consumption, and productivity of the crop rotation for medium (p = 50 %), dry (p = 70 %), and very dry (p = 90 %) years, the results of which are presented on Fig. 2. At the same time, crop rotation productivity is calculated as a weighted average indicator based on the actual values of the yield of cultivated crops, presented in the form of degrees in relation to the potential climate-agrotechnically justified yield of these crops, the value of which is taken as 100 degrees.

The presented results showed that the studied options with different levels of irrigation sufficiency are generally technologically effective, when the intensity of crop rotation productivity reduction is more than twice as low as the intensity of water and electricity consumption reduction. At the same time, the intensity of the decrease in the productivity of the projected crop rotation has a clear dependency on the year of the calculated sufficiency – with an increase in the aridity of the year, it increases from 4.9–8.1 % for the conditions of an average year, and up to 22.9–41 % for the conditions of a very dry year, when the sensitivity of the impact increases with the reduction of irrigation rate values.

3. Generalized weighted average indicators of water and energy resources consumption during sprinkler irrigation according to the studied options for the conditions of medium (p = 50 %), dry (p = 70 %), and very dry (p = 90 %) years

Indicators of resource (technological) efficiency of sprinkler irrigation by calculation groups of years		**Studied option**					
		control	**option 1**	**option 2**	**option 3**	**option 4**	**option 5**
Consumption of irrigation water, m^3/ha	p = 50 %	1722	1263	1208	1154	1076	907
	p = 70 %	4012	2944	2815	2686	2491	2095
	p = 90 %	6698	4913	4698	4482	4155	3495
Consumption of electricity for irrigation water supply, kWh/ha	p = 50 %	575	422	403	385	359	303
	p = 70 %	1340	983	940	897	832	700
	p = 90 %	2237	1641	1569	1497	1388	1167

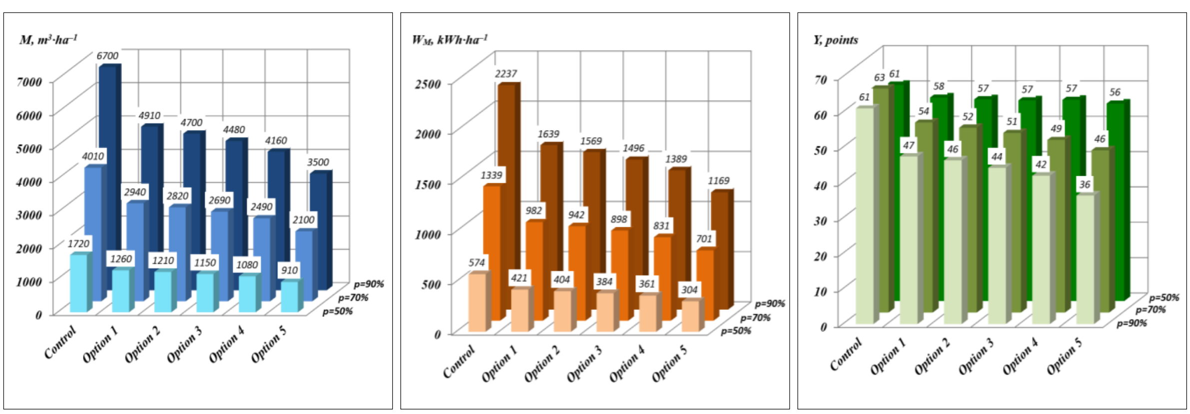


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Fig. 2. Comparative assessment of the resource (technological) efficiency of sprinkler irrigation of the projected crop rotation according to the studied options regarding the weighted average values of the irrigation rate (a), electricity consumption (b) and productivity (c) for medium (p = 50 %), dry (p = 70 %), and very dry (r = 90 %) years

The final decision regarding the expediency of reducing the consumption of water and energy resources can be made only on the basis of evaluating the economic and investment efficiency of irrigation according to the studied options.

According to [25, 26], the following indicators reflecting the economic component of irrigation efficiency were used to evaluate the economic efficiency of sprinkler irrigation of the projected crop rotation: *total current costs, UAH/ha; cost of gross production, UAH/ha; net income, UAH/ha; indicator of reduced costs taking into account weather and climate risk.*

Generalized among the set of crops from the projected crop rotation and calculation groups of years according to the conditions of heat and moisture supply during the growing season, the weighted average values of the main indicators of the economic efficiency of sprinkler irrigation of the projected crop rotation according to the studied options at different levels of irrigation sufficiency are presented in Table 4.

The sources of prices, which were used to calculate the main economic indicators presented in Table 4, are price tags, price lists, exchange prices, etc, as for 2019.

A comparative assessment of the change in average weighted values of resource (technological) and economic efficiency indicators of sprinkler irrigation according to the studied options relative to the control option is presented in percentages in Table 5.

The presented results (Table 4 and Table 5) showed that the studied options with different levels of irrigation sufficiency are generally economically profitable when the intensity of the decrease in the cost of gross production varies from 10.80 to 18.06 %, which is more than twice as low for the intensity of reducing water and electricity consumption from 27 to 48 %, with the achievement of net income from 11.4 to 5.7 thousand UAH/ha, respectively.

At the same time, the ecological component of the overall effectiveness of irrigation implementation consists in the decrease in the use of water and energy resources during the implementation of irrigation that a priori reflects the reduction of its negative impact on the environment. Therefore, these indicators can be used as possible criteria for evaluating the resource-ecological component of irrigation efficiency, which is a particular feature of the considered approach and meets the modern needs of changing approaches to the irrigation application under the conditions of climate changes, food, water, and energy crises, the transition of irrigated agriculture to nature oriented and resource-efficient solutions for achieving the sustainable development goals.

According to [27], the following indicators were used to evaluate the investment efficiency of sprinkler irrigation of the projected crop rotation: *investment profitability index, discounted net income, and discounted payback period.* The results of evaluating the investment effectiveness of sprinkler irrigation according to the studied options are presented in Table 6.

As shown by the results of the research of the impact of various studied options of reducing

4. Generalized weighted average values of indicators of economic efficiency of sprinkler irrigation according to the studied options

Indicators of economic efficiency	**Studied option**					
	control	**option 1**	**option 2**	**option 3**	**option 4**	**option 5**
Total current costs, UAH/ha	59632	56396	56438	56630	57453	56503
Cost of gross production, UAH/ha	76016	67808	67086	65901	65133	62285
Net income, UAH/ha	16384	11412	10648	9272	7679	5782
Indicator of reduced costs taking into account weather and climate risk	1,5	1,75	1,78	1,84	1,88	2,0

5. Comparative evaluation of the change in the weighted average values of the resource (technological) and economic efficiency of sprinkler irrigation according to the studied options

***Change in the values of resource (technological) and economic efficiency indicators**	**Studied option**				
	option 1	**option 2**	**option 3**	**option 4**	**option 5**
Reduction of water and electricity consumption, %	27	30	33	38	48
Decrease in the cost of gross production, %	10,80	11,75	13,31	14,32	18,06
Increase in the indicator of reduced costs taking into account weather and climate risk, %	16,67	18,67	22,67	25,33	33,33

Remark: 1. * – the data are indicated relative to the control version of the study; 2. Reduction of water and electricity consumption according to research options are identical, %

6. Indicators of investment efficiency of sprinkler irrigation according to the studied options

Indicators of investment efficiency	Studied option					
	control	option 1	option 2	option 3	option 4	option 5
Investment profitability index	2.24	1.68	1.60	1.44	1.26	1.05
Discounted net income, UAH/ha	89085	49007	42849	31755	18920	3625
Discounted payback period, years	5	7	8	9	10	14

the use of irrigation water on the indicator of the discounted payback period, several options may be acceptable according to this criterion, for which this indicator does not exceed the normative value of 10 years. Under such conditions, with the possible further implementation of the obtained results and the choice of the optimal option for implementation, it is necessary to take into account in each individual case, first of all, the limitations of availability and suitability of water resources for irrigation, the interests of investors and land users, availability of financial resources and opportunities, the scale of activities, the strategic importance of the object for economy, ecological acceptability and other conditions and criteria important for a specific object.

Conclusions. Thus, modern conditions and requirements for irrigation application, taking into account climate changes, the aggravation of food, water, and energy crises necessitate the transition to nature oriented and ecologically efficient solutions and changes in approaches for justification of optimal design solutions for the development and functioning of irrigation systems based on resource optimization. Such solutions meet the current needs for adaptation of various branches of economy, including irrigated agriculture, to existing challenges and threats along with the harmonization of their results with the concept of sustainable development of society, the main goal of which is systematically managed development with the establishment of a balance between meeting the modern needs of humanity and protecting the interests of future generations.

Therefore, reducing the consumption of water and energy resources during sprinkler irrigation is a fully justified decision from both a scientific and a practical point of view on the way to adapt irrigated agriculture to the modern conditions and requirements. Presented results showed that the intensity of the decrease in the productivity of cultivated crops, which is due to the decrease in the consumption of water and energy resources during the irrigation application, is significantly lower than the intensity of the decrease in the consumption of the resources themselves. This can be a scientific basis for the implementation of this approach in irrigation practice under existing changing conditions. That is why, the obtained results can be successfully used in the future for the justification of the nature oriented and ecologically effective solutions in irrigation in terms of implementation sustainable development concept in agricultural production under the conditions of global challenges and threats related to climate changes, water, food, and energy crises.

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СКОРОЧЕННЯ ЗАТРАТ ВОДНИХ Й ЕНЕРГЕТИЧНИХ РЕСУРСІВ ПРИ ЗРОШЕННІ НА ЗАСАДАХ РЕСУРСНОЇ ОПТИМІЗАЦІЇ

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Анотація. *Розглянуто необхідність подальшого розвитку зрошення на основі природоорієнтованих та екологоефективних рішень, насамперед щодо економії водних й енергетичних ресурсів для адаптації аграрного виробництва на зрошенні до наявних глобальних викликів і загроз та досягнення цілей сталого розвитку. Показано, що існує об'єктивна необхідність зміни методологічних підходів* *до оцінювання загальної ефективності й обґрунтування оптимальних рішень у проєктах будівництва, реконструкції та експлуатації зрошувальних систем за принципами ресурсної оптимізації. На основі введеного нами показника рівня забезпеченості зрошення, який відображає зниження досліджуваних поливних та зрошувальних норм щодо їх проєктних значень, виконано дослідження впливу зменшення використання водно-енергетичного ресурсу при різних режимах зрошення дощуванням на відповідне зниження рівня продуктивності вирощуваних сільськогосподарських культур. При цьому експериментально визначено, що інтенсивність (темпи) зниження продуктивності вирощуваних культур, яка зумовлена зниженням затрат водних й енергетичних ресурсів при реалізації зрошення, є суттєво нижчою за інтенсивність (темпи) зниження затрат самих ресурсів. Досліджувані варіанти скорочення затрат водних й енергетичних ресурсів в цілому виявились економічно рентабельними, коли при зниженні затрат води й електроенергії на 27–48 % має місце більш ніж удвічі нижче зниження вартості валової продукції на 10,80–18,06 % з досягненням чистого прибутку від 11,4 до 5,7 тис. грн. Вплив різних варіантів скорочення затрат води й електроенергії на дисконтований термін окупності інвестицій свідчить, що прийнятними можуть виявитись декілька варіантів, для яких термін окупності інвестицій не перевищує 10 років, а вибір оптимального рішення потребує врахування умов конкретного об'єкта, обмеженість водних ресурсів та інтересу інвесторів й землекористувачів. При цьому екологічна складова загальної ефективності реалізації зрошення полягає у тому, що зниження використання водно-енергетичного ресурсу апріорі відображає зниження негативного впливу зрошення на довкілля. Таким чином, скорочення затрат водних й енергетичних ресурсів є цілком виправданим рішенням на шляху адаптації аграрного виробництва на зрошенні до сучасних умов та вимог, а представлені результати можуть бути науковим підґрунтям впровадження даного підходу при реалізації зрошення на практиці.*

Ключові слова: *скорочення затрат, водні ресурси, енергетичні ресурси, зрошення, ресурсна оптимізація*

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ANALYSIS OF THE CALCULATION OF REFERENCE EVAPOTRANSPIRATION ACCORDING TO THE DATA OF THE STATE METEOROLOGICAL STATION

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Abstract. *Since direct measurement of reference evapotranspiration (ET_0) is a complex, time-consuming and expensive process, the most common procedure is to estimate ET_0 from climate data. The purpose of this study was to perform reference evapotranspiration calculations based on the data of the state meteorological station Askania-Nova and compare them with the actual ET_0 data obtained using an automatic Internet meteorological station. The data for the study were taken from the state meteorological station Askania-Nova (township Askania-Nova, Kakhovsky district, Kherson region, 46.45°N 33.88°E) and the automatic Internet meteorological station iMetos IMT 300 from the company "Pessl Instruments", which is located at the meteorological site of the Askaniysk DSDS (Tavrychanka village, Kakhovsky district, Kherson region, 46.55°N, 33.83°E). Standard evapotranspiration was calculated using the Penman-Monteith method (FAO56-RM). To assess the accuracy of ET_0 calculations, mean absolute percent error (MAPE), root mean square error (RMSE) and Standard Error of Estimate (SEE) were determined. According to the results of the comparison of indicators from two meteorological stations, it was found that the smallest errors are inherent in the daily average and maximum temperature and relative air humidity (MAPE<10 %), for the minimum temperature and relative air humidity, the MAPE errors are 18,1 and 13,7 %, respectively. The MAPE error for water vapor pressure deficit and solar radiation is 20,2 and 26,3 %, respectively. The largest MAPE error of 40,3 % was established for wind speed measurements. The average MAPE error between the calculated ET_0, based on the meteorological data of the Askania-Nova station, and the actual ET_0 data obtained from the automatic Internet meteorological station iMetos is 16,8 %, RMSE – 0,65 mm, SEE – 0,56 mm. Applying a coefficient of 0,92 when calculating ET_0 reduces the errors of MAPE, RMSE, and SEE by 3,2 %, 0,15 mm, and 0,05 mm, respectively, for all calculation periods. For the May-August period, the MAPE error was 10,7 %, which brings the calculations close to high accuracy (MAPE <10 %). Based on the results of the calculations, it was established that on average over the years of research, the actual ET_0 was 68 mm less than the calculated one. The absolute errors of determination of ETc depended on the crop and the average over the years of research ranged from 33 mm (winter wheat) to 68 mm (early tomatoes). The application of the refined value of ET_0 in calculations reduces the absolute errors in the determination of c over the years of research, this error did not exceed 6 mm (early tomato). Research results confirm the possibility of using meteorological indicators obtained from state meteorological stations to calculate ET_0. To increase the accuracy of calculations, it is necessary to use a refinement coefficient.*

Key words: *reference evapotranspiration, Penman-Monteith method, meteorological stations, meteorological parameters, errors*

Relevance of research. Evapotranspiration (ET) plays an important role in the formation of the water balance of the field, which is the main expenditure item of the balance, and determines the need for irrigation. Despite the huge role of ET in the vital activity of plants, it is not always measured directly. The complexity of methods of direct measurement of ET, as well as the need for a detailed study of the variability of ET in time and area, contributed to the development of many calculation methods for determining potential evapotranspiration, one of which is the Penman-Monteith method [1]. Quantification of reference surface evapotranspiration (ET_0) used in the Penman-Monteith method is necessary in the context of many issues, such as crop production, water management, irrigation planning. Since the direct measurement of ET0 is a complex, time-consuming and expensive process, the most common procedure is to estimate ET_0 from climatic data, such as solar radiation, temperature and relative humidity, wind speed [2, 3]. The Food and Agriculture Organization of the United Nations (FAO) recommends the Penman-Monteith method (FAO56-PM) for ET_0 calculation, which can be used as a standard method for ET_0 estimation [4–7]. Any calculation of ET_0 should provide consistent and reliable results, use only commonly available meteorological data and a minimum of calculations. The FAO56-PM equation requires solar radiation, wind speed, temperature and humidity data. The quality of meteorological data and the difficulties in collecting them can be serious limitations. Although meteorological parameters are measured regularly and widely presented on weather sites on the Internet, they must be checked for reliability.

The FAO56-PM method requires a large amount of data, so it is desirable to check which factors influence evaporation and consider only such factors to determine evapotranspiration. The accuracy of the calculation depends on this. One of the methods for calculating the Penman-Monteith formula is to use a constant wind speed (2 m/s), as recommended by Allen [6]. Another option is to ignore the wind speed data. In the climatic conditions of Hungary, the method with a constant wind speed was recognized as the best [8].

Analysis of recent research and publications. Calculation of ET_0 requires data on radiation, air temperature, atmospheric humidity and wind speed, which limits its application in regions where these data are not available; therefore, new alternatives are needed. In a semi-arid region of Mexico, the accuracy of ET0 calculated by the Blaney-Criddle (BC) and Hargreaves-Samani (HS) methods was compared with that of FAO56-PM using information from the Automated Weather Station (AWS) and the NASA-POWER platform (NP) over different periods. Information on maximum and minimum temperatures from the NP platform was suitable for estimating ET_0 using the HS equation. This data source is a suitable alternative, especially in semi-arid regions with limited climatological data from weather stations [9]. In the Andean highlands, meteorological monitoring is limited and high-quality data is lacking. Therefore, the FAO 56-PM equation can only be applied using an alternative method. A study was conducted on the feasibility of effectively using the FAO 56-PM method to estimate missing data for Páramo landscapes in the high Andes of Southern Ecuador. The researchers found that using estimated wind speed data had no significant effect on estimated ET_0, but when solar radiation data were evaluated, ET_0 estimates could be in error by as much as 24 %; if relative humidity data is evaluated, the error can reach 14 %; and if all data except temperature are evaluated, errors exceeding 30 % may occur. Methods of estimation of solar radiation, water vapor pressure deficit calculated based on average temperature, and taking the minimum temperature as a dew point to estimate the actual vapor pressure have been successful. The study demonstrates the importance of using high-quality meteorological data to calculate ET_0 in humid Páramo landscapes in southern Ecuador [10, 11]. Reference evapotranspiration can be estimated using various methods, for example: Penman-Monteith, Blaney-Criddle, Hargreaves, ANN and WNN, regression and fuzzy logic. Humidity, temperature, wind speed, and solar radiation are factors that have a significant impact on ET_0 estimates. In general, traditional methods are cumbersome because the determination of ET_0 requires experimental setups and additional climate data, which are not available in many developing countries. So, in this case, non-traditional techniques can give more accurate results [12].

Modern technologies enable agricultural producers to minimize the time and effort previously required to monitor evapotranspiration, especially in large fields. Modern meteorological stations help to monitor and forecast the status of ET_0 effectively. Thus, instead of doing the calculations themselves, farmers can use ready-made solutions from meteorological service providers [13]. However, due to the high cost of existing technologies, it is difficult for small farms to obtain accurate data on evapotranspiration. The most economically efficient solution for them is the calculation of ET_0 based on meteorological data [14, 15].

The purpose of the research was to calculate reference evapotranspiration based on the data of the Askania-Nova state meteorological station and compare them with the actual ET_0 data obtained using an automatic Internet meteorological station.

Materials and methods of research. Meteorological data for this study were obtained from the state meteorological station Askania-Nova (WMO_ID 33915 town of Askania-Nova, Kakhovsky district, Kherson region. 46.45°N 33.88°E) [16] for the period from the 1st of April 2013 to 30th October 2018 and from the automatic Internet meteorological station iMetos IMT 300 from the company "Pessl Instruments" [17], which is located at the meteorological site of the Askaniysk SARS (Tavrychanka village, Kakhovsky district, Kherson region. 46.55° N. 33.83°E). The distance between the meteorological stations is 12,5 km, which does not significantly affect the climatic indicators for the selected points, so the comparison of the calculated ET0 is correct [18, 19].

Average daily meteorological data were used to analyze and calculate the reference evapotranspiration (ET_0): maximum, minimum temperature and relative air humidity, wind speed, dew point temperature, cloudiness, solar radiation.

The reference evapotranspiration, according to the meteorological data of the Askania-Nova state weather station, was calculated using the Penman-Monteith method FAO56-RM [6]:

$$ET_0 = \frac{0,408\Delta\left(R_n - G\right) + \gamma\dfrac{900}{T+273}u_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0,34u_2\right)} \quad (1)$$

where ET_0 – reference evapotranspiration, mm/day; Rn – net radiation on the surface of plants, MJ/m²·day; G – soil heat flow density, MJ/m²·day; T – average daily air temperature at a height of 2 m, °C; u_2 – wind speed at a height of 2 m, m/s; e_s – saturated vapor pressure, kPa; e_a – actual pressure, kPa; Δ – gradient of the vapor pressure curve, kPa/°C; γ – psychometric constant, kPa/C.

To calculate e_s and e_a, the measured values of maximum and minimum air temperature and dew point temperature were used, respectively. The daily wind speed measured at the weather station (10 m above the ground) was calculated for a height of 2 m.

In the absence of observations of total solar radiation at the Askania-Nova meteorological station, it was calculated using the Savinov-Ongström formula [20]:

$$R_s = R_{so}\left[1 - \left(1 - k\right)n\right], \quad (2)$$

where Rs – total solar radiation, MJ/m²·day; Rso – solar radiation in the absence of clouds, MJ/m²·day; k – the coefficient that determines what part of the possible is the actual radiation under full cloud cover (k = 0,35 for 46.5° N); n – average cloudiness in fractions of one.

Other parameters included in formulas (1) and (2) were calculated according to the FAO56-RM method [6]. The calculated reference evapotranspiration was compared with the actual ET_o obtained from the Internet weather station iMetos IMT 300.

The evapotranspiration of crops was calculated according to the formula [6]:

$$ET_C = ET_0 \cdot K_C \quad (3)$$

where ET_C is evapotranspiration, mm/day; K_C is the crop's coefficient [21].

To assess the accuracy of reference evapotranspiration calculations, mean absolute percent error (MAPE), root mean square error (RMSE), and standard error of estimate (SEE) were determined [22, 23] (Table 1):

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{x-y}{x}\right|\cdot 100\,\%, \quad (4)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(x-y\right)^2}, \quad (5)$$

$$SEE = \sqrt{\frac{1}{(n-2)}\left[\left(y-\bar{y}\right)^2 - \frac{\left[\Sigma\left(x-\bar{x}\right)\left(y-\bar{y}\right)\right]^2}{\Sigma\left(x-\bar{x}\right)^2}\right]}, \quad (6)$$

where x – is ET_0 by the data of the Internet weather station iMetos; y – ET_0 calculated according to the FAO56-RM method; n – the size of the sample.

1. The value of the MAPE error and its interpretation [23]

MAPE, %	Interpretation
< 10	High accuracy
10–20	Good accuracy
20–50	Satisfactory accuracy
>50	Unsatisfactory accuracy

Research results and their discussion. To verify the calculations according to equation (1), we calculated ET_0 from the data received from the iMetos meteorological station and compared them with those calculated automatically. The years 2013, 2015, and 2018 were selected for analysis. The average errors of MAPE, RMSE, and SEE, respectively, were 3,20; 0,13 and 0,13 (Table 2). The MAPE error over the years varied from 2.85 % (2018) to 3,58 % (2015).

2. Errors of ET_0 calculation according to the Penman-Monteith method (FAO56-PM) and according to the data of the meteorological station iMetos

Error	2013	2015	2018	Average
MAPE	3,15	3,58	2,85	3,20
RMSE	0,11	0,15	0,15	0,13
SEE	0,11	0,14	0,14	0,13

To evaluate the efficiency of the calculations, the average daily ET_0 values obtained from the weather station are plotted in the form of a graph depending on the calculated values according to FAO56-PM. As can be seen from the graph, the obtained linear dependence almost coincides with the 1:1 line, the coefficient of determination R^2=0,9949 for the sample series n = 642 (Fig. 1).

The obtained results of the calculations confirm their reliability and provide an opportunity for further analysis of ET_0 calculated from the data of the meteorological station Askania-Nova.

According to the results of the comparison of the air temperature measured at the iMetos and Askania-Nova meteorological stations, it was found out that the MAPE (Table 3) for the average daily and maximum air temperature on average over the years of research was 3,6 and 3,3 %, respectively (high accuracy), and RMSE (Table 3) – 0,73 and 1,26 °C. Checking the minimum air temperature showed that the MAPE between the two weather stations was 18,1 % (good accuracy) and the RMSE was 1,49 °C. The analysis of relative air humidity indicated that the MAPE for average daily, maximum, and minimum relative air humidity was 7,7, respectively; 9,1 % (high accuracy) and 13,7 % (good accuracy), and RMSE is 6,44; 10,14; 6,63 %, respectively. The MAPE error for water vapor pressure deficit and solar radiation was 20,2 and 26,3 % (satisfactory accuracy), respectively, and the RMSE error was 0,17 kPa and 3,89 MJ/m^2, respectively. The greatest MAPE error of 40,3 % (satisfactory accuracy) was established for wind speed measurements, the RMSE error was 0,77 m/s.

Despite the errors of the meteorological data included in the Penman-Monteith formula, the average MAPE between the calculated ET0, according to the weather station Askania-Nova and iMetos, was 16,8 % (good accuracy), RMSE – 0,65 mm, SEE – 0,56 mmThe largest MAPE and RMSE for ET0 were observed in 2015 and were 22,4 % and 0,89 mm, respectively. It is worth noting that this year was characterized by the largest errors of MAPE and RMSE among all measured meteorological parameters. As an example, MAPE and RMSE for wind speed were 101 % and 1,45 m/s, respectively, and for maximum air temperature were 5,2 % and 2,10 °C, respectively.

The analysis of errors by calendar months (Table 4) revealed that the largest errors of MAPE for air temperature are inherent in April and October. By reducing the observation period from April to October to May-September, MAPE errors for average daily and maximum air temperature are reduced by 1,3 and 0,8 %, respectively. The greatest decrease in MAPE by 9.9 % was observed for the minimum air temperature. MAPE for relative air humidity almost did not change, but for wind speed, on the contrary, it increased by 3,7 %. For the deficit of water vapor pressure and solar radiation, MAPE decreased by 5 %.

During the observation period (April-October), MAPE ET0 was 16,8 %, which is 2,5 % more than in May-September. The RMSE errors for all meteorological indicators almost did not change.

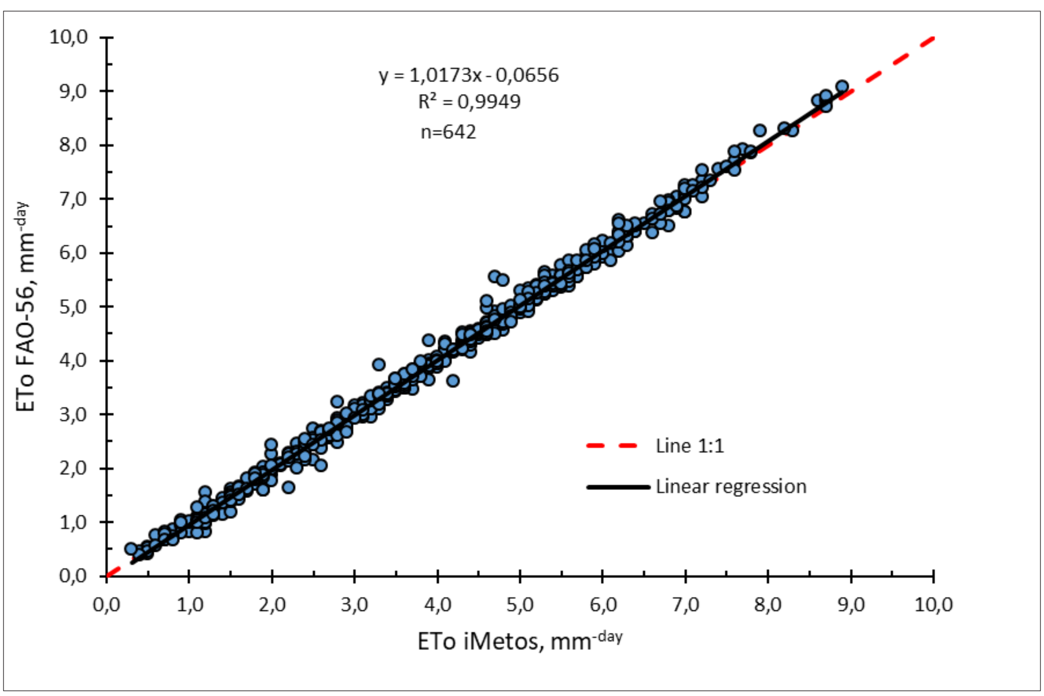

Fig. 1. Regression analysis to verify ET_0 calculations based on data from the iMetos meteorological station

3. MAPE and RMSE errors for iMetos and Askania-Nova weather stations (by year)

Year of research	Air temperature, °C			Relative air humidity, %			Wind speed, m/s	DWVP *, kPa	Solar radiation, MJ/m²	ET₀, mm/day
	aver.	max.	min.	aver.	max.	min.				
MAPE error										
2013	2,8	2,7	13,7	6,0	6,3	9,2	22,2	17,7	24,5	12,3
2014	3,6	2,9	16,7	7,8	10,4	9,9	16,6	20,1	24,9	13,3
2015	7,0	5,2	24,6	11,2	11,2	22,4	101,0	20,0	26,2	22,4
2016	2,6	2,6	17,2	6,7	8,6	15,5	27,0	22,2	29,4	15,6
2017	3,0	2,8	19,5	7,8	9,7	11,2	52,0	28,6	28,3	19,5
2018	2,6	3,4	16,6	6,6	8,4	14,2	22,8	12,7	24,6	10,5
Average	3,6	3,3	18,1	7,7	9,1	13,7	40,3	20,2	26,3	16,8
RMSE error										
2013	0,65	0,96	1,28	5,44	6,88	5,31	0,63	0,18	3,44	0,58
2014	0,52	0,88	1,30	6,11	10,88	4,57	0,47	0,17	3,83	0,60
2015	1,41	2,10	1,85	9,73	12,85	10,06	1,45	0,19	4,47	0,89
2016	0,63	0,70	1,68	5,97	10,56	8,10	0,67	0,15	3,80	0,60
2017	0,63	1,83	1,52	6,38	10,69	6,51	0,77	0,20	3,98	0,72
2018	0,56	1,06	1,28	4,97	9,00	5,22	0,61	0,15	3,82	0,50
Average	0,73	1,26	1,49	6,44	10,14	6,63	0,77	0,17	3,89	0,65

*DWVP – deficiency of water vapor pressure.

4. MAPE and RMSE errors for iMetos and Askania-Nova weather stations (by month)

Month of research	Air temperature, °C			Relative air humidity, %			Wind speed, m/s	DWVP, kPa	Solar radiation, MJ/m²	ETo, mm/day
	aver.	max.	min.	aver.	max.	min.				
MAPE error										
April	4,1	3,9	45,5	7,3	7,3	14,0	27,8	28,5	26,2	15,6
May	2,7	2,9	9,8	8,7	8,6	11,5	59,4	21,1	20,9	14,5
June	2,1	2,4	7,9	8,7	10,6	11,2	84,4	18,2	18,9	16,2
July	2,0	2,2	5,9	7,2	10,3	13,7	35,8	12,5	18,4	13,1
August	2,0	1,8	5,0	6,9	10,5	14,4	18,7	9,0	22,1	10,3
September	2,6	3,1	12,3	7,1	8,6	17,7	21,9	15,2	26,8	14,0
October	10,4	7,0	44,8	8,2	7,8	12,9	42,5	39,3	53,0	26,9
April-Oct.	3,6	3,3	18,1	7,7	9,1	13,7	40,3	20,2	26,3	16,8
May-Sept.	2,3	2,5	8,2	7,7	9,7	13,7	44,0	15,2	21,4	14,3
RMSE error										
April	0,52	0,97	1,30	6,88	8,36	7,50	0,70	0,11	3,88	0,46
May	0,68	2,06	1,05	7,35	10,01	7,36	0,88	0,16	4,12	0,65
June	0,60	0,89	1,84	6,82	11,64	5,39	0,94	0,19	4,03	0,79
July	0,64	0,94	1,20	5,65	11,40	7,06	0,60	0,21	4,01	0,77
August	0,66	0,73	1,12	4,57	10,30	4,49	0,59	0,19	3,90	0,67
September	0,67	1,20	1,61	6,69	9,62	6,96	0,76	0,20	3,72	0,63
October	1,42	2,02	2,11	7,87	10,45	8,70	1,19	0,13	3,61	0,60
April-Oct.	0,73	1,26	1,49	6,44	10,14	6,63	0,77	0,17	3,89	0,65
May-Sept.	0,65	1,16	1,36	6,22	10,60	6,25	0,75	0,19	3,96	0,71

According to the results of ET0 calculations according to the FAO56-PM formula, according to the data of the Askania-Nova meteorological station, it was established that the errors of MAPE, RMSE and SEE (Table 5) between the calculated and actual values for the period April-October (Fig. 2a, n=1280) are 16,8 %, respectively; 0,65 mm and 0,56 mm, coefficient of determination R^2=0.92. As can be seen from Figure 2a, the regression line of estimated ET_0 values passes above the 1:1 line, which means that the actual values are less than the estimated. The ratio of actual ET0 values to estimated values is 0,92. The coefficient of 0,92 in ET0 calculations reduces MAPE, RMSE, and

5. Errors between calculated and actual ET_0 values

Observation period	iMetos – Askania-Nova				iMetos – Askania-Nova (specified)			
	MAPE	**RMSE**	**SEE**	**R^2**	**MAPE**	**RMSE**	**SEE**	**R^2**
April – October	16,8	0,65	0,56	0,92	13,6	0,53	0,52	0,92
May – September	14,3	0,71	0,59	0,88	11,1	0,56	0,54	0,88
May – August	13,9	0,72	0,59	0,86	10,7	0,56	0,54	0,86

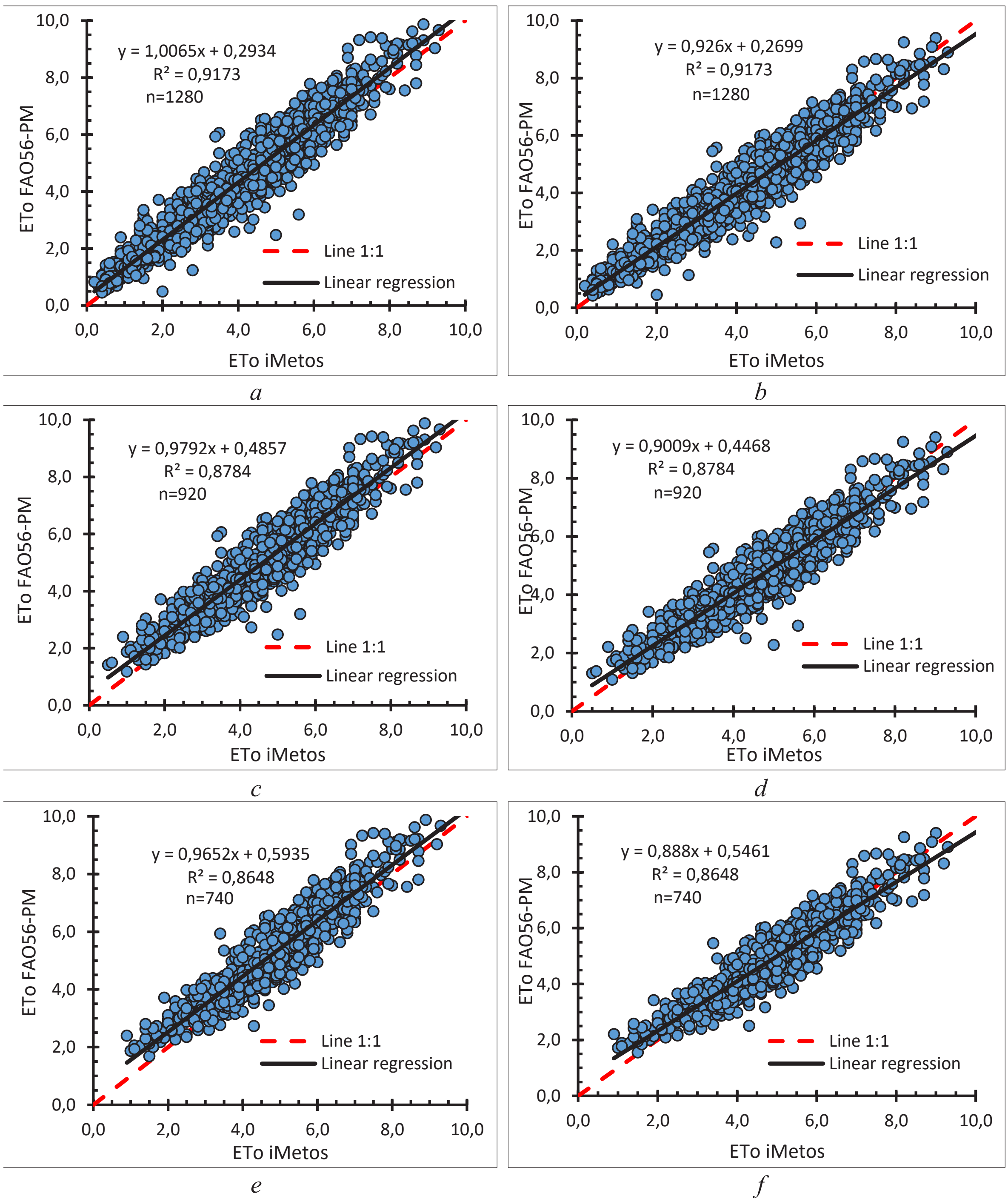

Fig. 2. Regression analysis for verification of ET0 calculations based on data from the Askania-Nova meteorological station for the period: April-October (*a*, *b*); May-September (*c*, *d*); May-August (*e*, *f*)

SEE errors by 3,2 %, respectively; 0,12 mm and 0,04 mm. The regression line and the 1:1 line intersect at point 4.0 (Fig. 2b). Up to ET0 values of 4,0 mm, the actual values are less than the calculated values, and then they begin to exceed them.

By reducing the observation period to May-September (Fig. 2c, *n* = 920), the MAPE error and the coefficient of determination R^2 decreased to 14,3 % and 0,88, respectively, and the RMSE and SEE increased and amounted to 0,71 mm and 0,59 mm, respectively. Application of the 0,92 factor in ET_0 calculations reduces MAPE, RMSE and SEE errors by 3,2 %, respectively; 0,17 mm and 0,05 mm for this calculation period. The regression line and the 1:1 line cross at point 4,5 (Fig. 2d). Up to ET_0 values of 4,5 mm, the actual values are less than the calculated values, and then they begin to exceed them. For the May-August period (Fig. 2d, n = 740), the MAPE error and the coefficient of determination R^2 between the calculated and actual ET0 values decreased to 13,9 % and 0,86, respectively, and the RMSE and SEE almost did not change to the May-September period and were 0,72 mm and 0,59 mm, respectively. The inclusion of the coefficient 0,92 in the ET_0 calculations reduces the MAPE, RMSE, and SEE errors by 3,2 %, respectively; 0,16 mm and 0,05 mm. The regression line and the 1:1 line intersect at point 5,0 (Fig. 2e). Up to ET_0 values of 5,0 mm, the actual values are less than the calculated values, and then they begin to exceed them.

To establish the errors of evapotranspiration (ET_C) of crops, which may arise when using ET_0 calculated according to the FAO56-PM formula, appropriate calculations were carried out for some crops. The K_C, specified in previous studies, were used to calculate the *ETS* [21]. ET_C were calculated for each day for each year of research. On average, over the years of the study, the actual ET_0 was 68 mm less than the calculated one (tabl. 6), by year this difference ranged from 26 (2018) to 109 mm (2017). As a result, ET_C for all cultures, when using the calculated ET_0 according to the data of the meteorological station Askania-Nova, also exceeded the actual values. The absolute error of ET_C determination

6. Evapotranspiration of crops and its error, according to the data of meteorological stations iMetos and Askania-Nova

Date / year	**ET_0**	**Winter wheat**	**Corn**	**Medium ripe soybeans**	**Late ripe soybeans**	**Early onions**	**Medium ripe onion**	**Early tomato**	**Medium ripe tomato**
Evapotranspiration, according to the data of the meteorological station iMetos									
2013	831	395	573	544	687	372	476	743	772
2014	887	347	602	563	726	399	493	755	788
2015	811	303	526	492	649	329	442	630	705
2016	790	315	539	498	642	349	445	677	707
2017	845	326	584	545	701	364	497	709	790
2018	948	407	581	541	719	364	482	727	776
Average	852	349	567	531	687	363	472	707	756
Evapotranspiration, according to the data of the meteorological station Askania-Nova									
2013	892	431	616	587	738	400	511	806	829
2014	956	361	655	611	789	433	537	818	857
2015	889	348	583	548	716	365	487	702	778
2016	855	346	589	546	700	385	484	749	770
2017	954	380	648	609	778	410	546	805	871
2018	974	422	610	571	752	386	503	771	813
Average	920	381	617	579	745	396	511	775	820
Absolute evapotranspiration error (iMetos – Askania-Nova)									
2013	–61	–36	–43	–43	–52	–28	–34	–63	–57
2014	–69	–14	–53	–48	–62	–35	–45	–63	–69
2015	–78	–45	–57	–56	–68	–36	–45	–72	–73
2016	–65	–31	–50	–48	–58	–35	–39	–72	–64
2017	–109	–54	–64	–64	–77	–46	–49	–96	–82
2018	–26	–15	–29	–30	–32	–22	–22	–44	–36
Average	–68	–33	–49	–48	–58	–34	–39	–68	–63

depended on the culture and the average over the years of research ranged from 33 (winter wheat) to 68 mm (early tomatoes). The highest ET_C determination errors were recorded in 2017 – 46 mm for early onion and 96 mm for early tomato.

The application of the refined value of ET_0 in the calculations reduces the absolute errors in the determination of ET_C (Table 7). So, over the years of research, this error did not exceed 6 mm (early tomatoes). In 2017, the absolute error of determination of ET_C for early onions decreased by 32 mm, and for early tomatoes by 64 mm, and in 2018, the corrected values of ET_C, on the contrary, became smaller than the actual ones. Thus, for early onions, the absolute error was 9 mm, and for medium-ripe tomatoes – 29 mm.

Based on the results of the analysis of the absolute errors of determining ETs by month (Table 8), it was found that the reduction of the calculation period to May-September did not affect the errors for most crops, only for winter wheat this error decreased by 6 mm. The distribution of errors by month depended on the crop. Thus, for mid-ripe tomatoes and late-ripe soybeans, the absolute error was –10 mm in June, and +12 and +9 mm in August, respectively.

Conclusions. The results of ET_0 calculations based on meteorological data obtained from the iMetos station confirm their reliability. The errors of MAPE, RMSE, and SEE between our calculated and actual values of ET_0 were 3,2 %, respectively; 0,13, 0,13 mm.

According to the results of the comparison of meteorological indicators, it was found that the minimal errors are inherent in the daily average, maximum temperature and relative air humidity (MAPE<10 %), for the minimum temperature and relative air humidity, the MAPE errors were 18,1 and 13,7 %, respectively. The MAPE error for the deficit of water vapor pressure and solar radiation was 20,2 and 26,3 %, correspondently. The maximal MAPE error of 40,3 % was for wind speed measurements. By shortening the observation period from April to October to May-September, MAPE errors are reduced by 1–10 %, depending on the meteorological indicator.

7. Refined evapotranspiration of crops and its error, according to the data of meteorological stations iMetos and Askania-Nova

Date / year	**ET_0**	**Winter wheat**	**Corn**	**Medium ripe soybeans**	**Late ripe soybeans**	**Early onions**	**Medium ripe onion**	**Early tomato**	**Medium ripe tomato**
Evapotranspiration, according to the data of the meteorological station iMetos									
2013	831	395	573	544	687	372	476	743	772
2014	887	347	602	563	726	399	493	755	788
2015	811	303	526	492	649	329	442	630	705
2016	790	315	539	498	642	349	445	677	707
2017	845	326	584	545	701	364	497	709	790
2018	948	407	581	541	719	364	482	727	776
Average	852	349	567	531	687	363	472	707	756
Evapotranspiration, according to the data of the meteorological station Askania-Nova									
2013	821	397	567	540	679	368	470	742	763
2014	880	332	602	563	725	399	494	753	789
2015	818	320	536	504	659	336	448	646	715
2016	786	318	542	503	644	354	445	689	709
2017	877	350	597	560	715	377	502	741	802
2018	896	388	561	525	692	355	463	709	748
Average	846	351	567	533	686	365	470	713	754
Absolute evapotranspiration error (iMetos – Askania-Nova)									
2013	10	–2	6	4	7	4	7	1	9
2014	8	15	–1	1	1	0	–2	2	0
2015	–7	–17	–10	–12	–10	–7	–6	–15	–11
2016	3	–3	–3	–4	–2	–5	0	–12	–2
2017	–33	–24	–12	–15	–15	–14	–5	–32	–12
2018	51	19	20	16	28	9	18	18	29
Average	6	–2	0	–2	1	–2	2	–6	2

8. Evapotranspiration of crops and its error, according to the data of meteorological stations iMetos and Askania-Nova, by month (using as the example 2017)

Date / month	ET_0	Winter wheat	Corn	Medium ripe soybeans	Late ripe soybeans	Early onions	Medium ripe onion	Early tomato	Medium ripe tomato
Evapotranspiration, according to the data of the meteorological station iMetos									
April	69	66	0	0	0	0	0	0	7
May	113	134	47	64	68	38	30	104	76
June	152	123	172	178	192	125	121	288	197
July	163	3	216	192	211	178	171	310	260
August	194	0	146	112	206	23	174	6	251
September	111	0	2	0	24	0	0	0	0
October	43	0	0	0	0	0	0	0	0
April-Oct.	845	326	584	545	701	364	497	709	790
May-Sept.	732	260	584	545	701	364	497	709	783
Evapotranspiration, according to the data of the meteorological station Askania-Nova (refined)									
April	75	71	0	0	0	0	0	0	7
May	123	145	53	71	75	42	34	116	83
June	159	130	181	187	202	132	127	303	207
July	166	4	221	196	216	181	175	316	266
August	186	0	139	106	197	22	166	6	238
September	118	0	3	0	25	0	0	0	0
October	50	0	0	0	0	0	0	0	0
April-Oct.	877	350	597	560	715	377	502	741	802
May-Sept.	752	279	597	560	715	377	502	741	795
Absolute evapotranspiration error (iMetos – Askania-Nova)									
April	–6	–5	0	0	0	0	0	0	0
May	–9	–11	–6	–7	–8	–4	–4	–11	–8
June	–8	–7	–9	–9	–10	–6	–6	–14	–10
July	–4	0	–5	–4	–5	–3	–4	–6	–6
August	8	0	7	6	9	0	9	0	12
September	–7	0	0	0	–1	0	0	0	0
October	–7	0	0	0	0	0	0	0	0
April-Oct.	–33	–24	–12	–15	–15	–14	–5	–32	–12
May-Sept.	–20	–18	–12	–15	–15	–14	–5	–32	–12

It was found, that the average error of MAPE between the calculated ET_0 based on the meteorological data of the Askania-Nova station and the actual data of ET_0 obtained from the automatic Internet meteorological station iMetos is 16,8 %, RMSE – 0,65 mm, SEE – 0,56 mm. Shortening the calculation period from April-October to May-August reduces the MAPE error for ET_0 by 2,9 %.

The use of a coefficient of 0,92 when calculating ET_0 reduces the errors of MAPE, RMSE, and SEE by 3,2 %, respectively; 0,15 and 0,05 mm for all calculation periods. For the May-August period, the MAPE error was 10,7 %, which brings the calculations close to high accuracy (MAPE <10 %).

Based on the results of calculations, it was found that on average over the years of research, the actual ET_0 was 68 mm less than the calculated one. The absolute errors of determination of ETs depended on the culture and on average over the years of research ranged from 33 (winter wheat) to 68 mm (early tomatoes). The maximal errors of ET_C determination were recorded in 2017, which were 46 mm for early onion and 96 mm for early tomato.

Application of the refined ET_0 value in the calculations reduces the absolute errors of ET_C determination, over the years of research this error did not exceed 6 mm (early tomato). In 2017, the absolute error of ET_C determination for early onion decreased by 32 mm, and for early tomato – by 64 mm.

So, the research results confirm the possibility of using meteorological indicators obtained from state weather stations to calculate ET_0. To increase the accuracy of calculations, it is recommended to use a refinement coefficient.

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АНАЛІЗ РОЗРАХУНКУ ЕТАЛОННОЇ ЕВАПОТРАНСПІРАЦІЇ ЗА ДАНИМИ ДЕРЖАВНОЇ МЕТЕОРОЛОГІЧНОЇ СТАНЦІЇ

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Анотація. *Оскільки пряме вимірювання еталонної евапотранспірації (ET_0) є складним, трудомістким і дорогим процесом, найпоширенішою процедурою є оцінювання ETo за кліматичними даними. Метою проведення цього дослідження було виконати розрахунки еталонної евапотранспірації за даними державної метеостанції Асканія-Нова та порівняти їх з фактичними даними ET_0, отриманими за допомогою автоматичної інтернет-метеорологічної станції. Дані для дослідження були взяті з державної метеорологічної станції Асканія-Нова (смт Асканія-Нова, Каховський р-н, Херсонська обл., 46.45° п.ш. 33.88° сх.д.) та з автоматичної інтернет-метеорологічної станції iMetos IMT 300 від компанії "Pessl Instruments", яка розташована на метеомайданчику Асканійської ДСДС (с. Тавричанка, Каховський р-н, Херсонська обл. 46.55° п.ш. 33.83° сх.д.). Еталону евапотранспірацію розраховували за методом Пенмана-Монтейта (FAO56-PM). Для оцінювання точності розрахунків ET_0 визначали середню абсолютну відсоткову помилку MAPE (Mean Absolute Percent Error), середньоквадратичну похибку RMSE (Root Mean Square Error) та стандартну похибку SEE (Standard Error of Estimate). За результатами порівняння показників з двох метеорологічних станцій встановлено, що найменші похибки притаманні для середньодобової та максимальної температури та відносної вологості повітря (MAPE<10 %), для мінімальної температури та відносної вологості повітря похибки MAPE відповідно становлять 18,1 і 13,7 %. Похибка MAPE для дефіциту тиску водяної пари та сонячної радіації відповідно становить 20,2 і 26,3 %. Найбільшу похибку MAPE 40,3 % встановлено для вимірювань швидкості вітру. Середня похибка MAPE між розрахованою ET_0, за метеорологічними даними станції Асканія-Нова, та фактичними даними ET_0, отриманими з автоматичної інтернет-метеорологічної станції iMetos, становить 16,8 %, RMSE – 0,65 мм, SEE – 0,56 мм. Застосування коефіцієнта 0,92 при* *розрахунку ET_0 зменшує похибки MAPE, RMSE та SEE відповідно на 3,2 %, 0,15 мм та 0,05 мм для всіх розрахункових періодів. За період травень-серпень похибка MAPE становила 10,7 %, що наближує розрахунки майже до високої точності (MAPE <10 %). За результатами розрахунків встановлено, що в середньому за роки досліджень фактична ET_0 була на 68 мм менша, ніж розрахована. Абсолютні похибки визначення ETc залежали від культури і в середньому за роки досліджень становили від 33 мм (пшениця озима) до 68 мм (томати ранні). Застосування в розрахунках уточненого значення ET_0 зменшують абсолютні похибки визначення ETc, за роки досліджень ця похибка не перевищувала 6 мм (томат ранній).Результати досліджень підтверджують можливість використання метеорологічних показників, отриманих з державних метеостанцій, для розрахунку ET_0. Для підвищення точності розрахунків необхідно використовувати уточнювальний коефіцієнт.*

Ключові слова: *еталонна евапотранспірація, метод Пенмана-Монтейта, метеорологічні станції, метеопараметри, похибки*

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ANALYSIS OF THE EFFICIENCY OF TRADITIONAL TECHNOLOGIES OF WATER PREPARATION OF THE KREMENCHUK RESERVOIR OF THE DNIPRO RIVER TO ENSURE DRINKING NEEDS

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Abstract. *An analysis of the efficiency of the surface water treatment systems of the Dnipro reservoirs when their quality is changed to ensure the normative indicators of the quality of drinking water were carried out. The study of the effectiveness of traditional water treatment technologies was carried out by analyzing the results of laboratory studies of source and drinking water at the Dnipro water treatment plant with water intake from the Kremenchuk Reservoir (data from the Svitlovodsk Water and Sewage Services (SWS) of the Regional Municipal Production Enterprise (RMPE) of the Dnipro-Kirovograd), establishing correlations of quality indicators and assessing the state of water resources by the requirements of water legislation. The treatment plants of the Dnipro water supply station are not designed to treat water with a high content of biogenic substances during active phytoplankton vegetation, and under such conditions, increased doses of preliminary chlorination are used. As a result, water is polluted with residual chlorine and organochlorine. An increase in the dose of aluminum-containing coagulants in the corresponding period leads to an increase in the aluminum content in drinking water to the limit of the normative value (0,5 mg/dm^3). According to the results of research in drinking water, turbidity was found to be 1,4 higher and permanganate oxidizability 1,3 higher than the standard content; excesses of color, iron, and residual chlorine content were found only sporadically and were on average within the upper limits of normative values. Correlation analysis (Pearson and Spearman correlations methods) of the influence of temperature on the following hydrometric, chemical, and physical factors was carried out: changes in turbidity, color, and changes in the concentration of total iron and ammonia. The analysis confirmed the visual connection of oxygen with temperature and water level and the influence of factors on oxygen concentration. The practical aspects of phytoplankton extraction during water intake from Dnipro reservoirs and water treatment at stations have gained further scientific justification.*

Key words: *water resources, drinking water, purification technology, phytoplankton, water quality*

Relevance of research. The surface waters of the Dnipro reservoirs are characterized by long-term and seasonal fluctuations in the concentrations of the components of the chemical composition, indicators of physical properties, etc., which occur under the influence of climatic changes, economic activity, and the conditions of military operations on the territory of Ukraine. According to the results of monitoring studies, it was determined that more than 38 % of water samples from Dnipro reservoirs taken at centralized water supply facilities do not meet regulatory requirements. The tendency to deterioration of the ecological condition of surface waters in terms of sanitary-chemical and sanitary-microbiological indicators necessitates the search for ways to improve the efficiency of their preparation for use in drinking water supply systems. [1].

Hardness, alkalinity, and total mineralization have low concentrations, their values are far from the maximum permissible values, which are standardized in DSTU 4808:2007 [2]. The main problem of the Dnipro reservoirs is the "blooming" of water in the summer. In this regard, based on the results of laboratory tests of the source water parameters, the specialists of the treatment plants constantly adjust the optimal technological modes of water treatment to ensure the proper quality of drinking water. This adjustment is carried out within the framework of existing technologies and the constructions of treatment plants, but their emergency state is not able to meet the requirements for the quality of drinking water according to certain normative safety indicators [1].

Analysis of recent research and publications. The analysis of the efficiency of surface water treatment systems in the Dnipro reservoirs with changes in their quality has made it possible to establish that the main technological methods of existing water treatment technologies are coagulation, sedimentation, and filtration. This technology is designed for source water of the 1st and 2nd quality categories [2]. Over the past decades, significant climatic changes have occurred, and the temperature, water, and hydrological regimes of the Dnipro River have changed accordingly. The water quality characteristics began to correspond to 3 and in some cases 4 quality categories [2–4]. The vast majority of water treatment plants have completed their design service life. Today, the technologies installed during the construction of treatment plants cannot effectively clean the water of the Dnipro River.

The processes of natural water purification and the issue of resource conservation in the water supply industry are studied by foreign and domestic scientists [5–8]. The study of modern effective methods of water preparation is disclosed in publications [9–14]. The attention to the analysis of the characteristics of surface water contaminants and their removal during water treatment and intensification of water purification processes from dissolved organic substances is paid in recent publications of experts [14–23]. In particular, the complex relationship between changes in temperature, dissolved oxygen, hydrological regime, and chemical composition, which together form the qualitative composition of water in surface sources of drinking water supply, has been scientifically confirmed. The lack of a clear direct thermal stratification causes a change in the species and number of phytoplankton to vertical levels and water areas. The season and rhythm of nature cause the cyclical development of the hydroclimate, the formation of different intensities of biological processes, and the development of biomass in reservoirs. As a result, the available estimates of the effectiveness of combating phytoplankton directly at treatment plants are relative and can only be considered as examples in specific cases [24, 25].

At the same time, it remains an important task not only to increase the efficiency of water purification to the standard indicators but also to reduce the load on the water purification station due to the retention of a significant part of the pollutants directly in the water source, which is implemented by modernizing intake and treatment plants.

The purpose of the research is to analyze the effectiveness of the traditional technology of cleaning the surface waters of the Dnipro reservoirs (in the example of the Kremenchuk reservoir) to ensure the normative indicators of drinking water quality.

Research materials and methods. Research methods: empirical – when determining the specifics of the purification technology and water quality research; mathematical modeling using the regression analysis method – for the study of quality indicators of water resources and substantiation of the reliability of obtained results. The study of the effectiveness of traditional water purification technologies at water supply stations will be carried out by analyzing the results of laboratory studies of source and drinking water from a clear water reservoir (CWR) at the Dnipro water treatment plant with water intake from the Kremenchuk reservoir (data from the Svitlovodsk Water and Sewage Services of the Regional Municipal Production Enterprise of the Dnipro-Kirovograd, further – SWSS of the RMPE of the Dnipro-Kirovograd), the establishing correlations of water quality indicators and assessing the state of water resources by the requirements of water legislation.

To study water quality indicators, the data of the systematic production control of water safety and quality of the water supply laboratory of the SWSS of the RMPE of the Dnipro-Kirovograd were analyzed in the water intake and before entering the water supply network (from CWR). Per the procedure for monitoring water quality indicators, we analyzed the average monthly data of full chemical analysis of the quality of surface water for 2018–2023, daily (9:00 and 21:00) indicators of surface water quality for the summer months of 2018–2023, average daily (9:00) indicators of the content of hydro organics in the surface water of the reservoir for 2019–2023, average monthly indicators of full analysis (including 13 characteristic physicochemical indicators) of drinking water quality from CWR for 2018–2023.

Research results and their discussion. In recent years, the operation of water intake facilities, as well as the operation of water treatment plants with water intake from the Dnipro reservoirs, has been significantly complicated by peak, in fact, catastrophic outbreaks of phytoplankton reproduction (Table 1, Fig. 1), mainly cyanobacteria, which are associated with climate change – global warming, which leads to a decrease in the amount of oxygen in water [1]. The phytoplankton content varies by more than 150 times within a month (for example, in January 2019 from 245 cells/dm^3 to 201000 cells/dm^3, and in July 2023 from 40,000 cells/dm^3 to 368,000 cells/dm^3).

Existing treatment facilities are not designed to treat water with a high content of nutrients, and in such conditions, treatment plant specialists use increased doses of pre-chlorination. As a result, water is contaminated with residual chlorine and organochlorine. It has been established that the degradation of extracellular microcystin by chlorine depends on pH, chlorine exposure, and the presence of cyanobacterial cells [1, 26].

Indicators of the efficiency of surface water treatment systems of the Dnipro reservoirs to provide the population with drinking water. The water treatment process at the SWSS of the RMPE of the Dnipro-Kirovograd water supply station with water intake from the Kremenchuk reservoir consists of the following stages: oxidation with liquid chlorine (primary chlorination), coagulation before mixers, clarification in horizontal settling tanks, filtration with rapid filters and disinfection with liquid chlorine (secondary chlorination) before CWR (Table 2).

The drinking water purification technology at the researched units of the water treatment station of the SWSS of the RMPE of the Dnipro-Kirovograd, which uses the water of the Dnipro River as the source, includes the following water facilities: mixers, reaction chambers, horizontal settling tanks, fast filters with quartz sand filling, tanks of clean water.

1. The content of phytoplankton in the water of the Kremenchuk Reservoir in 2019–2023

The date	**Phytoplankton content, cells/dm^3**		
	maximum	**minimum**	**average monthly**
January 2019	201 000	1 270	54 472
July 2019	14 862 000	190 050	4 713 828
January 2020	1 714 000	4 070	129 022
July 2020	358 500	1 230	38 553
January 2021	2 605	365	835
July 2021	3 104 000	245	292 722
January 2022	1 220	230	648
July 2022	218 000	900	43 643
January 2023	8 150	290	2 112
July 2023	368 000	40 000	127 786

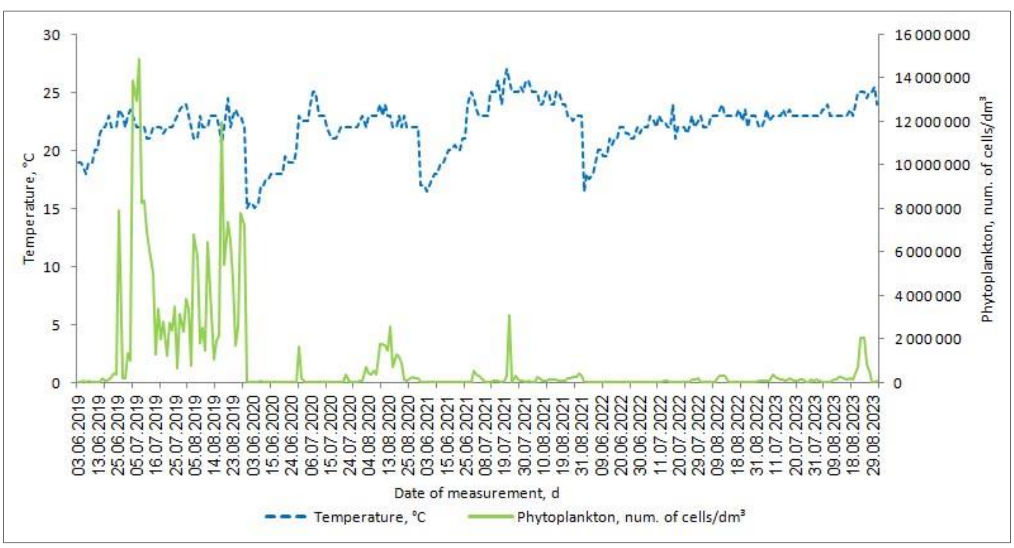

Fig. 1. Phytoplankton content in the water of the Kremenchuk Reservoir in the summer period of 2019–2023

The evaluation of the efficiency and adequacy of the water purification technology is carried out based on the results of summarizing the average monthly data of laboratory studies of the full chemical analysis of the quality of the surface and drinking water of CWR into the average annual content for the years 2018–2023 (Tables 3, 4).

Based on the analysis of the quantitative characteristics of some of the most priority indicators of water quality, which demonstrate the state of the sources of drinking water supply, the average and worst values of the group water quality indices characterizing the surface water at the water intake point of the Kremenchuk

2. Reagents used at the water supply station at the SWSS of the RMPE of the Dnipro-Kirovograd

Reagent	Purpose	The SWSS of the RMPE of the Dnipro-Kirovograd
Sodium hypochlorite	primary chlorination	+
Hydroxychloride of aluminum	coagulation	+
Flocculant Extraflock N 160, or equivalent	flocculation	–
Sodium hypochlorite	secondary chlorination	–
Liquid chlorine		+

3. Sanitary and chemical parameters of the surface water of the Kremenchuk Reservoir

Parameter	Measure	Average annual content in the surface water						The class of water quality according to DSTU4808:2007 [2]
		2018	2019	2020	2021	2022	2023	
Turbidity	NTU	4.59	3.65	3.44	3.72	2.98	3.71	1
Color	degr.	44.46	32.13	29.17	38.83	45.5	66.92	2
Hydrogen indicator	units of pH	8.18	8.23	8.43	7.65	7.77	7.79	2–3
Ammonium ions	mg/dm^3	0.244	0.21	0.182	0.354	0.217	0.312	2–3
Nitrate ions	mg/dm^3	1.973	0.287	0.288	0.313	0.269	0.533	2–4
Nitrite ions	mg/dm^3	0.029	0.01	0.007	0.008	0.015	0.012	2–3
Total iron	mg/dm^3	0.347	0.295	0.29	0.339	0.38	0.505	3
Manganese	mg/dm^3	0.022	0.01	0.01	0.05	0.05	0.05	2
Aluminum	mg/dm^3	0.02	0.02	–	–	–	–	1
Permanganate oxidizability	mg/dm^3	8.99	8.47	7.78	8.6	8.84	9.64	2
Petroleum products	mg/dm^3	0.3	0.3	0.3	0.3	0.3	0.3	4
Chloride ions	mg/dm^3	18.16	23.39	24.28	21.13	18.94	17.49	1
Dissolved oxygen	mgO_2/dm^3	10.56	9.7	10.01	10.65	9.71	9.36	1

4. Sanitary and chemical parameters of the drinking water quality produced by the SWSS of the RMPE of the Dnipro-Kirovograd from the water of the Kremenchuk Reservoir

Parameter	Measure	Average annual content in drinking water from the CWR						Normative content by DSanPiN 2.2.4-171-10 [27]
		2018	2019	2020	2021	2022	2023	
Turbidity	NTU	1.7	**1.3**	**1.33**	**1.1**	**1.1**	**1.09**	≤ 1.0
Color	degr.	19.25	12.2	11.88	14.13	17.33	18.04	≤ 20
Hydrogen indicator	units of pH	7.53	7.5	7.73	6.8	7.09	6.83	6.5–8.5
Ammonium ions	mg/dm^3	0.12	0.068	0.078	0.138	0.138	0.139	≤ 0.50
Nitrate ions	mg/dm^3	1.331	0.809	1.083	1.15	0.884	1.206	≤ 50
Nitrite ions	mg/dm^3	0.003	0.004	0.003	0.004	0.003	0.005	≤ 0.1
Total iron	mg/dm^3	0.176	0.12	0.108	0.123	0.14	0.174	≤ 0.20
Manganese	mg/dm^3	0.009	0.01	0.01	0.01	0.01	0.01	≤ 0.05
Aluminum	mg/dm^3	0.12	0.085	0.099	0.097	0.113	0.159	≤ 0.5
Permanganate oxidizability	mg/dm^3	–	**6.4**	**5.6**	**6.04**	**7.0**	**7.31**	≤ 5.0
Free chlorine residual	mg/dm^3	0.44	0.52	0.482	0.487	0.48	0.491	≤ 0.5
Chloride ions	mg/dm^3	25.4	32.05	34.0	32.33	30.03	31.94	≤ 250

Reservoir of the SWSS of the RMPE of the Dnipro-Kirovograd as “good” were determined, clean water of acceptable quality (Table 3) [2].

Among the indicated indicators, turbidity and permanganate oxidizability in the drinking water of the SWSS of the RMPE of the Dnipro-Kirovograd were found in concentrations that exceeded the normative values according to DSanPiN 2.2.4-171-10 [27]; excesses of color, total iron, chlorine residual content were found only sporadically and on average were in the upper limits of the normative values (in individual samples and in different years) (Table 4). This may be due to the difference in the composition of organic substances in the source water during the year.

A significant role in the constant seasonal deterioration of water quality and overspending of washing water and reagents is played by seasonal peaks of overloading of treatment facilities with phytoplankton, for which they are unsuitable for retention (Fig. 1). Accordingly, the picture of the use of reagents has changed in comparison with the technological map that was laid down during the design of typical treatment facilities. Aluminum-containing coagulants to purify water from pollutants that are in a colloidal state and are used on the SWSS of the RMPE of the Dnipro-Kirovograd with surface water intake from the Kremenchuk Reservoir. Working coagulant doses in the autumn-winter period, when water color is 30 degr., turbidity up to 3 mg/dm^3, are 10–30 mg/dm^3. Doses of a coagulant during the flood period and the “blooming” period of the Kremenchuk Reservoir reach 100–150 mg/dm^3 with the color of the source water 70–90 degr., turbidity 8–9 mg/dm^3. An increase in the dose of aluminum-containing coagulants during the specified period leads to a rise in the aluminum content in drinking water to the limit of the normative value (0,5 mg/dm^3).

Based on the observation data for the summer period of 2018–2023, an analysis of the influence of temperature on the following hydrometric, chemical, and physical factors was carried out at the water intake from the Kremenchuk Reservoir: changes in turbidity, color, and concentration of total iron and ammonium ions (Fig. 2–5).

To clarify the visually obtained connections of the analyzed factors (Fig. 2–5), the nature of their mutual influence, a correlation analysis of archival data of observations on the water intake of the Kremenchuk city for the period from May 30, 2014, to April 6, 2016, was carried out, regarding the impact on the concentration of dissolved oxygen of the following hydrometric, chemical, and physical factors: changes in the water level; changes in water influx and discharge; changes in Mn^{2+} and NH_4 concentration; temperature t (°C). Given that the data distribution does not correspond to normal law, both the parametric Pearson method and the non-parametric Spearman method were used to determine correlations. The results of statistical data processing are presented in the form of correlation tables (Tables 4, 5) [1].

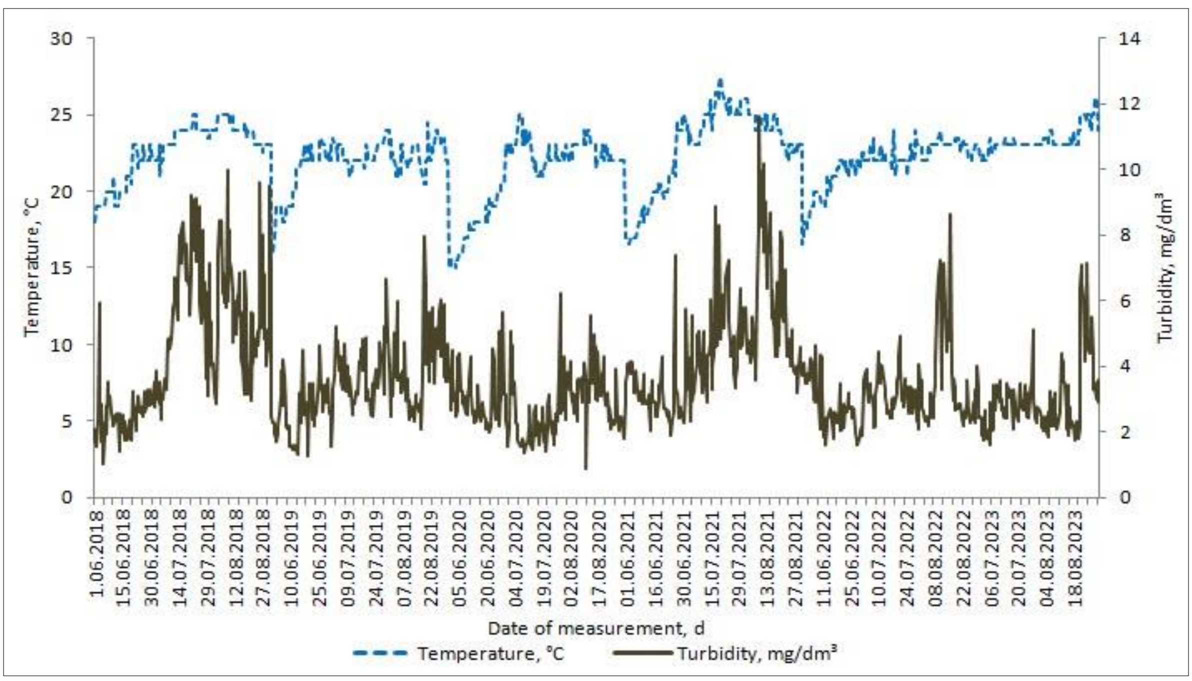

Fig. 2. Changes in the temperature and turbidity of surface waters at the water intake from the Kremenchuk Reservoir in the summer period of 2018–2023

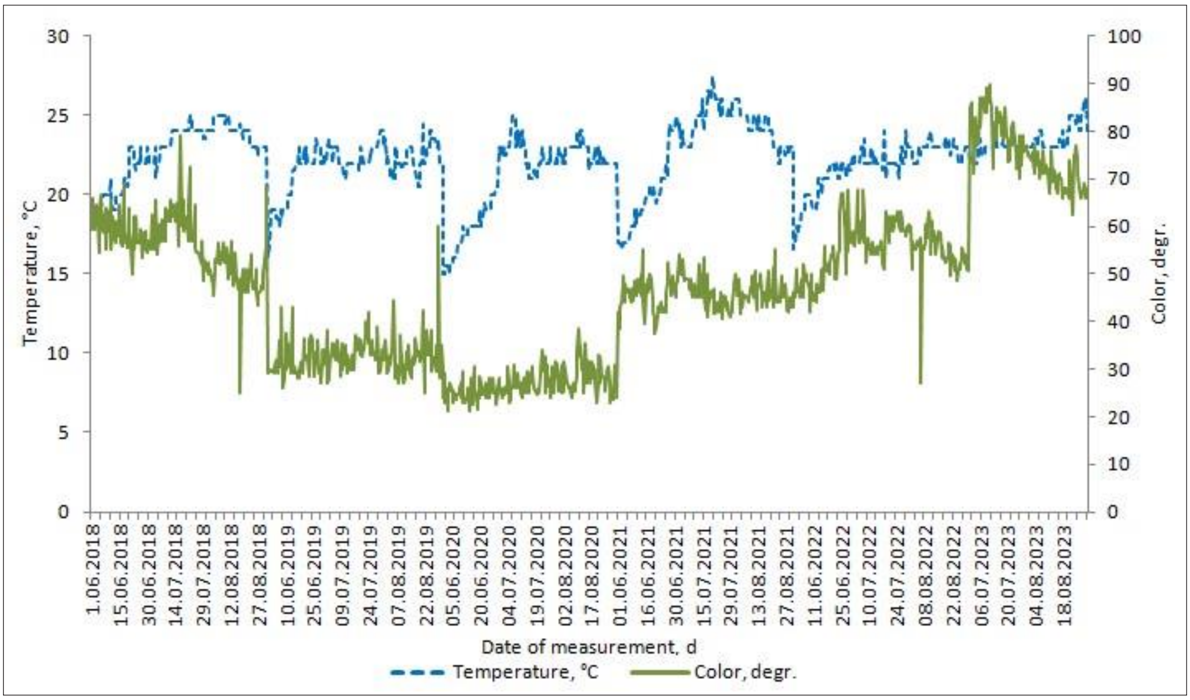

Fig. 3. Changes in the temperature and color of surface water at the water intake from the Kremenchuk Reservoir in the summer period of 2018–2023

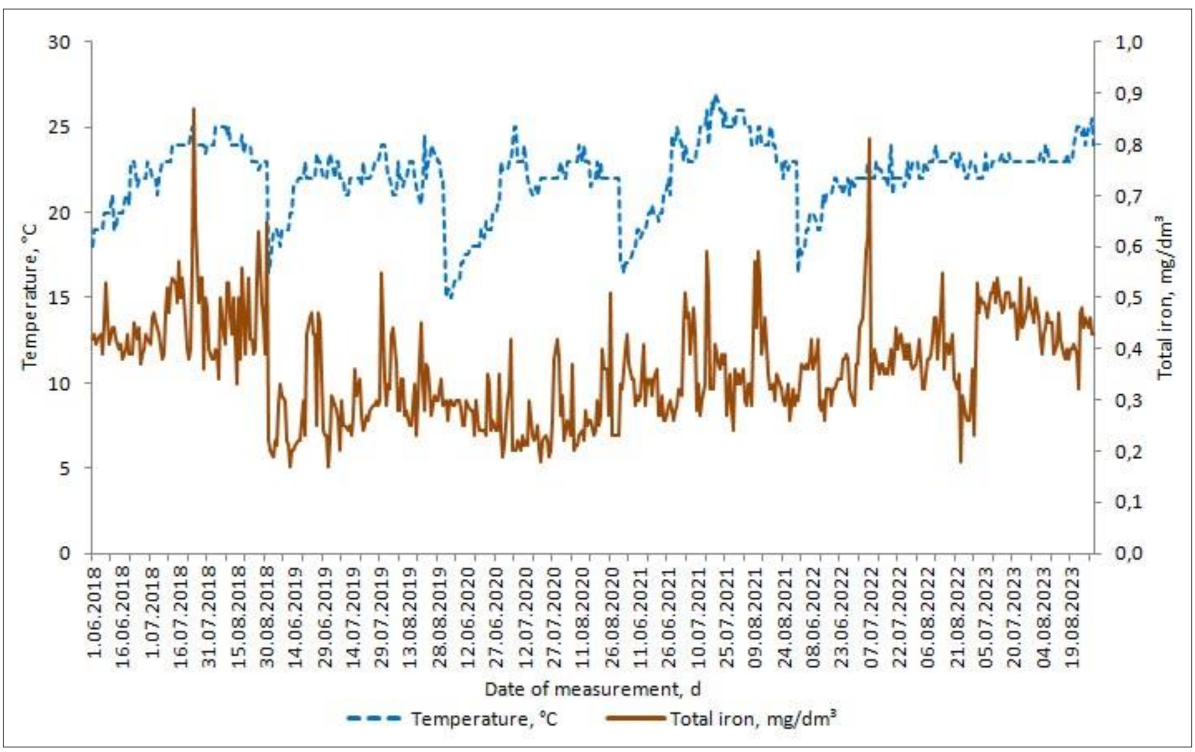

Fig. 4. Changes in the temperature and total iron concentration of surface water at the intake from the Kremenchuk Reservoir in the summer period of 2018–2023

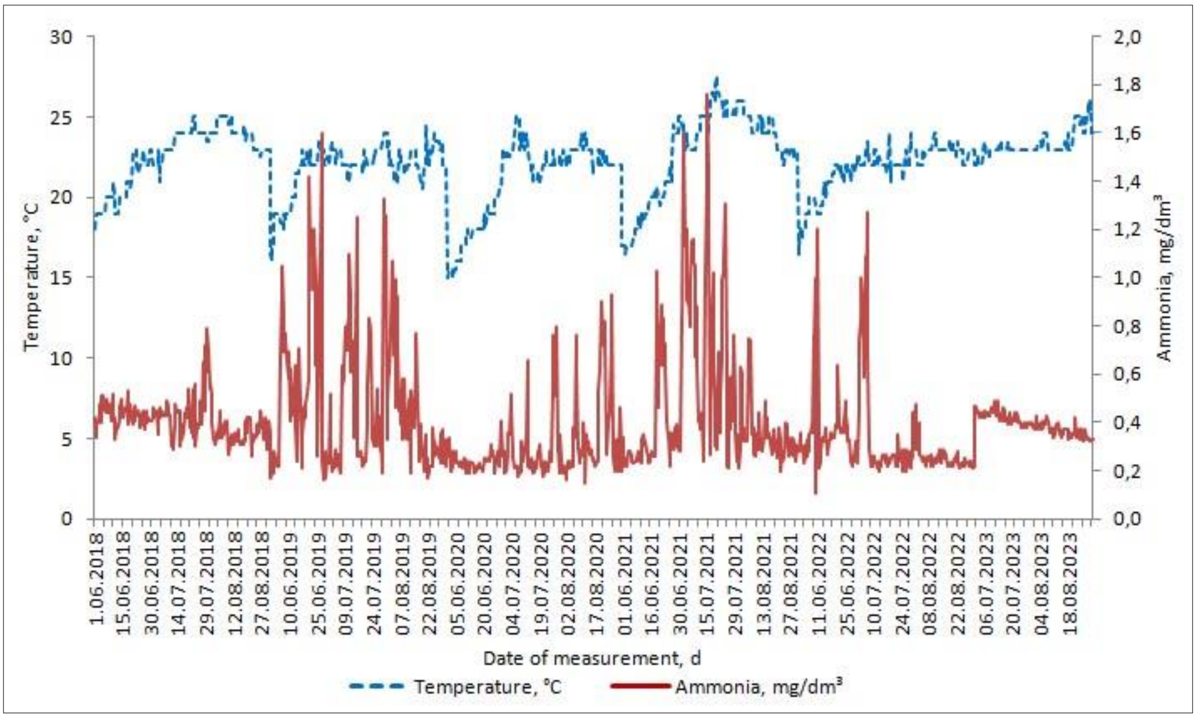

Fig. 5. Changes in the temperature and ammonia concentration of surface water at the water intake from the Kremenchuk Reservoir in the summer period of 2018–2023

4. Correlation of changes in water indicators at the Kremenchuk city water intake according to Pearson

	O_2	Mn	NH_4	t, °C	Level	Influx	Discharge
O_2	1.000	–0.329	–0.420	–0.743	–0.660	0.152	–0.011
Mn	–0.329	1.000	0.524	0.275	–0.042	–0.146	0.106
NH_4	–0.420	0.524	1.000	0.069	0.219	0.271	0.248
t, °C	–0.743	0.275	0.069	1.000	0.593	–0.303	0.015
Level	–0.660	–0.042	0.219	0.593	1.000	0.303	0.165
Influx	0.152	–0.146	0.271	–0.303	0.303	1.000	0.499
Discharge	–0.011	0.106	0.248	0.015	0.165	0.499	1.000

5. Correlation of changes in water indicators at the Kremenchuk city water intake according to Spearman

	O_2	Mn	NH_4	t, °C	Level	Influx	Discharge
O_2	1.000	–0.363	–0.440	–0.691	–0.644	0.256	–0.168
Mn	–0.363	1.000	0.466	0.564	0.150	–0.150	0.227
NH_4	–0.440	0.466	1.000	0.158	0.199	0.206	0.244
t, °C	–0.691	0.564	0.158	1.000	0.803	–0.336	–0.019
Level	–0.644	0.150	0.199	0.803	1.000	0.062	0.050
Influx	0.256	–0.150	0.206	–0.336	0.062	1.000	0.275
Discharge	–0.168	0.227	0.244	–0.019	0.050	0.275	1.000

The determining method of correlation analysis is the non-parametric method of Spearman, the additional one is the parametric method of Pearson. A comparison of the coefficients obtained by the two methods confirms their non-contradiction.

Correlation analysis confirms the visual connection of oxygen with temperature and water level (Tables 4, 5). This is evidenced by the correlation coefficients: −0,691 and −0,644, respectively, this is a pronounced influence of these factors on the oxygen concentration. That is, there is a significant negative relationship between temperature and the level of oxygen content in water. The higher the temperature and level, the lower the oxygen concentration. The effect of the correlation coefficient of ammonium nitrogen is also quite significant: -0,44, although it is not a vivid illustration of the inverse dependence (Table 5).

Regression analysis is used to determine the contribution of individual independent variables and the forecast of values.

The dependent variable – is oxygen concentration, independent variables: are temperature, soluble manganese, ammonium nitrogen, water level, influx, and discharge.

By constructing a multiple linear regression equation, we determine the contributions of individual independent variables. Using the method of least squares, the equation is obtained:

$$O_2M1 = 165{,}660995 - 0{,}203042912 \times Mn - 4.67263708 \times NH4 - 0{,}189655268 \times t - 1{,}96944342 \times Level + 0{,}16194699 \times Influx + 0.0234157502 \times Discharge$$

where: O_2M1 – concentration of soluble O_2, mg/dm^3; *Mn* – concentration of Mn^{2+}, mg/dm^3; *NH4* – concentration of NH_4, mg/dm^3; *t* – temperature, °C; *Level* – water level, m; *Influx* – water influx, hundreds of m^3/s; *Discharge* – water discharge, hundreds of m^3/s.

The model is characterized using the coefficient of multiple correlation, coefficient (index) of multiple determination, and adjusted coefficient of determination.

The coefficient (index) of multiple correlation R is used to assess the closeness of the joint influence of factors on the dependent variable. To assess the adequacy of the regression model, the coefficient of determination R^2 serves as a measure of the quality of the regression equation. The resulting model has the following characteristics: multiple correlation coefficients R = 0,875; coefficient of determination R^2 = 0,766; adjusted coefficient of determination $R^2_{adjusted}$ = 0,755.

In Fig. 6 shows the real values of the oxygen concentration in the water of the Kremenchuk Reservoir and the resulting model.

Fig. 6. demonstrates the high correlation between the results of experimental studies and the obtained O_2M1 model, which confirms its adequacy.

The contribution of individual independent variables to the variation of the dependent variable is obtained from the equation and visualized on the Pareto chart (Fig. 7).

The way to improve the ecological condition of the Dnipro and its reservoirs is not to draw down them in stages, the ecological and economic effect of which is negligible compared to the projected total damage that may be caused to the nature and economy of Ukraine, but in

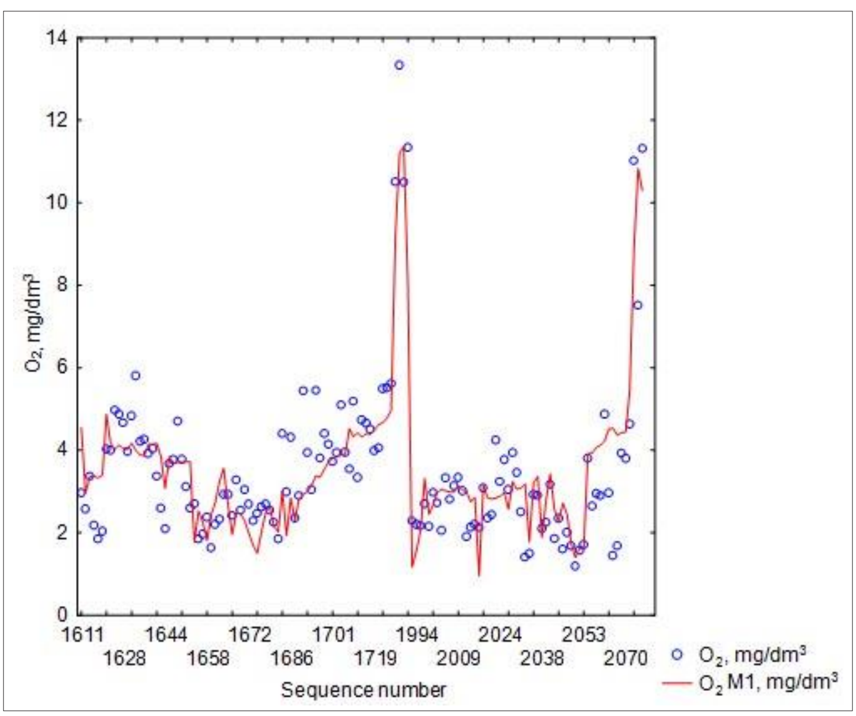

Fig. 6. Comparison of real values of oxygen concentration in the surface waters of the Kremenchuk Reservoir and the obtained O_2M1 model

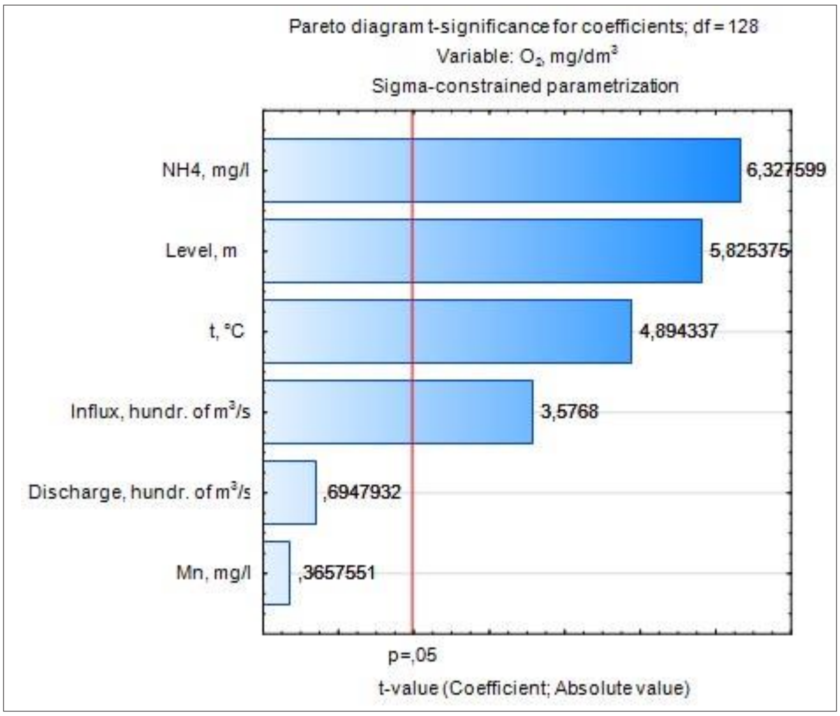

Fig. 7. The contribution of individual independent variables to the variation of the dependent variable according to the O_2M1 model for the surface waters of the Kremenchuk Reservoir

the implement environmentally and resource-saving technologies (innovations), scientifically based reconstruction and optimization of water using of the Dnipro reservoirs. The development of optimization of water supply and sewerage systems for cities whose water supply is provided by the Dnipro River should be consistent with river basin management plans and the post-war reconstruction of Ukraine [28–30].

Conclusions. An analysis of the effectiveness of traditional water treatment technologies at the Dnipro water treatment station with water intake from the Kremenchuk Reservoir showed that these treatment facilities are not designed to treat water with a high content of biogenic substances during the period of active phytoplankton vegetation (summer period of elevated temperatures) and under such conditions, used increased doses of the previous chlorination. As a result, water is polluted with residual chlorine and organochlorine, and the aluminum content in drinking water rises to the limit of the regulatory value (0,5 mg/dm^3). Turbidity 1.4 times higher and permanganate oxidizability 1,3 times higher than the standard content were found in the drinking water of the CWR. Correlation analysis of the effect of temperature on changes in turbidity, color, and changes in the concentration of total iron and ammonia confirmed the visual connection of oxygen with temperature and water level: the higher the temperature and level, the lower the oxygen concentration.

The practical aspects of phytoplankton extraction during intake of surface water from Dnipro reservoirs and water treatment at water treatment stations with the development of recommendations for the operation of water intake facilities have gained further scientific justification. Areas of work should include several normative-legal, engineering-technical, material-energy, economic, and other measures to improve the quality of drinking water; increasing the reliability of the water supply system; increasing the efficiency of the use of material and energy resources of the water supply system; scientific, technical and design support for the implementation of measures.

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АНАЛІЗ ЕФЕКТИВНОСТІ ТРАДИЦІЙНИХ ТЕХНОЛОГІЙ ПІДГОТОВКИ ВОДИ КРЕМЕНЧУЦЬКОГО ВОДОСХОВИЩА РІЧКИ ДНІПРО ДЛЯ ЗАБЕЗПЕЧЕННЯ ПИТНИХ ПОТРЕБ

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Анотація. *Проведено аналіз ефективності роботи систем очистки поверхневих вод дніпровських водосховищ при зміні їх якості для забезпечення нормативних показників якості питної води. Дослідження ефективності традиційних технологій водопідготовки здійснювали шляхом аналізу результатів лабораторних досліджень вихідної та питної води на Дніпровській водоочисній станції із забором води Кременчуцького водосховища (дані СВКГ ОКВП «Дніпро-Кіровоград»), встановлення кореляційних зв’язків якісних показників та оцінки стану водних ресурсів відповідно до вимог водного законодавства. Очисні споруди Дніпровської водоочисної станції не розраховані на очищення води з великим вмістом біогенних речовин у період активної вегетації фітопланктону і за таких умов застосовують підвищені дози попереднього хлорування. Як наслідок, відбувається забруднення води залишковим хлором і хлорорганікою. Зростання дози внесення алюмовмісних коагулянтів у відповідний період призводить до зростання вмісту алюмінію у питній воді до межі нормативного значення (0,5 мг/дм^3). За результатами досліджень в питній воді виявлені перевищення каламутності в 1,4 та перманганатної окиснюваності в 1,3 раза від нормативного вмісту; перевищення забарвленості, заліза, вмісту залишкового хлору виявлялися лише епізодично та в середньому знаходилися у верхніх межах нормативних значень. Проведено кореляційний аналіз (методами Спірмана та Пірсона) впливу температури на наступні гідрометричні, хімічні та фізичні чинники: зміни каламутності, забарвленості, зміни концентрації заліза загального та аміаку. Аналіз підтвердив візуальний зв’язок кисню з температурою і рівнем води та вплив факторів на концентрацію кисню. Набули подальшого наукового обґрунтування практичні аспекти вилучення фітопланктону при заборі поверхневої води дніпровських водосховищ і обробці води на станціях водопідготовки.*

Ключові слова: *водні ресурси, питна вода, технологія очистки, фітопланктон, якість води*

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THE ROLE OF ESG BUSINESS REPORTING IN WATER MANAGEMENT

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Abstract. *The rational use of water resources by business structures requires the development of appropriate strategies and their adherence to the chosen policy in terms of management of these objects: drawing up programs and plans, introducing environmental protection actions, displaying the economic effect and documenting all transactions, minimizing negative impacts on the environment and presentation of the positive and negative consequences of the use of natural resources in the format of ESG reporting, which discloses information about the activities of companies in the field of* ***E****nvironmental aspects,* ***S****ocial responsibility and Corporate* ***G****overnance. This practice positions companies as an active participant in sustainable development and allows them to increase their own ratings, which makes it possible to have advantages in attracting investments and targeted financing, increasing one's own competitiveness due to improved trust in such companies, etc. Improving the quality of information in ESG reporting on water resources management and related processes allows stakeholders to receive complete and reliable information when making management decisions. On the basis of the study of ESG reporting of 8 corporations from Ukraine in terms of the use of water resources during the implementation of the strategy of sustainable development, positive and problematic practices of companies were identified when preparing the necessary data for reporting. During this analysis, the experience and legislative guidelines on the exploitation of water resources and the use of ecological and economic accounting of water in the countries were taken into account. In addition, approaches to applying the level of materiality in ESG reporting were analyzed when reporting in this format. The results of the study made it possible to rank the elements of water resources management of economic entities according to the rule of materiality of data in ESG reporting and to propose an algorithm for compiling ESG reporting in the part of water resources management, taking into account the level of materiality. The article substantiates the directions of providing companies with adequate information on water resources management measures and reflecting such practices in ESG reporting to meet the needs of internal and external users. The directions of further scientific research in the field of reporting on the use of water resources by various business entities are also outlined. A critical analysis of the peculiarities of ESG reporting in the area of water resources management can provide an opportunity for top managers of domestic companies to improve the quality of financial and non-financial information, which, in turn, will contribute to the improvement of the corporate governance system on the one hand, and on the other hand, improve the satisfaction of information users. requests of all stakeholders when making their own management decisions.*

Key words: *Environmental aspects, Social responsibility, Corporate Governance, ESG reporting, sustainable development, materiality, water management*

Relevance of research. Goal 6 "Ensuring availability and sustainable management of water resources and sanitation" [1] was defined as an integral component of achieving the sustainable development goals of Ukraine by 2030. To achieve this goal, adequate modern approaches to water management are required. That poses businesses In Ukraine the implementation and use of a system of indicators in water use areas, which must meet the requirements of sustainable development. Key performance indicators (KPI) can serve as one of the important tools in the field of ESG.

To increase the volume of sustainable investments and combat the laundering of financial funds by unscrupulous companies (subjects that unreasonably apply for investments within the scope of implementing sustainable development – ESG-investing), when conducting "green" businesses many countries are introducing requirements for disclosing the information on ESG and the need for risk assessment when implementing a sustainable development strategy [2]. Thus, non-financial reporting, especially reporting on sustainable development, should be considered within the framework of a single concept of ESG in the long term [3].

Compliance with the recognized ESG investment criteria (investor requirements) for sustainable development is an important factor in the competitive advantages of business entities, which allows them to position themselves as the most advantageous on the capital market and in the eyes of civil society.

Therefore, it is expedient to study the approaches to disclosing and improving organizational and methodological tools in the modern accounting system, which will optimally meet current information requests and the format of ESG reporting, the quality content of which can be recognized as one of the methods of verifying the sustainable development of modern effective business [4].

Analysis of recent publications. An analysis of the use of materiality level in preparing corporate reporting in terms of water management in the ESG format [5] proved that EU regulations require the presence of a criterion of the absence of significant damage to other ESG goals [6]. In this regard, business entities need to assess the financial impact on the environment at the legislative level when determining ESG risks [7]. It is worth noting that practitioners focus on the growing tendency to reassess traditional interpretations of the principle of materiality in ESG [8], which makes it possible to prepare reports using traditional financial indicators of the enterprise's economic activity, considering achieving generally accepted goals of sustainable development [3]. Publishing these data in open access allows companies to demonstrate the effective use of all natural resources, in particular water when implementing ESG strategies [9–16]. However, there is no proper scientific generalization of the accounting and reporting component regarding the frugal use of water resources based on ESG strategies.

The purpose of the article. The purpose of the article is to resolve the current issues of ESG business reporting by companies in terms of water management based on the actualization of a materiality principle, which will ensure its high-quality content, as well as informational value regarding the use of water resources for all stakeholders.

Research methods. This study used:

– logical and abstract methods (analysis of regulatory and legal acts, assessment of the significance of water management components, analysis of scientific sources);

– system analysis (summarization of research results and implementation of best practices by domestic and foreign companies regarding the use of water resources based on ESG principles);

– historical and logical methods (analysis of the data from official reports of Ukrainian corporations and advanced global practices of effective use of water resources);

– analytical and synthetic methods (processing of information and synthesis of results in the form of consolidated data on the qualitative characteristics of the use of water resources).

Research results and discussion. ESG reporting regarding water management was studied based on specifying the importance of preparing such information, analysis of the advantages and disadvantages of using water by domestic corporations, applying a materiality level in activities, and report preparation.

The results of the analysis of legal acts on regulating business reporting in terms of water use according to ESG principles.

At the current stage, improving the efficiency of business economic activity is influenced by implementing the concept of sustainable development, taking into account the interests of society, by voluntarily assuming responsibility for the impact of one's activities on other subjects of the business environment and members of society, which goes beyond the obligations, established by law. The form of such responsibility is the preparation and publication of sustainable development reports by business entities, one of the modern mechanisms of which is the concept of ESG, which is institutionalized through the adoption of standards and initiatives, the mandatory use of which is fixed by a directive [3]. According to Directive 2022/2464/EU [2], from 2024, the rules for reporting on sustainable development will change; instead of voluntary reporting, an imperative principle of business reporting will be introduced in the territory of the EU, which establishes a mandatory reporting procedure, including regarding water use by businesses.

For domestic companies, the researchers suggest that information on the impact of the company's activities on the environment, the industry in which the company operates, and introducing environmental protection measures have to be shown in the "Environmental Aspects" section of the Management Report. It also has to specify reducing its activity impact on the environment. Given these aspects, it is recommended to show the data on the rational use of water in the Management Report, namely: volumes and shares of water intake; volumes and shares of wastewater; volumes and shares of malignant compounds that enter water bodies due to draining used water by the company; share of suppliers using quality standards for water used in the production cycle; financial effect of introducing "green" technologies for water purification; volumes of industrial water consumption in areas with a shortage of drinking water for the population; ecological coefficient of product safety; coefficient of "ecological ballast"; coefficient of waste rational use; profitability of products from waste; environmental pollution coefficient; degree of environmental pollution; index of environmental protection activities, etc. [17–19]. It is worth noting that permanent management of these key indicators is expedient since regulators in the regulatory framework require a reduction of some ESG indicators, for example, malignant compounds in reservoirs as the result of economic activity [20].

The Annex on ESG, by the Corporate Governance Principles, provides for environmental protection measures that must be included in the reported policy of the company. Thus, the company's activity on ESG issues in the area of environmental protection is encouraged [8]. In addition, Ukrainian companies should adhere to International Financial Reporting Standards, the norms of which, in particular IAS 1 "Presentation of Financial Statements" [21], recommend the provision of additional information, for example, environmental reports for those business entities whose activities are significantly affected by environmental factors, and the staff is an important group of corporate reporting users. Ukrainian companies are recommended to implement other existing EU norms regarding sustainable development. The business practice of displaying the information on water use in ESG reports in open access also spreads in Ukraine.

According to national statistics, in 2017, 58.6 % of the total volume of water resources was used for industrial needs in Ukraine. Instead, in 2023, this figure was 62.1 %. In 2017, 17.1 % of total water resources were consumed for drinking water supply, sanitary, and hygienic purposes, and in 2023-21.1 %. 22.6 % of water volume was used for irrigation in 2017, and only 5.5 % in 2023 [22, 23].

Water management measures have to be performed in the legal ecological and economic fields. According to the EU Water Framework Directive water supply is recognized as a public interest service [24]. While complying with the requirement of social justice, the service provider does not seek to obtain a direct economic benefit. Therefore, services of general economic interest, which are basic, and those provided for a fee are distinguished. These services are governed by European internal market and competition rules. However, deviations from these rules may occur if there is a need to protect citizens' access to such services.

It is also necessary to consider the recommendations of environmental accounting [25], which corresponds to existing areas of water use by respondents in their economic activities. Recommendation implementers should assess the applicability and practicality of such recommendations, given their specific features, such as identified user needs, resources, priorities, and respondent burden. Making these recommendations the basis of data collection on water issues will be an important factor in their management, in particular, recognizing the need to improve basic data on water use and integrating these data with social, economic, and environmental aspects to form ESG-reporting.

Positive results of evaluating the meaningful content of ESG reports.

Table 1 shows the analysis of information on water use in terms of implementing the ESG strategy and its presentation in the corporate reporting of domestic corporations. The reports indicate the goal of the company's activity in the field of ESG and the degree of its achievement, in particular, in terms of water management, namely rational water use, ensuring effective use and reproduction of natural resources (surface and underground water), determining the impact on the environment, achieving the goals of the GRI 303 "Water and Wastewater" standard, responsible consumption of water, reducing water losses, improving programs and specifying the level of ambition, as well as adding new goals and measures. Also, the reports emphasize compliance with instructions, descriptions of rules, procedures, and regulations regarding implementing the sustainable development policy, state maximum increase in water reuse, reduction of water intake to a minimum, clarify the results of activities, and determine the measures to eliminate deficiencies.

1. Water use and display of information about it in ESG reports by Ukrainian companies

Name/main areas of activity/source	**Report name and status**	**Purpose of reporting, degree of goal achievement**	**Quantitative results**	**Measures for the rational water use**	**Multifaceted factors**
1	2	3	4	5	6
Metinvest/ Metallurgy [14]	Report on sustainable development	Water resources; Sewage; Waste assigned to the highest level of priority	Reuse of 81 % of total water withdrawn from all sources, including previously recycled water. In 2020, the Group's enterprises reduced the total volume of water intake and discharge by 4 % and 3 %, respectively, compared to 2019.	– reduction of water consumption and waste generation; – a set of measures to minimize the impact on water resources; – improvement of operational efficiency and maintenance	Risks are classified as non-commercial and related to: – lack of water; – efficiency of consumed water and wastewater control; – implementation of environmental projects, – introduction of a closed cycle of water circulation
Kernel/ AIC (plant production) [9]	Annual reports on sustainable development activities	Impact on the environment; Water and wastewater (GRI 303); Achieving the general goal of rational water use	Compliance with current legislation; Prevention of water bodies pollution; Restoration of the internal sewage treatment system; Accounting for water use, reduction of water consumption for cooling; Compliance with limits on discharges into water bodies.	– areas of water use; – prevention of water bodies pollution; – land irrigation; – environmental protection policy; – the company's own environmental protection standards	Implementation of measures to overcome a plant water stress (irrigation) and preserving soil moisture; Implementation of sustainable farming systems; Considering the impact of the interaction of all water users in conditions of limited water resources on the effective use of irrigation systems (irrigation/water supply).
MXP/ AIC (animal production) [10]	Sustainable development, environmental protection	×	Compliance with the requirements of environmental protection legislation; Reduction of water losses in water use	×	Specialists responsible for environmental protection
Carlsberg Ukraine / Production of beer and soft drinks [15]	ESG program, ESG report	There is no water losses	×	×	Replenishment of water reserves in areas with high water risks

Table 1 (ending)

1	2	3	4	5	6
Ferrexpo / Mining industry [11]	Report on responsible conduct of business	Rational water use; Restoration of biodiversity up to 98 %.	Responsible water use; Reducing the negative impact on the environment; Increasing water reuse; Water quality control.	Use of rainwater from the quarry for production activities; Reuse of water from the processing complex; Effective use of water for specific purposes; Reduction of water intake from open sources.	Considering water shortage risks
Nibulon/ AIC (plant production) [16]	Report, section “Environmental policy”	Protection, efficient use and reproduction of natural resources; Ecological safety.	Use of phosphate-free detergents; Application of purification technologies for household water and rainwater; Protection of groundwater used for water supply.	×	Water protection from pollution; Implementation of technologies with minimal impact on the environment.
Astarta/ AIC (sugar production) [12]	Report on sustainable development	Responsible water consumption	***Abstracti***on of surface and underground water is performed in accordance with the established limits; Starting from 2021, water intake and water withdrawal in the segments “Agriculture” and “Animal Production” have been separated; Closed cycles of process water use have been introduced.	Water is used for crop irrigation; Wastewater is discharged to treatment facilities; The quality of treated wastewater is monitored.	Implementation of water-saving irrigation systems (drip irrigation); Ensuring water recirculation in greenhouses; Water buffering in lakes and aquifers; Selection of crop rotations with lower water consumption; Introduction of circular agriculture.
Corteva/ Production of seeds and plant protection products [13]	Management report	Promotion of effective water management	Оптимізація користування водними ресурсами в господарствах. Ефективне використання води Optimization of water use in farms; Efficient water use.	All water intake points are equipped with water meters	×

Source: compiled by the authors

In addition, the investigated reports provide data on water use in the technological processes of the companies' activities and state the stages of these processes, emphasizing the priority of the wastewater treatment stage. The reports show differentiated water-related measures in the regions of companies' activities as to water stress for plants (water shortage risk). The investigated reports of the companies declare the importance of implementing technologies associated with minimal negative impact on the environment and offer different approaches to water management.

In ESG reporting, domestic companies pay considerable attention to taking into account environmental risks; showing the closed cycle of water circulation; a set of measures to minimize the company's impact on water resources; changes in technological processes of wastewater treatment; preventing pollution of water bodies; reducing water consumption for cooling; technologies for purification household water and rainwater; minimizing water losses; maximum increase in water reuse; wastewater accumulation and water quality control; modern irrigation technologies; cultivation of crops with lower water demand.

A comprehensive ecological approach to environmental protection is one of the key areas of corporate social responsibility, which requires the development of programs for implementing the best available practices and technologies in labor, health, and environmental protection, including reducing water consumption and waste generation.

It is necessary to evaluate the attitude of the business owners and management toward the importance of sustainable development approaches reflected in defining environmental goals and implementing special measures, making and publishing ESG reports regularly to improve the quality of ESG reports. Regarding the measures to improve the efficiency of water use, business activities have to aim at the implementation of necessary techniques for accurate assessment of the impact on the efficiency of water use and its fair distribution, as well as its displaying in ESG -reports for information needs of various interested users.

Problem areas of business corporate reporting regarding water management. In reporting documents, it is appropriate to indicate the company's structural divisions responsible for the implementation of its strategies and responsibility for the proper use of natural resources, in particular, water resources. At the same time, actions related to the implementation of strategies have to be displayed in the official duties of the personnel. In corporate reporting, it is necessary to define the terms used and their content: responsible water use, philosophy of sustainable agriculture, effective water management, etc. It is expedient to specify in the corporate reporting the description and provide a quantitative assessment of the proposed measures and application technology: areas for water use optimization; implementation of information technologies for annual and operational planning of irrigation; implementation of farming monitoring systems (meteorological stations, ERS, control and measuring devices); implementation of precision farming systems, etc. [26, 27].

Also, to improve the quality of information in the ESG reporting of domestic companies, it is appropriate to display data related to the monetary assessment of the impact of production fixed assets on the pollution of water used by the company in its production cycle; monetary evaluation of the negative impact of water on the functional state of the basic means of production. In addition, given the impossibility of quantitative and monetary assessment of all important points regarding water use and management, it is advisable to display the following information in the form of a descriptive part: water intake control measures; implementing purification technologies for reservoirs used by companies for production purposes; measures performed by the company to clean water bodies, preserve fauna and microclimate in the areas of such water bodies, etc. [29].

Consideration of the materiality factor in ESG reporting. When making ESG reporting, the company relies on the generally recognized postulates of providing reliable information about its activities, and an important characteristic of the provided data is the level of their materiality.

Materiality is the fundamental principle of preparing reporting on sustainable development [5], which provides the criterion of information sufficiency [27], necessary for a complete and unambiguous understanding by all stakeholders of the situation regarding the information provided in such reporting [2, 3, 5]. Information is recognized as material if it significantly influences the company, assessments, and the decisions of stakeholders and when it is useful for decision-making by all interested parties satisfying their information expectations. At the same time, the International Accounting Standards Board defines information as material if "… its omission, distortion or concealment may affect the decisions taken by the main users of general purpose financial statements…".

The regulatory acts consider the concept of "double materiality", which consists of both the company's financial impact on the environment, society, and other stakeholders and their impact on the situation in the company [3]. Also, an important term is "dynamic materiality", under which it is appropriate to understand information that may not be financially significant now but may become financially significant in the near, medium, and long term.

The new vision of materiality in ESG reporting is not the information that can predictably move the market, but rather information that provides a deep, long-term understanding of a company's risks, prospects, and drivers of success. Businesses should be aware that the attitude towards what is considered essential is changing [8]. Instead, investors need consistent, comparable, and useful information to realize ESG risks and opportunities to consider them in the decision-making process [20].

Based on the conducted expert assessment, it is possible to propose essential elements of water management by materiality degree, which corresponds to the principle of strategic orientation of ESG reporting [5], presented in Table 2.

Algorithm for compiling ESG-reporting regarding water management by materiality degree. Reporting of Ukrainian companies on water management by the materiality factor involves the following actions:

– determining the purpose of activities and specific tasks to be achieved in the reporting period (reference is made to the program and environmental policy of the company); choosing a report format indicating compliance with ESG requirements and selection of metrics for data collection; ensuring compliance with a unified approach to water use and conservation; displaying the developed and used materiality criteria (materiality matrix), as well as the areas of responsibility of the respondent company and developing its standards for environmental protection;

– collecting, auditing, analyzing, and summarizing data on implementing programs

2. Elements of water management when considering materiality degree in ESG reporting

Materiality degree	**Components of water management by materiality degree**
High	– indicating the goal of the company's activities in the field of ESG and reporting about the goal achievement; – achieving the goals of the GRI 303 program "Water and Wastewater (GRI 303)"; – offering data that provide a comprehensive long-term realizing the risks, prospects, and drivers of the company's success regarding efficient water use; – displaying the results of the optimization of water use; – assessing potential benefits, cost of implementing measures for water efficient use, and potential losses in case of non-implementation; – assessing the possibility of financial impact and absence of harm to other ESG goals; – using available reserves, limitations, and diversification of the company's activities; – achieving a high level of data integration; – introducing measures aimed at preventing/eliminating damage caused to the environment by companies.
Average	– introducing advanced "green" technologies; – availability of accredited laboratories; – availability of internal environmental audit; – keeping ecological water accounting [25]; – monitoring of water quality; – assessing environmental impact (depending on the industry in which the company operates); – assessing environmental protection measures, reducing the negative impact on the environment; – rational water use; – environmental pollution coefficient; – making water reserves and funding for environmental protection measures; – assessing military risks; – displaying in reporting extraordinary events, including those that occurred regardless of the company's activity; – risk insurance.
Low	– considering the interests of all water users, assessing the impact of their activities on water management; – reducing water losses; – stating the facts on fulfilling the obligations.

Source: compiled by the authors

and environmental projects on environmental water accounting; coordinating the ESG report with other reportings of the company (financial, tax, statistical, etc.);

– considering approving and publishing ESG reporting; determining the company's rank in the ESG strategy implementation ratings, and considering ways to improve the company's reputation by adjusting materiality characteristics;

– searching for financing for implementing water management measures, since the economic corporate management plays a leading role; cost planning for data preparation and ESG reporting, as well as for environmental and social measures.

Thus, the information from ESG reports regarding efficient water use provides for determining the goal, stating compliance with the regulatory requirements of such practice, and displaying water use measures. The respondents of ESG reporting have to focus on compliance with the obligations of water users and responsibility for violations of water legislation [30].

Conclusions. For effective water management, it is necessary to introduce a set of rules in the regulations of the companies, according to which the companies' activities and reporting related to water use will meet the requirements for sustainable development accepted in the world, in particular, the requirements of the best practices of ESG reporting. The function of the materiality degree consists of a scientifically based rating of the components of water management performed by companies, establishing task priorities focusing not only on the future economic benefits but also on the responsibility of companies for rational water use in their economic activities, as well as increasing the number of responsible persons in the area of nature management and environmental protection.

Areas for further research. Further scientific research should provide for the development of an appropriate toolkit for the use of the terminological apparatus, in particular, considering the latest understanding of water management [25], methods of data formation, specification of the goal considering risks, improvement of methodological approaches for assessing a financial impact and identifying risks in ESG conditions, application of integrated water management by the basin principle, clarification of the companies' responsibility for violations of environmental regulations.

The article analyzes the reports of Ukrainian companies for 2019–2021, that is, before the COVID-19 pandemic started and during it. Analysis of such reports on business activities during the war and post-war recovery period in Ukraine will enable us to establish how businesses used water resources and achieved positive results by introducing broad reforms in rational water use.

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РОЛЬ ESG-ЗВІТНОСТІ КОМПАНІЙ В УПРАВЛІННІ ВОДНИМИ РЕСУРСАМИ

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Анотація *Раціональне використання водних ресурсів компаніями потребує впровадження стратегій та дотримання ними обраної політики в частині управління цими об'єктами: складання програм та планів; запровадження дій природоохоронного спрямування, відображення економічного ефекту та документального оформлення усіх трансакцій; мінімізація негативних впливів на навколишнє середовище; представлення позитивних та від'ємних наслідків використання природних ресурсів у форматі ESG-звітності (англ. – ESG reporting), у якій розкривається інформація про діяльність компаній у сфері взаємовпливу навколишнього середовища (**E**nvirontental aspects), соціальної відповідальності (**S**ocial responsibility) та корпоративного управління (corporate **G**overnance). На основі дослідження ESG-звітності восьми корпорацій з України щодо користування водними ресурсами визначено позитивні практики та вузькі місця при підготовці компаніями необхідних даних. Під час проведення цього аналізу враховано іноземний та вітчизняний досвід, а також законодавчі норми в частині екологічного обліку, зокрема використання водних ресурсів. Крім того, проаналізовано підходи до застосування рівня суттєвості у ESG-звітності. Результати дослідження дали змогу здійснити ранжування елементів управління водними ресурсами суб'єктів господарювання за рівнем суттєвості у ESG-звітності та запропонувати алгоритм складання такої звітності у частині управління водними ресурсами. У статті обґрунтовано необхідність забезпечення компаніями належною інформацією щодо використання водних ресурсів у ESG-звітності для задоволення інформаційних потреб усіх стейкхолдерів. Також окреслено напрями подальших наукових досліджень у сфері звітування щодо користування водними ресурсами різними суб'єктами господарювання.*

Ключові слова: *ESG, ESG-звітність, сталий розвиток, суттєвість, управління водними ресурсами*

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ACCUMULATION OF SYMBIOTIC NITROGEN BY PERENNIAL LEGUMINOUS CROPS IN THE SOUTHERN STEPPE OF UKRAINE

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Abstract. *The use of perennial leguminous crops is an energetically and economically beneficial and ecologically friendly measure for improving the nitrogen balance of soils, which implementation requires specification and additional research of certain soil and climatic conditions and farming systems. The work aimed at studying the accumulation of biologically fixed nitrogen by alfalfa and Hungarian sainfoin in single-species crops, as well as in wheatgrass-alfalfa and wheatgrass-sainfoin grass mixtures on the dark-chestnut soil of southern Ukraine. Laboratory, field, and statistical research methods were applied. The obtained results showed that the accumulation of nitrogen in the biomass of leguminous perennial grasses in single-species crops of blue hybrid alfalfa, Hungarian sainfoin, and intermediate wheatgrass and their grass mixtures depended on the hydrothermal conditions of the growing season, changes in species botanical composition by the years of grass stand used. During the first and second years of use, the nitrogen content in the biomass of alfalfa was 3,54–3,75 %, sainfoin – 3,49–3,65 %, and was significantly higher than in single-species crops of intermediate wheatgrass – 2,62–2,77 % to dry matter. The removal of total nitrogen by intermediate wheatgrass during this period did not exceed 90 kg/ha; by alfalfa and sainfoin, it was 125–134 kg/ha, including symbiotic nitrogen removed by the alfalfa crop – 35–39 kg/ha and Hungarian sainfoin – 37–44 kg/ha. In the fractional composition of nitrogen in the soil of the experimental field after three years of using alfalfa when inoculating seeds with the complex microbial preparation Ecovital, the nitrogen content was the highest compared to other types of crop rotation, including total nitrogen – 1006,3–1428,8, mineral nitrogen – 24,9–46,3; alkaline hydrolyzed nitrogen – 113,8–186,0 mg/kg of soil. The obtained results allow us to conclude that the creation of highly productive symbiotic systems when using the latest biological preparations will contribute to improving soil nitrogen balance, eliminate the catastrophic decrease in fertility and soil degradation, improve the fodder base for animal production, and reduce the ecological burden on agricultural lands.*

Key words: *biological nitrogen, symbiotic systems, perennial leguminous grasses, nitrogen regime, extreme weather conditions*

Relevance of research. The increase in the production of high-quality plant products in Ukraine, given the limited supply of energy products and the constant increase in their prices, is generally solved by further increasing the production of mineral nitrogen fertilizers. The production of nitrogen fertilizers is an energy-intensive process since producing 1 ton of mineral nitrogen fertilizers consumes about 6 million kcal, which is as much as 5 tons of hard coal when burning. Over the past 10 years, the rate of mineral nitrogen fertilizers application was 97 kg/ha of active substance (a.d.), against 141 kg/ha in 1990 [1]. Since the beginning of the full-scale russian invasion of Ukraine, only two factory – "Rivneazot" and Cherkasy "Azot" have produced nitrogen fertilizers. Therefore, the volume of mineral fertilizer application will continue to decrease as a result of the challenges of wartime.

When cultivating most crops in recent years, mostly mineral fertilizers were used, while applying organic fertilizers significantly decreased [2]. The latter is associated with a significant reduction in cattle population in all regions of Ukraine. In 1990, with a cattle population of 25,2 million heads (including 8,5 million cows) in Ukraine, 257,1 million tons of organic fertilizers were produced and 8,6 tons of organic matter were applied per hectare of sown area. In general, during the period 1990–2020, the number of dairy herds in Ukraine decreased by 6,4 million heads, that is 74,6 %. The production of organic fertilizers decreased to 9,8 million tons in recent years, due to which only 0,5 tons of organic and 41 kg/ha (dry matter) of mineral fertilizers were applied per hectare of sown area [3–5]. A decrease in nitrogen application rates disrupts the ratio of carbon and nitrogen in the soil; it leads to the situation when plants compensate for the lack of nitrogen by consuming it from humus compounds. Such processes cause dehumification and degradation of arable land [4].

Currently, there are two ways to improve the nitrogen balance in the soil in Ukraine: a) expansion of the production of nitrogen mineral fertilizers on an industrial basis, b) creation of agrotechnological conditions for increasing the sown area of leguminous crops and perennial leguminous grasses, characterized by the maximum nitrogen-fixing activity of symbiotic and free-living diazotrophs [6–8]. Expanding the sown areas of perennial leguminous grasses, which provide high nitrogen-fixing activity of symbiotic and free-living bacteria, is an extremely urgent issue in modern farming conditions [9]. In recent years, there has been an increase in the aridity of the climate and xerophytization of vegetation. Therefore, the development of measures to ensure the stable production of fodder products in the conditions of global climate change is becoming increasingly urgent [10]. Despite the relevance of these issues in the conditions of Southern Ukraine, they remain little studied.

Analysis of recent research and publications. Nitrogen in the earth's crust is in the form of various compounds, which make up 0,005 % of the earth's crust mass [11]. The budget, distribution, and evolution of the earth's nitrogen are regulated by biological and geological cycles. The biological cycle provides the geological cycle with nitrogen, which, in turn, supplies part of the nitrogen to the Earth's interior [12]. It is known, that the main mass of nitrogen is in the air of the atmosphere, where molecular nitrogen is up to 78.08 %, the mass of which is 4×10^{15} tons. However, plants consume only nitrogen from mineral compounds and, due to the inability to assimilate molecular nitrogen from the air, they often experience its deficiency.

Leguminous crops play an important role in soil nitrogen balance. During symbiotic nitrogen fixation from the air by nodule bacteria, leguminous crops, and nodule bacteria function in a close interaction in a biological system, and a connecting electron and transport chain between them is leghemoglobin. Leguminous crops are a source of carbon-containing compounds – products of photosynthesis, which are energy material, necessary for activating and reduction N_2 to NH_{4^+}.

Among the leguminous grasses, clover, birdsfoot deer vetch, and Hungarian sainfoin are characterized by high productivity, but in this regard, alfalfa is considered the most effective [13–16]. Perennial legumes in symbiosis with nodule bacteria, which fix atmospheric nitrogen, accumulate it in phytomass. In the experiments with short crop rotations, it was found that biological nitrogen compensates the total removed amount of nitrogen with the yield in crop rotations with peas and soybeans by 25–62 % and with alfalfa by 89 % [17]. In the post-harvest and root residues of the specified types of leguminous perennial grasses, up to 20–30 t/ha of organic matter is accumulated, which is equivalent to 70–80 t/ha of high-quality humus, due to which winter wheat after alfalfa, without the use of mineral nitrogen fertilizers, forms a grain yield of up to 3,5–4,5 t/ha [18]. The amount of nitrogen accumulated by annual and perennial leguminous plants was determined in a long-term field experiment on typical black soil: for 3 years, alfalfa in a seven-field crop rotation accumulated 39,7–43,5 kg of nitrogen per hectare for a year in the form of above-ground biomass; during that period, the following crops took 14,9 kg of nitrogen from the soil [19].

The temperature regime and the thermotolerance of various strains of nodule bacteria, which have their specific temperature optimums for development and active nitrogen fixation, play an important role in the interaction of nodule bacteria and leguminous plants. The maximum nitrogen fixation of leguminous plants is observed at a temperature of 20–25 °C, and 30 °C and above, there is a decrease in nitrogen accumulation.

Among leguminous perennial grasses, alfalfa and Hungarian sainfoin are characterized by the highest potential of symbiotic nitrogen fixation [13]. Inoculation of leguminous perennial grass seeds with microbial preparations based on effective strains of nodule bacteria before sowing is economically and ecologically appropriate since the indicated crops during the second and third years of cultivation form an effective symbiotic apparatus and fully provide themselves with nitrogen, forming high yields of both above-ground mass and seeds. The expansion of the sown areas of leguminous grasses (alfalfa) ensures an increase in the yield of the least energy-intensive plant protein, an increase in soil fertility and, in general, a decrease in the anthropogenic load on agricultural land. In the EU countries with highly developed agriculture, up to 20–25 % of arable and natural fodder lands are under leguminous perennial grasses [20].

Comparative studies of the nitrogen balance and productivity of leguminous and non-leguminous crop cultivation systems in European agriculture showed that the highest contribution of biologically fixed nitrogen is achieved when the share of legumes in a crop rotation is about 50 % [21]. The ecologists emphasize that along with the increase in the production of organic feed, the cultivation of leguminous crops contributes to the improvement of the environmental ecological balance, and the preservation of the biodiversity of plants and animals [22–24]. Studies carried out in different climatic zones with different types of leguminous grasses revealed that the inclusion of leguminous crops in grass mixtures increases the productivity of meadows by 1,5–2,5 times and the yield of crude protein by 2–3 times compared to cereals grass stands [25–27].

The role of perennial leguminous grasses alfalfa and safflower in the nitrogen regime on non-irrigated lands of the southern Steppe of Ukraine has not been sufficiently studied.

The purpose of the research is to study the accumulation of biologically bound nitrogen by alfalfa and Hungarian sainfoin in single-species crops, as well as in wheatgrass-alfalfa and wheatgrass – sainfoin mixtureson the dark chestnut soil of Southern Ukraine.

Research materials and methods. Field and laboratory studies on the productivity of blue hybrid alfalfa, sand Hungarian sainfoin, and intermediate wheatgrass in single-species crops and wheatgrass-alfalfa and wheatgrass – sainfoin mixtures were conducted on the dark chestnut soil of the experimental farm "Kopani" of the Institute of Irrigated Agriculture of the National Academy of Agrarian Sciences of Ukraine

The area of the experimental farm "Kopani" of Bilozersky District, the Kherson Region is located in the Black Sea Lowland. The soil-forming process in the greater part of the farm area was going in the conditions of a flat topography on carbonate-forest underlying bedrocks. Soils of different fertility, including dark chestnut, were formed in the farm territory, influenced by climate, vegetation, bedrock, groundwater depth, and human economic activity.

The sowing of perennial grasses in a two-factor field experiment was carried out in the early spring of 2020; the experiments were performed in the growing seasons of 2021–2022. The seed sowing rates in crops were (kg/ha): intermediate wheatgrass (variety Vitas) – 32,0, blue hybrid alfalfa (Unitro variety) – 24,0, Hungarian sainfoin (Ingulsky variety) – 90; in grass mixtures: wheatgrass + blue hybrid alfalfa – 16,0 and 12,0, respectively; intermediate wheatgrass + Hungarian sainfoin – 16,0 and 45,0; intermediate wheatgrass + blue hybrid alfalfa + Hungarian sainfoin – 12,0, 8,0 and 30,0. The experiment was laid out by the method of split plots, where the main plots (plots of the first order) are single-species crops of perennial grasses, and sub-plots (plots of the second order) are grass mixtures. The area of the sowing plot was 60 m^2, and the accounting area was 20 m^2. Inoculation of seeds of perennial legumes was carried out with the complex preparation Ecovital, made based on complementary strains of nodule bacteria and phosphate-mobilizing bacilli from the collection of the D. K. Zabolotny Institute of Microbiology and Virology of the National Academy of Sciences of Ukraine.

The content of dry matter in plants before mowing was determined by the weight method in two non-adjacent repetitions by the variants of the field experiment. Forage evaluation of the nutritional value of monospecies crops of blue hybrid alfalfa and Hungarian sainfoin and their grass mixtures with wheatgrass was performed when determining the chemical composition of perennial grasses and grass mixtures. Chemical analysis of fodder was made by infrared spectroscopy on a NIP Systems 4500 analyzer. The content of crude and digestible protein, crude fat, crude fiber, crude ash, as well as fodder units, non-nitrogenous extractive compounds, gross and exchangeable energy, and fodder mineral composition were determined in the dry matter. After determining the total moisture, when hygroscopic moisture and air-dry matter in the samples were taken into account, recalculation of nutrient content in fodder as a percentage of absolutely dry matter was performed. Fodder units and gross and exchangeable energy were calculated based on the chemical composition of plants using the coefficients of nutrient productive action and digestibility [28].

The amount of symbiotic nitrogen fixed from the atmosphere by blue hybrid alfalfa of the

Unitro variety and Hungarian sainfoin of the Ingulsky variety was determined using a modified comparative method [29]. The difference between the nitrogen content (removal) in the above-ground mass and roots of alfalfa or Hungarian sainfoin and intermediate wheatgrass of the Vitas variety was determined with correction for seed nitrogen. Since under the same conditions of their cultivation, the specified crops consumed the same amount of nitrogen from the soil, the difference in nitrogen uptake by leguminous grasses and wheatgrass was attributed to symbiotic nitrogen fixed from the air. The coefficient of nitrogen fixation was calculated based on the ratio of the growth of nitrogen removal by leguminous perennial grasses to the total crop nitrogen removal. Statistical processing of the obtained data was performed according to [30].

Research results and their discussion. It was established that along with a high yield of fodder units and digestible protein, the sowing of leguminous perennial grasses contributed to the accumulation of symbiotic nitrogen, which during all the years of field experiments significantly depended on the yield of absolutely dry matter, the nitrogen content of plants, the lack of moisture supply and the duration of the use of grass stands.

The symbiotic fixation of nitrogen by single-species seed crops of blue hybrid alfalfa and Hungarian sainfoin of the first and second years of use was studied in years with different precipitation availability. By hydrothermal conditions, 2021 was classified as wet (50 %) in terms of precipitation availability, and 2022 – as moderately dry (75 %). The symbiotic fixation of nitrogen by single-species crops of blue hybrid alfalfa, Hungarian sainfoin, and wheatgrass + alfalfa and wheatgrass + sainfoin grass mixtures depended significantly on the change in the species botanical composition of the grass stands over the years of use and the nitrogen content in perennial grasses. Nitrogen content in single-species crops of blue hybrid alfalfa, Hungarian sainfoin, and intermediate wheatgrass and their grass mixtures depended significantly on the hydrothermal conditions of the growing season of each year of the field experiment. Compared to single-species wheatgrass crops, the nitrogen content in leguminous perennial grasses during all years of the field experiment was significantly higher.

The average nitrogen content in single-species wheatgrass crops in the first year of use was 2,73 and 2,77 %, and in the second year – 2,62 and 2,66 %. In single-species alfalfa crops nitrogen content increased to 3,54 and 3,75 % in the first year and 3,60 and 3,64 in the second year. In single-species Hungarian sainfoin crops nitrogen content also increased up to 3,62 and 3,65 % in the first year and up to 3,49 and 3,63 % of absolutely dry matter in the second year.

During the first and second years of use, the removal of total nitrogen by the intermediate wheatgrass did not exceed 90 kg/ha, by the blue hybrid alfalfa and Hungarian sainfoin – 125 and 129 kg/ha, and 127 and 134 kg/ha, respectively; including the removal of symbiotic nitrogen by blue hybrid alfalfa – 35 and 39 kg/ha and Hungarian sainfoin – 37 and 44 kg/ha. The removal of symbiotic nitrogen over the years of the study by the intermediate wheatgrass + blue hybrid alfalfa grass mixture was 38 and 41 kg/ha, by the intermediate wheatgrass + Hungarian sainfoin grass mixture – 33 and 41 kg/ha, and by the intermediate wheatgrass + blue hybrid alfalfa + Hungarian sainfoin three-component grass mixture – 37 and 44 kg /ha (Table 1).

The coefficient of nitrogen fixation, as the ratio of the growth of nitrogen removal by leguminous perennial grasses to the total crop removal, under conditions of natural moistening (without irrigation) in the southern part of the Steppe zone, significantly depended on presence of alfalfa and Hungarian sainfoin in the species botanical composition, precipitation availability, and the duration of the use of grass stands over the years. For blue-hybrid alfalfa of the Unitro variety in the first and second year of use, it was 28,0 and 30,2 % respectivly, and for Hungarian sainfoin of the Ingulsky variety – 29,1 and 32,8 % respectively (Table 1).

The cultivation of single-species crops of blue hybrid alfalfa, Hungarian sainfoin, and their grass mixtures with intermediate wheatgrass made it possible to obtain green fodder, balanced with digestible protein, without applying mineral nutrients and to provide cereal grain crops with the best forecrops during all the years of scientific research.

The determined fractional composition of nitrogen in the 0–20 cm and 20–40 cm layers of the dark chestnut soil of the experimental field of EE “EF “Kopani” after three years of using alfalfa when inoculating seeds with Ecovital shows that, compared to other types of the crop rotation, it was the highest and, depending on the soil layer, consisted of: total – 1006,3 and 1428,8 mg/kg, mineral – 24,9 and 46,3, alkaline hydrolyzed – 113,8 and 186,0, heavily hydrolyzed – 155,5 and 214,4 and non-hydrolyzed nitrogen – 712,1 and 982,1 mg/kg of soil (Table 2).

Sufficient accumulation of all forms of nitrogen in the soil is due to inoculating alfalfa seeds with the complex biological preparation Ecovital.

1. Accumulation of symbiotic nitrogen by perennial legumes in the first and second years of use

Types of grass and grass mixtures	Removal of nitrogen by yield and roots			Nitrogen fixation coefficient, %	Equivalent to mineral nitrogen in	
	Total removal		Including symbiotic nitrogen, kg/ha			
	kg/ha	%			kg/ha	GJ/ha
First year of use (2021)						
Intermediate wheatgrass	90	100	–	–	–	–
Alfalfa	125	139	35	28,0	105	9,1
Intermediate wheatgrass + Alfalfa	128	142	38	29,7	114	9,9
Hungarian sainfoin	127	141	37	29,1	111	9,6
Intermediate wheatgrass + Hungarian sainfoin	123	137	33	26,8	99	8,6
Intermediate wheatgrass + Alfalfa + Hungarian sainfoin	127	141	37	29,1	111	9,6
LSD_{05}	13,8	15,4	2.0	1,3	6,1	0,3
Second year of use (2022)						
Intermediate wheatgrass	90	100	–	–	–	–
Alfalfa	129	143	39	30,2	117	10,1
Intermediate wheatgrass + Alfalfa	131	145	41	31,3	123	10,7
Hungarian sainfoin	134	149	44	32,8	132	11,4
Intermediate wheatgrass + Hungarian sainfoin	131	145	41	31,3	123	10,7
Intermediate wheatgrass + Alfalfa + Hungarian sainfoin	134	149	44	32.8	132	11,4
LSD_{05}	19,5	20,9	2,2	1,1	6,7	0,6
On average for 2021–2022						
Intermediate wheatgrass	90	100	–	–	–	–
Alfalfa	127	141	37	29,1	111	9,6
Intermediate wheatgrass + Alfalfa	130	144	40	30,5	119	10,3
Hungarian sainfoin	131	145	41	31,0	122	10,5
Intermediate wheatgrass + Hungarian sainfoin	127	141	37	29,1	111	9,7
Intermediate wheatgrass + Alfalfa + Hungarian sainfoin	131	145	41	31,0	122	10,5
LSD_{05}	16,7	18,2	2,1	1,2	6,4	0,5

2. Fractional composition of nitrogen in different types of crop rotation (EE "EF "Kopani" of the Institute of Irrigated Agriculture of NAS)

Type of crop rotation	Soil layer depth, cm	Fractional composition of nitrogen, mg/kg				
		total	mineral*	alkaline hydrolyzed	heavily hydrolyzed	non-hydrolyzed
Alfalfa	0–20	1428,8	46,3	186,0	214,4	982,1
	20–40	1006,3	24,9	113,8	155,5	712,1
Winter wheat	0–20	1176,0	19,2	121,2	179,7	855,9
	20–40	892,0	21,1	95,1	132,6	643,2
Sunflower	0–20	1123,0	22,3	110,7	168,4	821,6
	20–40	834,0	12,6	81,6	127,1	612,7
Black fallow	0–20	1231,0	39,4	146,4	170,8	874,4
	20–40	917,0	25,1	99,5	134,3	658,1
LSD_{05} (0–20 cm), mg/kg		152,90	15,03	38,34	24,36	79,32
LSD_{05} (20–40 cm), mg/kg		82,04	6,69	15,19	14,28	47,62

*Note: mineral nitrogen – (N –NO3+N–NH4).

The high content of mineral and alkaline hydrolyzed nitrogen in the dark chestnut soil during the cultivation of alfalfa for fodder purposes and seeds makes it possible to obtain sufficiently high yields of grain crops, winter rape, and sunflower in conditions of natural moisture supply without applying mineral nitrogen fertilizers. Therefore, the expansion of alfalfa sown areas in combination with complex inoculation in modern farming conditions is one of the most effective solutions to overcome the difficult situation that small-scale and private farms of the Southern Steppe of Ukraine have faced in recent years.

Restoration of degraded dark-chestnut soil fertility was achieved by the long-term use of drought-resistant perennial leguminous grasses, namely blue hybrid alfalfa and Hungarian sainfoin, which are the most adapted to the natural and climatic conditions of the Southern Steppe subzone. At the same time, high productivity of single-species crops of blue hybrid alfalfa in the range of 1,33–2,67 t/ha of fodder units and 0,30–0,62 t/ha of digestible protein, in the southern part of the Steppe zone was obtained under conditions of natural water supply (without irrigation).

The obtained results emphasize the important role of perennial legumes in increasing the production of fodder protein, which was confirmed by the experiment results in different natural and climatic zones of Ukraine [31, 32]. An increase in the productivity of perennial legumes is provided by the pre-sowing treatment of seeds with complementary strains of nodule bacteria [33]. As shown by the results of our research, the accumulation of nitrogen by perennial leguminous grasses is significantly activated when using nodule bacteria in a complex with phosphate-mobilizing bacteria. In the arid climate of southern Ukraine, the complex application of nodule and phosphate-mobilizing bacteria contributed not only to effective symbiotic nitrogen fixation but also increased the resistance of plants to adverse weather conditions. It is an important factor that ensures the sustainable development of agriculture in the conditions of climate aridization, which has been observed in recent years in the Steppe zone.

Conclusions. Cultivation of single-species crops of blue-hybrid alfalfa, Hungarian sainfoin, and their grass mixtures with wheatgrass when using complex bacterial preparations allows us to accumulate 37–41 kg/ha of symbiotic nitrogen, obtain nitrogen-enriched green fodder containing 141–145 kg/ha of nitrogen in the phytomass. The creation of highly productive symbiotic systems of single-species agrophytocenoses of perennial leguminous grasses and leguminous-cereal grass mixtures, resistant to adverse climatic factors, in combination with the introduction of the latest biological preparations, contributes to increasing the content of mineral (nitrate and ammonium) and alkaline hydrolyzed nitrogen in the soil. Increasing the sown area with alfalfa, alfalfa-cereal, and sainfoin-cereal grass mixtures will avoid a decrease in soil fertility and soil degradation, improve the fodder base for animal production, reduce the use of nitrogen mineral fertilizers, decrease the ecological burden on agricultural land, and provide grain, technical and vegetable crops with the best forecrops.

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НАКОПИЧЕННЯ СИМБІОТИЧНОГО АЗОТУ БАГАТОРІЧНИМИ БОБОВИМИ ТРАВАМИ В УМОВАХ ПІВДЕННОГО СТЕПУ УКРАЇНИ

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Анотація. *Використання посівів багаторічних бобових культур є енергетично і економічно вигідним та екологічно безпечним заходом поліпшення азотного балансу ґрунтів, упровадження якого потребує конкретизації і додаткових досліджень стосовно певних ґрунтово-кліматичних умов і систем землеробства. Метою роботи було вивчення накопичення біологічно зв'язаного азоту люцерною й еспарцетом піщаним в одновидових посівах, а також в пирійно-люцернових* *і пирійно-еспарцетових травосумішках на темно-каштановому ґрунті півдня України. Застосовано лабораторні, польові та статистичні методи дослідження. Отримані результати засвідчили, що накопичення азоту в біомасі бобових багаторічних трав в одновидових посівах люцерни синьогібридної, еспарцету піщаного й пирію середнього та їх травосумішок залежало від гідротермічних умов вегетаційного періоду, зміни видового ботанічного складу за роками використання травостоїв. У продовж першого і другого років використання вміст азоту в біомасі люцерни становив 3,54–3,75 %, еспарцету піщаного – 3,49–3,65 % і був істотно вищим, ніж в одновидових посівах пирію середнього – 2,62–2,77 % до абсолютно сухої речовини. Винос загального азоту врожаєм пирію середнього за цей період не перевищував 90 кг/га, люцерною та еспарцетом – становив 125–134 кг/га, зокрема симбіотичного азоту врожаєм люцерни – 35–39 кг/га і еспарцету піщаного – 37–44 кг/га. У фракційному складі азоту в ґрунті дослідного поля після трирічного використання люцерни за інокуляції насіння комплексним мікробним препаратом Ековітал вміст азоту був найвищим порівняно з іншими ланками сівозміни, зокрема загального – 1006,3–1428,8, мінерального – 24,9–46,3; лужногідролізованого – 113,8–186,0 мг/кг ґрунту. Отримані результати дають змогу дійти висновку, що створення високопродуктивних симбіотичних систем за умов застосування новітніх біопрепаратів сприятиме поліпшенню азотного балансу ґрунту, допоможуть усунути катастрофічне зниження родючості й деградацію ґрунтів, поліпшить кормову базу для тваринництва, знизить екологічне навантаження на сільськогосподарські угіддя.*

Ключові слова: *біологічний азот, симбіотичні системи, багаторічні бобові трави, азотний режим, екстремальні погодні умови*

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FEATURES OF FORMING WATER AVAILABILITY FOR WINTER WHEAT IN THE SOUTH OF UKRAINE

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Abstract. *The article examines the importance of considering several factors affecting the soil water regime in the context of developing models for forecasting productive soil moisture reserves. It was established that the main factors, such as the type of soil, its density, and mechanical composition, remain constant in different soil and climatic regions of Ukraine. The second group of factors, such as air temperature, precipitation, and soil moisture, are subject to changes throughout the growing season and even over short periods. Therefore, the dynamics of soil moisture as a function of the main variables, such as average air temperature and precipitation, was considered using calculations. Initial moisture reserves are used in the calculations for more accurate forecasting of moisture reserves at the end of a specified period. Hydrothermal conditions considered as predictors in the regression equation are also used. The reliability of the conducted research is confirmed by the analysis of independent input and output information from the Kherson weather station in the period from 2018 to 2021 regarding the actual reserves of productive moisture in the soil at a depth of 0–20,0–50 and 0–100 cm.*

The average error between actual and calculated data did not exceed +13,5 %. It confirms the reliability and precision of the conducted research making it the basis for further analyses and conclusions. The conclusions noted the need for accurately determining soil moisture to effectively manage agrometeorological conditions and optimize crop yield. The authors believe that the research work presented in this article can significantly contribute to developing modern approaches to water availability in agriculture and agrometeorology. That will contribute to the gradual and improved development of soil moisture forecasting methodology, which is key to ensuring sustainable and productive development in agriculture.

Key words: *soil water regime, forecasting of moisture reserves, modeling, influencing factors, hydrothermal conditions, productivity, agriculture, climate change*

Relevance of research. In modern conditions of climate change, in particular global and regional warming, there is a change in the ratio between the physical evaporation of moisture from the soil and its direct use by plants. The rate of moisture absorption by plants also changes with increasing temperature. These potential changes in water consumption need to be quantified, considering the influence of all factors that form the basis of precision agriculture. To determine the mechanism of forming the dynamics of water availability for crops during the growing season, it is necessary to take into account the variable nature of hydrothermal conditions and the potential plant productivity, which is proposed to be done using ground and remote monitoring data. It is possible to predict changes in moisture reserves for the decade by the forecast of air temperature and amount of precipitation when using developed models and having information about the actual or determined reserves of productive moisture at the beginning of the decade.

Analysis of recent research and publications. Global climate change has different manifestations in different regions of the world, and its impact on the environment and socio-economic development is becoming more and more noticeable and is one of the pressing problems of our time. Assessing the impact of this change on all aspects of human life plays an important role in the fundamental science of the 21st century as well as in global economics and politics. One of the main consequences of climate change is a change in the hydrological regime, the amount and quality of water resources, which affects various areas of the economy, especially agriculture.

In modern conditions, the lack of water availability becomes one of the main limiting factors for the sustainable development of agriculture. For this reason, attention to the problem of water management in agriculture is growing. Over the past decades, many studies have been devoted to this topic, which resulted in a significant increase in publication activity. For example, during 1993–2017, the number of publications on this topic increased 67 times. In [1], the impact of climate change on available water resources in agriculture was investigated, given global trends and perspectives. The authors analyzed changes in the precipitation regime, distribution, and water availability for irrigation and production. An assessment of changes in the hydrological regime in agricultural areas under various climate change scenarios was also carried out [2].

Scientists have analyzed changes in river flow, groundwater levels, and water demand for various crops. The review study [3] considered the modeling of the impact of climate change on plant water demand and irrigation needs. Scientists have analyzed changes in water availability for various crops and irrigation requirements depending on climatic conditions. It was established that if water availability decreases in the future, soils with high water-holding capacity will be preferable for use to reduce the impact of drought on crop productivity. In works [4, 5], the authors investigated the vulnerability of the main field crops to climate change. They analyzed the impact of climate change on yields, drought risks, and other factors affecting production sustainability and assessed the impact of climate change on countries' adaptation strategies.

Ukrainian scientists have made databases for assessing [6] and rational use of agricultural resource potential of areas, analyzed the impact of global and regional climate change on increasing evaporation and moisture deficit, as well as on decreasing precipitation in the Southern Steppe subzone [7]. Four basic models of climate change are commonly used now. Summarizing the above and conducting our research will not only contribute to the development of scientific approaches to the problem of water availability of main field crops (in our case, it is winter wheat) but will also make it possible to develop specific practical recommendations and innovative solutions for farmers and agricultural enterprises to effectively cope with the challenges, posed by climate change.

The purpose of the research is to study the features and establish the dependencies between the dynamics of water availability of winter wheat and the hydrothermal conditions of the growing season in the South of Ukraine.

Research materials and methods. The research was conducted at the Institute of Water Problems and Land Reclamation of the NAAS by processing the data from long-term field experiments, weather forecasts, data from the Hydrometeorological Center, and further processing of the obtained information using automation tools.

Research results and their discussion. Environmental constraints on water, temperature, and energy balance are known as key factors that can vary independently in time and space. Studies by many scientists show that these factors have complex spatial and temporal relationships, which are important to be considered when analyzing ecological systems. Spatial co-variances, such as relationships between air temperature, atmospheric humidity, and soil moisture, indicate the effect of landscape structures on climatic conditions. Changes in the landscape can affect the distribution and availability of water, as well as air temperature and other environmental parameters. Time co-variance is also a significant factor, especially regarding climate change. Correlated daily or seasonal fluctuations in air temperature and atmospheric humidity indicate changes in climatic conditions over time [8].

Global climate change generates joint trends in changing air temperature and water availability that have been manifested over many years [9]. That can have serious consequences for ecological systems, in particular for resources distribution. Simultaneous changes in precipitation, water availability, and environmental humidity can amplify or weaken the effects of climate change depending on the patterns of changes in the hydration state of organisms. That indicates the importance of carefully investigating the changes in air temperature and environmental water availability for understanding ecological processes in a changing climate environment. In arid regions in particular in the South of Ukraine, the spatial-temporal distribution and availability of water resources are studied at different levels (local, regional, and global) [10, 11]. These studies identify vulnerable to water scarcity areas and develop ecosystem management strategies. They are a key tool for the development of effective water management policies and adaptation to climate change [12].

In crop cultivation water availability is a key factor. It directly affects the yield and determines the cultivation technology. Most agricultural producers pay attention to the average amount of precipitation, but it is also important to consider its distribution during plant development [13, 14]. It is important to determine the soil moisture in the early spring period at the initial stages of plant growth to prevent material and yield losses due to the moisture lack [15, 16].

The main factors affecting moisture dynamics were considered when developing models for forecasting productive moisture reserves. They include soil type, density, and mechanical composition, which almost do not change over a long period and practically remain constant in each soil and climate region. The second group of factors, on the contrary, changes significantly both during the entire vegetation period (growth phases, plant height, and stem density) and short periods: months, decades, and days (air temperature, precipitation, soil moisture, etc.). Moisture consumption for evaporation from the soil surface increases with the rise of temperature, which is accompanied by a decrease in air humidity [17]. Plant transpiration also significantly affects the intensity of total evaporation depending on soil moisture [18].

When developing models for forecasting moisture reserves at the end of any period (a decade, one or two months), it is necessary to consider the initial moisture reserves in the soil layer as a predictor for the regression equation at the time of making the forecast (*Wn*) [19, 20]. Other independent variables in the equation are indicators of hydrothermal conditions, such as average air temperature (Tn) and precipitation (*Rn*). Therefore, the change in moisture in the soil layer over a certain (n^{th}) period (ΔWn) is a function (*F*) of the following main variables:

$$\Delta Wi = F(\Delta Wi, ti, Ri, P, S),$$

where *P* is a soil type and its mechanical composition; *S* is a condition of crop sowing area (phase of plant development, height and density of stems).

Due to the stability of soil type and its mechanical composition, which change little over time but significantly vary within the territories, it is possible to include them in forecasting models of moisture reserves. That can be done by developing separate models for regions with similar or predominant soil characteristics, typical for steppe, forest-steppe, and steppe soil zones. Due to the different water-physical properties of these soils, the formation of moisture reserves in their layers is not the same. Also, the hydrothermal regime formed in these regions affects the dynamics of moisture reserves differently. The change in the reserves of productive moisture per decade (ΔWi) in the 0–20, 0–50, and 0–100 cm soil layers under winter wheat is determined by the algorithm:

$$\Delta Wi = a + bW\text{н}i + cti + dRi,$$

where *Wi* is the initial moisture reserves at the beginning of the *i-th* decade; ti, *Ri* is the average air temperature and amount of precipitation per decade; *a, b, c, d* are multiple regression coefficients that differ depending on the natural and climatic conditions, soil layer, month and decade for which the change in moisture reserves is calculated.

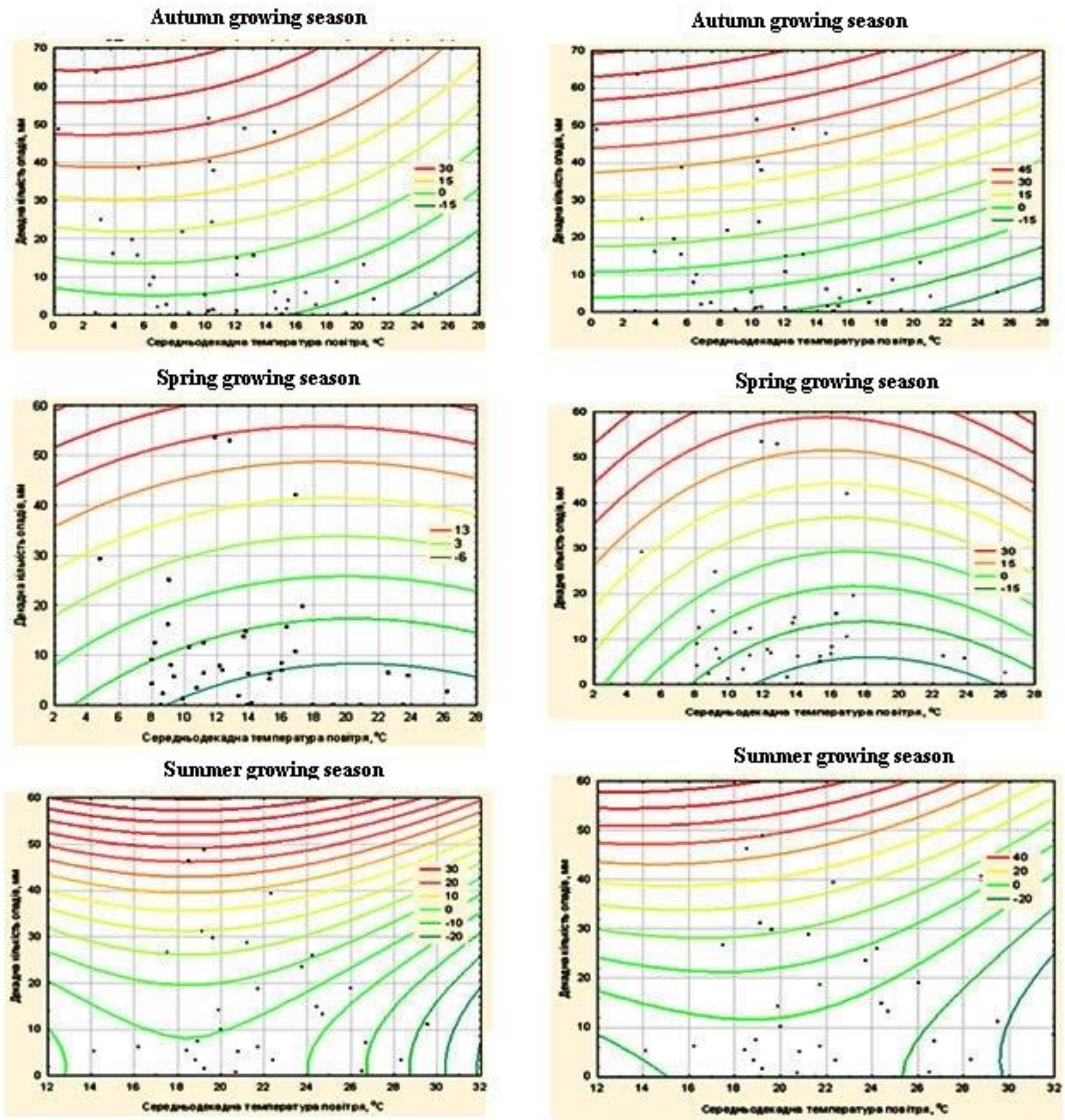
The results of the author's verification show that their reliability in the vast majority exceeds 80 %. Quantitative dependencies and models of hydrothermal indicators' influence on moisture reserves in soil layers 0–20, 0–50, and 0–100 cm were investigated per decade. Average decadal air temperature and decadal precipitation were used as input variables. The dynamics of soil moisture reserves (*ΔWn*) was estimated as the difference between the values of the current decade (*Wn*) and the previous one (*Wn–1*):

$$\Delta Wn = Wn - Wn{-}1$$

The determination coefficient (*R2*) of the established mechanism, depending on the estimated soil layer and the crop growing season, ranges from 0,82 to 0,94.

Graphical models for evaluating the dynamics of soil moisture reserves under winter wheat were investigated on soil layers 0–20, 0–50 and 0–100 cm (Fig. 1).

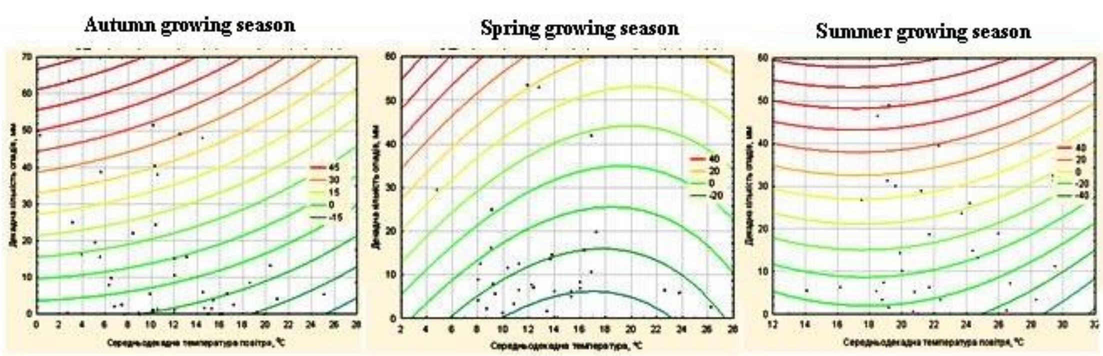
The results of the analysis of independent input and output information regarding the actual reserves of productive moisture in the soil at a depth of 0–20 and 0–100 cm for the period from 2018 to 2021, using the data from a weather station located in the city of Kherson, confirmed the high reliability of the developed models (Figure 2). Figure 2 illustrates the results of verification of the models used to forecast changes in productive moisture reserves in the soil under winter wheat in the period from 2018 to 2021, according to the data of the Kherson weather station.



0–20 cm

0–50 cm

Fig. 1. Graphical models for evaluating the dynamics of soil moisture reserves under winter wheat in the 0–20, 0–50, and 0–100 cm soil layer



0–100 cm

Fig. 2. Results of verifying models of changes in productive moisture reserves in the soil under winter wheat (Kherson meteorological station, 2018–2021)

The obtained results allow us to conclude that it is possible to determine the expected changes in soil moisture reserves during the decade, based on the analysis of actual and simulated data, given the forecast air temperature and the expected amount of precipitation. This approach enables users to calculate expected moisture reserves at the end of a specified period, given a reliable meteorological forecast. When having actual data on soil moisture reserves at the beginning of calculations, the calculation process remains unchanged, and the actual values of moisture reserves are taken as the basic values. This approach increases the accuracy and reliability of soil moisture forecasts and is important for agricultural resource management and decision-making in agriculture.

Conclusions. It was established that the correlation analysis of hydrometeorological factors affecting the formation of soil moisture reserves shows a significant influence of initial moisture reserves on their amount in subsequent periods (correlation coefficient varies from 0,45 to 0,84). The dependence of soil moisture reserves on air temperature is averagely significant, and the general trend shows a decrease in the direct influence of the temperature regime with an increase in the depth of the calculated soil layer.

The investigated dependences and models of the dynamics of water availability for winter wheat in the south of Ukraine, considering the condition of crop sowing area and hydrothermal conditions of the growing season in the soil layers 0–20, 0–50 and 0–100 cm per a decade, have a determination coefficient (*R2*) ranging from 0,82 to 0,94. Verification of the accuracy of the above models when using independent data for 2017–2020 proved their reliability. The average error between actual and calculated data did not exceed +13,5 %.

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УДК 633.854.54;633.854

ОСОБЛИВОСТІ ФОРМУВАННЯ ВОЛОГОЗАБЕЗПЕЧЕННЯ ПШЕНИЦІ ОЗИМОЇ НА ПІВДНІ УКРАЇНИ

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Анотація. *У статті досліджується важливість урахування низки факторів, які впливають на водний режим ґрунту у контексті розробки моделей для прогнозування запасів продуктивної вологи в ґрунті. Встановлено, що основні фактори, такі як тип ґрунту, його щільність та механічний склад, залишаються сталими у різних ґрунтово-кліматичних регіонах України. Друга група факторів, таких як температура повітря, опади та вологість ґрунту, піддаються змінам упродовж вегетаційного періоду та навіть коротких проміжків часу. Тому подальшими обчисленнями враховано динаміку вологості ґрунту як функцію основних змінних, таких як середня температура повітря та кількість опадів. Для більш точного прогнозування запасів вологи на кінець визначеного періоду використовують початкові запаси вологи, а також гідротермічні умови, розглянуті як предиктори у рівнянні регресії. Достовірність проведених досліджень підтверджується аналізом незалежної вхідної та вихідної інформації з метеостанції м. Херсон у період з 2018 по 2021 рр. щодо фактичних запасів продуктивної вологи в ґрунті на глибині 0–20, 0–50 та 0–100 см. Середня похибка між фактичними та розрахунковими даними не перевищувала +13,5 %. Це підтверджує надійність та прецизійність проведеного дослідження, роблячи його основою для подальших аналізів і висновків. У висновках відзначено необхідність точного визначення вологості ґрунту з метою ефективного управління агрометеорологічними умовами та оптимізації врожайності сільськогосподарських культур. Автори підкреслюють, що науково-дослідна робота, яка лягла в основу цієї статті, здатна зробити вагомий внесок у розвиток сучасних підходів до вологозабезпечення у галузі сільського господарства та агрометеорології. Це сприятиме поступовому та вдосконаленому розвитку методології прогнозування вологості ґрунту, що є ключовим для забезпечення стійкого та продуктивного розвитку сільського господарства.*

Ключові слова: *водний режим ґрунту, прогнозування вологозапасів, моделювання, фактори впливу, гідротермічні умови, врожайність, сільське господарство, зміна клімату*

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CORN FOR GRAIN IN CONTINUOUS GROWING UNDER DIFFERENT FERTILIZER SYSTEMS AND WEATHER CONDITIONS

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Abstract. *On the experimental field of the Poltava State Agricultural Experimental Station named after M. I. Vavilov of the The Institute of Pig Breeding and Agro-Industrial Production of the National Academy of Agrarian Sciences of Ukraine, during 1984-2023, on typical chernozem in conditions of unstable moisture of the Left-Bank Forest-Steppe, were conducted researches to study the continuous growing of corn for grain and its productivity. Precipitation is the leading factor in providing corn with available moisture in this region. Different hydrothermal conditions, especially the amount of moisture during the agricultural year and the vegetation, led to sharp fluctuations in grain yield over the years, which occurred in a wide range. The analysis of the average values of corn productivity for each 10 consecutive years of conducting these studies made it possible to establish that during the first decade of observations, the dynamics of this indicator in subsequent periods took place in the paradigm of its growth, albeit at a different level. Maize grain yield and its correlation with different weather conditions and fertilization systems, regardless of the replacement of maize hybrids, ranged from direct to inverse and from low to high. Long-term application of different doses and ratios of organic and mineral fertilizers contributed to changes in both quantitative and qualitative indicators of humus in the soil. It was determined that the content of total carbon in the fertilized areas was higher by 3,0 and 3,3 relative percent compared to the unfertilized ones. Special attention was paid to the ratio between humic and fulvic acids, which directly depends on the fertilization system. The different effect of this agrotechnical measure on the amount of humus accumulation in the soil is shown. Thus, in areas without fertilizers (control), its accumulation occurs at the level of an average indicator and a weak effect of organic acids on the mineral part of the soil, while under the organo-mineral fertilization system, this process takes place intensively, and the mineral part remains almost unchanged.*

Key words**:** *corn, continuous growing, hydrothermal conditions, productivity, humus, humus accumulation*

Relevance of research. The formation of sustainable agrosystems in agriculture is closely related to the optimization of the structure of crop rotations and the system of fertilization and soil cultivation [1–5].

In recent years, the specialization of farms has significantly narrowed, agriculture production has focused on the cultivation of certain economically attractive crops. The consequence of this transformation was systemic changes in the structure of crop rotations and their transition to short-rotational and repeated crops, especially corn, which many farmers sow in one field for several years [6–8].

Maize (Zea mays L.) is the most productive among all-purpose cereal crops. In the world, about 20 % of corn grain is used for food purposes, 15–20 % for technical purposes, and 60–65 % for fodder purposes [9, 10].

Analysis of recent research and publications. According to previous studies, corn has the ability to grow on the same plot as a monoculture without reducing productivity, as well as in crop rotations with a short rotation, subject to compliance with all technological elements of its cultivation [11–13].

At the same time, the generalization of the research results of other domestic and foreign scientists does not allow us to draw unambiguous conclusions regarding the productivity of corn depending on the place of its placement and fertilization. Disagreements were revealed regarding the lack of nutrients, optimal physical properties, water-air regime, as well as other unfavorable indicators of the quality of the soil and the negative impact of pests and diseases [14–15, 18]. Because of this, long-term experiments with monoculture of corn in the conditions of global climate change on the planet are widely represented in many countries of the world. The results of such studies can be one of the elements in solving the problem of short-rotational crop rotations [5, 12–17]. Inadequate accumulation of available soil moisture plays an important role in crop growth, development and formation, and in some dry years crop productivity is completely dependent on it.

Solving the problem of soil organic matter occupies one of the main places in agricultural science and is gaining more and more applied importance.

Humus is the most important component of soil organic matter. It is an integral indicator of its fertility, which, together with its mineral part, forms an absorption complex and determines the physico-chemical and physical absorption capacity, improves water permeability, heat capacity, moisture retention capacity, nutritional regime, microbiological activity of the soil [18–20].

The purpose of the research is to identify and conduct a comparative evaluation of the long-term application of fertilizers during the continuous cultivation of corn for grain on its productivity, group and fractional composition of typical chernozem humus under different weather conditions. From a practical point of view, the results of such studies make it possible to predict the level of productivity of the crop and to grow it in short-rotational crop rotations or without changes until a certain time.

Research materials and methods. Research on the continuous growing of corn for grain at the experimental field of the Poltava State Agricultural Research Station named after M. Vavilov of the Institute of Pig Breeding and Agro-Industrial Production of the National Academy of Agrarian Sciences of Ukraine has been held since 1964 [21].

The soil of the experimental field is a typical medium-humus heavy loam chernozem on a loess rock. It is characterized by the following main agrochemical and agrophysical indicators: humus content – 3,9–4,2 %; easily hydrolyzed nitrogen (according to Tyurin and Kononova) – 119,1–127,1 mg/kg; P_2O_5 in acetic acid extract (according to Chirykov) – 100,0–131,0 mg/kg; exchangeable potassium (according to Maslova) – 171,0–200,0 mg/kg of soil. Soil density is 1,05–1,17 g/cm^3. The eotal porosity is 55,5–59,8. Field moisture content – 29,7–31,5 %. The total moisture content is about 39 %. The range of active moisture is about 25 mm. The moisture content of the rupture of capillary bonds is 20–22 %.

Total study area – 8640 m^2, accounting area – 29,4 m^2. Three fold replications.

Fertilization scheme in the experiment:

1. Without fertilizers (control).
2. Manure 20 t/ha + +$N_{60}P_{40}K_{60}$ every year.
3. Manure 20 t/ha (once every 3 years) + $N_{51}P_{51}K_{55}$.

The technology for growing corn included cultivating the soil with disc tools to a depth of 8–10 cm after harvesting the crop. The main tillage is plowing to a depth of 24–25 cm. In the spring, harrowing was carried out in 2 rows with heavy tooth harrows, the first cultivation at 4–5 cm, the pre-sowing at 6–7 cm. After that, corn was sown in a wide-row method with a row spacing of 70 cm using a precision seed drill with a sowing rate of 60,000 grains per 1 ha. During the growing season, inter-row loosening was carried out.

In the experiment, zoned varieties and hybrids of corn were grown: 1964–1974 Bukovynskyi 3; 1975–1987 Zherebkivskyi 86 MV; 1988–2001 Dniprovsky 273 MV; 2002–2005 Cadre 267 MV; 2006–2012 Podilskyi 274 MV; since 2013 – hybrid Orzhitsa 273 MB.

The protection system provided for the application of herbicides for weed control, particu-larry, soil applicable Proponit (propizachlor, 720 g/l) – 3,0 l/ha, and for vegetation in the phase of 5-6 leaves with tank mix Milagro 040 SC (dr. nicosulfuron, 40 g/l) – 1,25 l/ha + Prima (2,4D 2-ethylglyxyl ether 300,0 g/l and florisulam 6,25 g/l) – 0,4 l/ha with a working fluid consumption of 250 l/ha. The harvest was recorded manually, and the grain in each plot was weighed with an adjustment for the standard moisture content (14 %). The grain moisture content during harvesting was determined using the thermostat-weight method, the total area was collected using a combination of grinding and leaving by-products in the field.

Research results and their discussion. In Poltava region, as in most regions of Ukraine, one of the limiting factors of high productivity of crops is the amount of moisture reserves in the soil. The main source of providing rainfed crops with this natural component is precipitation. The hydrothermal conditions that formed during the years of observation were quite diverse both during the agricultural year in general and during the growing season in particular (Table 1).

Thus, the lowest air temperature during the full vegetation of corn, as well as during the critical period of its growth and development (the phase of shedding the panicle), and during the agricultural year in general, was observed in the first decade – 18,9; 21,0; 8,2 °C, and the highest during these periods in 2014–2023 – 20,5; 23,2; 9,5 °C. At the same time, the largest amount of precipitation during these periods of time was recorded in the second decade – 222,0; 70,8; 571,6 mm, and the smallest in the first – 194,8; 37,3; 457,8 mm.

Variability of corn grain yield under unchanged sowing and different fertilization systems occurred within wide limits (Table 2). The analyzed average productivity of this crop throughout the entire period of research within hybrids showed that the lowest among hybrids was observed on unfertilized plots in Dniprovskyi 273 MV (1988–2001) – 3,51 t/ha, and on fertilized ones in Zherebkivskyi 86 MV (1975–1987): manure: 30 t/ha every year + $N_{60}P_{40}K_{60}$ – 4,27 t/ha and manure 30 t/ha + 1 time in 3 years + $N_{51}P_{51}K_{55}$ – 4,37 t/ha. And it was the highest in the hybrid Kadr 267 MV (2002–2005) and, according to the variants of the experiment, was 6,63; 6,92; 7,06 t/ha, while on average for 46 years of observations, these indicators were equal to 4,55; 5,43; 5,63 t/ha.

The interval range between the maximum and minimum yield of corn grain, under different fertilization systems, respectively, was within the following limits: Zherebkivskyi 86 MW – 198,6; 294,3; 246,8; Dniprovsky 273 MW – 355,1; 377.4; 447,9; Cadre 267 MV – 160,0; 116,0; 110,6; Podilsky 274 MW – 403,8; 237,6; 121,1; Orzhitsa 273 MV – 172,2; 119,6; 112,4 %. The highest, this indicator, both for the control without fertilizers and for the application of mineral fertilizers on the background of manure, was observed in Dniprovsky 273 MB, and the lowest – in Kadra 267 MB. In such corn hybrids as Kadr 267 MV, Podilskyi 274, Orzhitsa 273 MV, fertilizers contributed to the reduction of the gap between their maximum and minimum productivity, and in Zherebkivskyi 86 MV and Dniprovskyi 273 MV – to an increase.

Calculations and analysis of research results made it possible to establish the dynamics of the productivity of this crop not only for the years of growing hybrids, but also for every 10 consecutive years of conducting this experiment. The lowest grain yield was observed in 1984-1993 and in the control (without fertilizers) it was equal to 3,22 t/ha, and in the options: manure 30 t/ha every year + $N_{60}P_{40}K_{60}$ – 4,51 t/ha and manure 30 t/ha ha + once every 3 years + $N_{51}P_{51}K_{55}$ – 4,66 t/ha. In the next 3 decades (1994–2003, 2004–2013, and 2014–2023), these indicators not only did not decrease, but even increased by 29,8, respectively, compared to the first decade; 11,8; 9,2 % and 62,1 %; 38,8; 42,3 and 45,0; 35,5; 33,3 %.

Therefore, the dynamics of this indicator to the first decade in subsequent years of observation took place in the paradigm of its growth, albeit at a different level.

Mathematical analysis of the data obtained from the results of research on the yield of corn grain and the effect on this indicator of different fertilization systems and weather conditions for the agricultural year in general and for the vegetation phases of its plants showed that the correlation between them covered a wide range from direct to inverse and from low to high.

Thus, the correlation coefficient between the indicators of corn productivity and the temperature regime during the growing season under different fertilization systems, control (without fertilizers), manure: 30 t/ha every year + $N_{60}P_{40}K_{60}$, manure 30 t/ha + once in 3 years +

1. Hydrothermal conditions during the research

Years	Weather conditions					
	Average air temperature, °C			Precipitations, mm		
	vegetation period	critical period	for the agricultural year	vegetation period	critical period	for the agricultural year
1984–1993	18.9	21.0	8.2	194.8	37.3	457.8
1994–2003	19.2	22.3	8.2	222.0	70.8	571.6
2004–2013	19.3	23.0	9.2	207.0	45.8	510.7
2014–2021	21.2	23.6	8.8	208.9	31.6	527.3
Average	*19.7*	*22.5*	*8.6*	*208.2*	*46.4*	*516.9*

2. The level of productivity of corn per grain under unchanged cultivation under different fertilization systems (t/ha)

Time period (10 years)	Hybrid	Years of cultivation	Duration of cultivation, years	Productivity level	Fertilization system					
					without fertilizers (control)		manure30 t/ha per year + $N_{60}P_{40}K_{60}$		manure 30 t/ha once every 3 year + $N_{51}P_{51}K_{55}$	
					for the entire period of hybrid cultivation	average for 10 years	for the entire period of hybrid cultivation	average for 10 years	for the entire period of hybrid cultivation	average for 10 years
	Zherebkivskyi 86 MV	1975–1983	13	max	4,39		6,23		5,34	
1984–1993	Zherebkivskyi 86 MV	1984–1987		min	1,47	3,22	1,58	4,51	1,54	4,66
				average	3,58		4,27		4,37	
	Dniprovsky 273 MV	1988–1993	14	max	4,87		5,92		6,63	
1994–2003	Dniprovsky 273 MV	1994–2001		min	1,07	4,18	1,24	5,04	1,21	5,09
				average	3,51		4,62		4,81	
	Cadre 267 MV	2002–2003	4	max	7,93		8,10		8,36	
2004–2013	Cadre 267 MV	2004–2005		min	3,05	5,22	3,75	6,26	3,97	6,63
				average	6,63		6,92		7,06	
	Podilsky 274 MV	2006–2012	7	max	8,05		8,71		8,40	
				min	1,60		2,58		3,80	
				average	4,66		5,98		6,47	
	Orzhitsa 273 MB	2013	11	max	6,56	4,67	7,38	6,11	7,52	6,21
2014–2023	Orzhitsa 273 MB	2014–2023		min	2,41		3,36		3,54	
				average	4,36		5,35		5,48	

$N_{51}P_{51}K_{55}$ was respectively at low level: r = 0,25; 0,18; 0,15, while for the critical period of plant growth and development and the full agricultural year, respectively, at high: r = 0,79; 0,71; 0,66 and r = 0,87; 0,93; 0,94.

A completely different correlation dependence was observed between the level of corn grain yield, organo-mineral fertilization systems and the amount of precipitation. If, in general, during the growing season and the agricultural year, these indicators were at an average level in control, the correlation coefficient was 0,43 and 0,45, and in the fertilized variants it was low, respectively r = 0,24; 0,15 and 0,26; 0,17, then already during the critical period of its development, their values were as follows: r = 0,13; −0,01; −0,06.

Long-term use of different doses and ratios of organic and mineral fertilizers contributed to changes in the soil's quantitative and qualitative indicators of humus (Table 3).

It was found that the content of total carbon in the soil in unfertilized plots was equal to 3,01 %, while in fertilized (30 t/ha every year + $N_{60}P_{40}K_{60}$) and (manure 30 t/ha + 1 time in 3 years + $N_{51}P_{51}K_{55}$) it was higher and, respectively was equal to 3,11 and 3,10 %.

Agrochemical analysis of the soil to determine the group and fractional composition of humus showed the unequal influence of fertilization systems on the number of humic and fulvic acids fractions in percentages, as individually and in their sums. On plots without fertilizers (control), the sum of fractions of humic acids was 32,8 %, and on fertilized plots (30 t/ha every year + $N_{60}P_{40}K_{60}$) – 44,3 % and (manure 30 t/ha + 1 time in 3 years + $N_{51}P_{51}K_{55}$) – 43,9 %. Fulvic acid according to fertilization systems – 67,0; 43,9 and 44,1 %.

Separately, it is worth paying attention to the ratio between humic and fulvic acids. As is known, the overall activity of humic acids relative to the mineral part of the soil depends on the value of this indicator. The observations made it possible to establish that in plots without fertilizers (control), this value was at the level of 0,49, and led to an average rate of humus accumulation and a weak effect of organic acids on the mineral part of the soil. Another regularity was observed for organo-mineral fertilization systems, where the ratio between these organic acids was at the level of 1,01 and 1,00, which shows an intensive accumulation of humus in the soil, and the mineral part remains almost unchanged.

Conclusions. The weather conditions over 39 years of observations have been quite diverse. The average air temperature for the agricultural year from 1984 to 1993 corresponded to the value of 8,2 °C, and from 2004 to 2013 – 9.2 °C and from 2014 to 2023 – 9,5 °C, while precipitation respectively – 457,8 mm, 510,7 mm, 577,2 mm.

Corn hybrids grown in a permanent crop have different average productivity by year, which largely depends on weather conditions and fertilization systems. The variability of the average yield of corn grain, its level over a decade under unchanged cultivation and different fertilization systems occurred within wide limits and depended to a lesser extent on the research period. The correlation between corn productivity to different fertilization systems and weather conditions ranged from direct to inverse and from low to high.

In unfertilized areas, humus accumulates moderately, and the effect of organic acids on the mineral part of the soil is weak, while in fertilized areas, humus accumulates intensively, and the mineral part remains constant.

3. The influence of different fertilization systems on the group and fractional composition of typical heavy loamy chernozem humus under unchanged grain corn cultivation (soil layer 0–20 cm)

The fertilization system	Carbon (C) general,%	Humic acids, fractions, %				Fulvic acids, fractions, %					Humin, %	Ratio humic acids / Ratio fulvic acids
		1	2	3	sum	1[a]	1	2	3	sum		
Without fertilizer (control)	3,01	4,9	20,2	7,7	32,8	8,9	12,6	23,9	21,6	67,0	29,9	0,49
Manure 30 tons/ha every year + + $N_{60}P_{40}K_{60}$	3,11	5,5	30,9	7,9	44,3	6,6	8,7	21,5	13,7	43,9	33,6	1,01
Manure 30 tons/ha Once every 3 years + + $N_{51}P_{51}K_{55}$	3,10	5,2	30,2	8,5	43,9	4,9	7,9	17,1	14,2	44,1	32,4	1,00

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КУКУРУДЗА НА ЗЕРНО У БЕЗЗМІННОМУ ПОСІВІ ЗА РІЗНИХ СИСТЕМ УДОБРЕННЯ ТА ПОГОДНИХ УМОВ

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Анотація. *На дослідному полі Полтавської державної сільськогосподарської дослідної станції ім. М. І. Вавилова Інституту свинарства і агропромислового виробництва НААН України упродовж 1984–2023 рр. на чорноземі типовому в умовах нестійкого зволоження Лівобережного Лісостепу проводили дослідження з вивчення беззмінного вирощування кукурудзи на зерно та її продуктивність. Провідним фактором забезпечення рослин кукурудзи доступною вологою у цьому регіоні є атмосферні опади. Різні гідротермічні умови, особливо кількість вологи за сільськогосподарський рік та вегетаційний період, призвели до різкого коливання врожайності зерна за роками, яке відбувалося у широкому діапазоні. Аналіз середніх величин продуктивності кукурудзи за кожні 10 послідовних років проведення цих досліджень дав можливість встановити, що за перше десятиріччя наших спостережень динаміка цього показника у наступні періоди відбувалася у парадигмі його зростання хоч і на різному рівні. Урожайність зерна кукурудзи та її кореляційний зв'язок з різними погодними умовами і системами удобрення, незалежно від заміни гібридів кукурудзи, перебувала у діапазоні від прямого до оберненого та від низького до високого. Довготривале застосування різних доз та співвідношень органічних і мінеральних добрив сприяло зміні як кількісних, так і якісних показників гумусу у ґрунті. Визначено, що на удобрених ділянках вміст загального вуглецю щодо неудобрених був більшим на 3,0 і 3,3 відносного відсотка. Особлива увага була приділена на співвідношенню між гуміновими і фульвокислотами, яке напряму залежить від системи удобрення. Показано різну дію цього агротехнічного заходу на величину гумусонакопичення у ґрунті. Так, на ділянках без добрив (контроль) його акумулювання відбувається на рівні середнього показника та слабкої дії органічних кислот на мінеральну частину ґрунту, тоді як за органо-мінеральної системи удобрення цей процес проходить інтенсивно, а мінеральна частина залишається майже беззмінною.*

Ключові слова: *кукурудза, беззмінний посів, гідротермічні умови, продуктивність, гумус, гумусонакопичення*

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THE EFFECT OF DIFFERENT LIME RATES ON THE YIELD AND QUALITY OF WINTER WHEAT UNDER MINERAL FERTILIZATION ON A SOD-PODZOLIC SOIL

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Abstract. *Stable productivity, essential for winter wheat as a strategic crop, can only be achieved by meeting its growth and development requirements, especially nutrition. Soddy-podzolic soils, typically highly acidic in their natural state, are unsuitable for realizing winter wheat's full yield potential. Combined fertilizer and lime application is a key factor for grain yield and quality. While lime (CaCO3) is widely used to reclaim acidic soils, determining the optimal application rate, particularly in combination with mineral fertilizers, is crucial. This research investigated the effect of applying 0,5–2,0 lime norms based on soil hydrolytic acidity (Hh, mmol/100 g) combined with a moderate norm of N60P60K60 mineral fertilizers on winter wheat grain yield and quality. The soil had an initial pHKCl of 4.8 and a hydrolytic acidity of 2,3 mmol/100 g of soil. Field, laboratory, calculation, statistical, and generalization methods were employed. The experiment revealed the lowest grain yield in the control and N60P60K60 treatments without liming. Lime application at various rates with N60P60K60 increased grain yield by 0,74–0,89 t/ha compared to the control, with the 1,5 CaCO3 norm by Hh achieving the best results. The application of 2,0 norms of CaCO3 led to a statistical decrease in yield by 0,14 t/ha (p≤0,05) due to a reduction in available nutrient compounds in the soil. Liming also affected the main indicators of grain quality of winter wheat. An increase to the control was found for the weight of 1000 grains and protein content, while the actual weight of the grain decreased. As the most optimal treatment, regarding grain quality, was found out the option of 1,0 CaCO3 norm based on soil hydrolytic acidity in combination with N60P60K60, with the winter wheat grain yield of 3,54 t/ha and an increase in the protein content in it by 6,8 % to the background.*

Key words: *winter wheat, liming, mineral fertilizers, yield, protein, grain nature, grain weight*

Relevance of research. Acidic soils are a significant problem for Ukrainian agriculture, especially in the Polissia zone, where sod-podzolic soils predominate, with a soil reaction of 4,4–5,5 units. The main reasons for the formation of this acidic environment include the leaching type of soil water regime, low carbonate content in the parent rock, human activities such as the application of physiologically acidic mineral fertilizers, environmental pollution, acid rain, and an imbalance of calcium in soils. Global climate change and the spread of calciphilic crops in Polissia further intensify these negative acidification processes [1].

Liming, which restores soil pH to optimal ranges for crops, is an important agronomic measure to increase crop yields, particularly for winter wheat. This crop best realizes its potential productivity at pH 6,5–7,2. Losses in crop production due to excessive soil acidity exceed 2,0 million tons of grain annually, with an estimated cost of UAH 10–12 billion [2].

Maintaining an optimal pH level improves the physical and chemical properties of the soil, stimulates microbial activity and increases the availability of nutrients [3]. Liming can have a complex effect on soil organic matter. Research by Malynovska [4] shows that it both weakens the mineralization process and stimulates overall biological activity in the soil. Specifically, the study found that liming decreased the mineralization of soil organic matter: without mineral fertilizer – by 2,1 times, with mineral fertilizer – by 4,07 times, and against the background of plowing green manure biomass and by-products of the predecessor – by 1,36 times.

Analysis of the latest research and publications. Studies by domestic and foreign scientists show that the liming of acidic soils can lead to a significant increase in winter wheat yields. Polovyi V. and Yashchenko L. [5] found that applying $N_{120}P_{60}K_{90}$ increased wheat grain yield by 1,04 t/ha compared to the control. However, this increase was not enough to be economically beneficial for acidic sod-podzolic soils. The researchers found that only the combined use of fertilizers and limestone materials provided a significant yield increase in their experiment. Warner J. et al. [6] indicate that a change in pH from 5,5 to 6,5 increases wheat grain yield by 22 %, and at lower levels, the use of nitrogen fertilizers is less cost-effective.

Jelic M. et al. [7] found that the combined use of $N_{120}P_{100}K_{60}$, 5 t/ha of lime ($CaCO_3$), and 20 t/ha of manure significantly reduces aluminum levels in grain and increases winter wheat yield. Similar results were obtained by Chauhan N. et al. [8], who recorded the highest wheat yield (2.8 t/ha) with the recommended fertilizer rate (120 kg N, 26 kg P, 25 kg K) combined with 10 t/ha of manure, although it was statistically comparable to the NPK + lime variant (2,6 t/ha). These studies collectively demonstrate that the integrated use of lime together with chemical fertilizers is crucial for both maintaining the productivity of acidic soils and improving the quality of winter wheat products [9].

Despite the proven effectiveness of liming, some farmers hesitate due to the upfront cost of limestone materials. However, liming is a long-term investment that not only significantly increases winter wheat yields in the current year, but also improves soil fertility for many years to come, ultimately leading to greater returns on investment.

The purpose of the study is to investigate the response of winter wheat yield to different norms of lime: this will allow us to develop recommendations for optimizing its use and increasing the efficiency of agricultural production on acidic sod-podzolic soils.

Materials and methods of research. To evaluate the response of winter wheat to different rates of lime, the field experiment on the sod-podzolic soil of Western Polissia, employed the following treatments:

1. Control (without fertilizers).
2. $N_{60}P_{60}K_{60}$ – background.
3. Background + 0,5 norms of $CaCO_3$ by hydrolytic acidity (Hh) (0,5 $CaCO_3$).
4. Background + 1,0 norm of $CaCO_3$ by Hh (1.0 $CaCO_3$).
5. Background + 1,5 norms of $CaCO_3$ by Hh (1,5 $CaCO_3$); 6. Background + 2,0 norms of $CaCO_3$ by Hh (2,0 $CaCO_3$).

Winter wheat was grown in an 8-month crop rotation, with alfalfa as a predecessor. The soil of the experimental plot was sod-podzolic sandy, characterized by the following agrochemical parameters: humus content 1.2 %, mobile nutrients (mg/kg soil): P_2O_5 (according to Kirsanov) – 62,0; K_2O (according to Kirsanov) – 75,0, pH_{KCl} – 4,8; hydrolytic acidity – 2,3 mmol/100 g of soil; degree of saturation with bases – 62 %.

The area of the plots in the experiment was 198 m^2 (33×6) and 100 m^2 (25×4). Replication: three times.

Mineral fertilizers were applied in the form of ammonium nitrate, granular superphosphate, and potassium chloride. Phosphorus-potassium fertilizers were applied for autumn plowing, nitrogen fertilizers – half the norm for plowing, and the rest in spring as fertilizing. Chemical reclamation was carried out by ground lime with an active ingredient content in terms of $CaCO_3$ of 83,7–92,1 %.

The grain harvest was recorded by continuous mowing and weighing from the recorded area. Grain quality was determined according to generally accepted methods [10]. The statistical difference of the data was determined using a one-factor ANOVA analysis with the subsequent calculation of Fisher's test at $p \leq 0{,}05$.

Research results and discussion. The application of various chemical amendments and fertilizers can create variations in the growing environment for winter wheat plants. These factors significantly impact plant nutrition, ultimately affecting crop yields [11].

Research has shown that applying mineral fertilizers at $N_{60}P_{60}K_{60}$ rates without liming can decrease soil fertility. This decline is caused by the acidifying effect of these fertilizers, which deteriorates the soil's physical and chemical properties. Consequently, the crop yield obtained with $N_{60}P_{60}K_{60}$ without liming (2,62 t/ha) was statistically similar to the yield achieved with the natural fertility of sod-podzolic soil (Table 1).

Liming significantly increased crop productivity compared to both the control and the background. However, different rates of lime provided different yield increases in both absolute and relative units. The use of 0.5 $CaCO_3$ on the $N_{60}P_{60}K_{60}$ background contributed to a 29.4 % increase in yield compared to the background. Further increase in the lime rate provided a statistically significant difference in yield only at 1.5 $CaCO_3$.

The yield increase compared to the control was 1,08 t/ha or 40,8 %. When applying 2,0 $CaCO_3$, grain yield decreases compared to the previous variant.

1. Average yield of winter wheat in crop rotation at different norms of lime on sod-podzolic soil

Treatments	Grain yield, t/ha	Yield to control ratio	
		t/ha	%
Control (without fertilizers)	2,65	–	–
$N_{60}P_{60}K_{60}$ – background	2,62	–0,3	–
Background + 0,5 $CaCO_3$	3,39	0,74	27,9
Background + 1,0 $CaCO_3$	3,54	0,89	33,6
Background + 1,5 $CaCO_3$	3,73	1,08	40,8
Background + 2,0 $CaCO_3$	3,59	0,89	35,5
LSD_{05}	0,13		

Gospodarenko G. and O. Karnaukh [12] explain this by the occurrence of microelements due to the increased amount of calcium that enters the soil with limestone material. Excessive amounts of calcium supplied with a high rate of lime can reduce the availability of a number of nutrients for plants, which causes their deficiency in crop nutrition, especially when their content in the soil is low.

Liming of soddy-podzolic soil affected the quality indicators of winter wheat products (Table 2).

Important technological indicators of wheat grain quality that affect the milling and baking properties of the grain are the weight of 1000 grains, the nature of the grain, and the protein content. The weight of 1000 grains is to a greater extent a genetic trait of the wheat variety. In the experiment, this criterion ranged from 37,0–39,1 g. Depending on the norm, liming increased the weight of 1000 grains compared to the background by 3,8–7,9 relative %. The highest absolute weight index was obtained under the application of 2,0 rates of $CaCO_3$ – 39,9 g. It should be noted that there was no statistical difference between the weight of 1000 grains in the variants with 1,0 and 1,5 norms of lime.

It was determined that the application of 0,5–2,0 lime norms decreased the actual grain weight by 0,7–2,0 %, which was within the error of the experiment. This is due to the formation of a larger number of grains, which become less filled. A significant decrease in the natural weight was obtained against the background of mineral fertilization compared to the control and variants with lime.

The protein content of wheat grain is significantly affected by the level of nitrogen nutrition. In the experiment the introduction of $N_{60}P_{60}K_{60}$ contributed to an increase in protein content by 0,5 absolute % compared to the control. Compared to the background, 1,0 and 2,0 norms of $CaCO_3$ had a significant effect on increasing the protein content, while at a 1,5 Hh, norms this quality indicator decreased, which may be due to growth dilution for the formation of the highest grain yield in this variant.

Prospects for further research should focus on optimizing crop nutrition conditions to further increase winter wheat yield and grain quality. This could involve improving the soil nutrient profile and identifying economically viable fertilizer application norms.

Conclusions. When growing winter wheat on sod-podzolic soil with a medium acid reaction of the soil solution, liming is a prerequisite for increasing crop productivity. Based on the results obtained, the application of 1,5 norms of $CaCO_3$ on the background of $N_{60}P_{60}K_{60}$ resulted in 3,73 t/ha of winter wheat grain. However, taking into account the quality indicators, the best option should be considered the use of 1,0 norm of $CaCO_3$ established by the hydrolytic acidity of the soil, which contributes to grain yield at the level of 3,54 t/ha and an increase in protein content in grain by 6,8 % compared to the background.

2. Average quality indicators of winter wheat grain in crop rotation at different norms of lime on sod-podzolic soil

Treatments	1000 grain weight, g	Grain nature, g/l	Protein content, %
Control (without fertilizers)	38,4	750	11,8
$N_{60}P_{60}K_{60}$ – background	37,0	720	12,3
Background + 0,5 $CaCO_3$	38,4	745	12,1
Background + 1,0 $CaCO_3$	39,2	740	12,6
Background + 1,5 $CaCO_3$	39,2	735	12,2
Background + 2,0 $CaCO_3$	39,9	735	12,5
LSD_{05}	0,27	13,6	0,18

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РЕАКЦІЯ УРОЖАЙНОСТІ ТА ЯКОСТІ ПШЕНИЦІ ОЗИМОЇ НА РІЗНІ НОРМИ ВАПНА НА ДЕРНОВО-ПІДЗОЛИСТОМУ ҐРУНТІ

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Анотація. *Озима пшениця як стратегічна культура потребує стабільної продуктивності, якої можна досягти лише задовольняючи її потреби для росту та розвитку, особливо щодо живлення. Дерново-підзолисті ґрунти, які зазвичай мають підвищену кислотність ґрунтового розчину без додаткового поліпшення є малопридатними для реалізації потенціалу продуктивності пшениці озимої. Однією із основних умов формування урожайності та якості зерна є сумісне застосування добрив і вапнякових матеріалів. Найбільш широко для хімічної меліорації кислих ґрунтів застосовують вапно ($CaCO_3$), проте необхідним є визначення його оптимальної норми, особливо у поєднані з мінеральними добривами. Вихідний показник грунту pH_{KCl} 4,8 і гідролітична кислотність 2,3 ммоль/100 г ґрунту. Метою досліджень було встановити вплив 0,5–2,0 доз вапна визначених за показником гідролітичної кислотності ґрунту (Нг, ммоль/100 г ґрунту) у поєднанні з внесенням помірної норми мінеральних добрив $N_{60}P_{60}K_{60}$. Методи досліджень: польовий, лабораторний, розрахунковий, статистичний, узагальнення. Результати досліджень показали, що найнижча урожайність зерна пшениці озимої у досліді отримана у контролі та за внесення $N_{60}P_{60}K_{60}$ без вапнування. Застосування на фоні $N_{60}P_{60}K_{60}$ вапна у різних нормах сприяло підвищенню урожайності зерна на 0,74–0,89 т/га відносно контролю, кращою у цьому відношенні була 1,5 норми $CaCO_3$ за Нг. Внесення 2,0 норми $CaCO_3$ спричинило статистичне зниження урожайності на 0,14 т/га ($p \leq 0,05$). Вапнування також вплинуло на основні показники якості зерна пшениці озимої. Підвищення відносно контролю встановлено для маси 1000 зерен і вмісту білка, тоді як натурна маса зерна знизилася. Найбільш оптимальним із урахуванням показників якості зерна у досліді визнано варіант внесення 1,0 норми $CaCO_3$ встановленої за гідролітичною кислотністю ґрунту на фоні $N_{60}P_{60}K_{60}$ із урожайністю 3,54 т/га зерна пшениці озимої і підвищенням вмісту білка у ньому на 6,8 % відносно фону.*

Ключові слова: *пшениця озима, вапнування, мінеральні добрива, урожайність, білок, натура зерна, маса зерен*

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IMPROVING THE ASSESSMENT OF THE ECOLOGICAL STATE OF SURFACE WATERS BY SATELLITE DATA

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Abstract. *The article presents the results of research into the ecological state of surface waters using newly developed scientific approaches based on the use of high spatial resolution satellite data. The systematization of all available indicators and the development of new methodological approaches significantly improves the existing methodology for determining the ecological state of water bodies, which is the goal of research. In the studies of water bodies within the city of Kyiv, Obolon Bay and Lake Verbne, the optimal set of such indicators as spectral indices was determined, which made it possible to comprehensively assess the state of water bodies: NDWI – for distinguishing vegetation and water bodies, GCI – to assess the extent of blue-green algae, NDTI – to determine turbidity, IO – to determine the presence of soluble iron in water, NDSI – to assess the extent of flooding. According to the NDSI, NDWI indices and a combination of the red and infrared channels of the Sentinel-2 L2A satellite, the flooding of the floodplain of the Irpin River was traced, caused by the destruction of a hydraulic structure near the village of Kozarovichi. Wave abrasion of the shores was studied on the example of the Kremenchuk Reservoir near the villages of Pronozivka and Mozoliivka using Landsat4 (1984) and Landsat8 (2016) satellite images. The study of the reshaping of the coastline near the village of Tsybli in the Kyiv region used the method of determining spatio-temporal changes of the coastline as a result of its erosion. The assessment of spatio-temporal changes of the coastline should be carried out taking into account the water levels on the dates of the measurements. The conducted studies established that all the identified evaluation indicators can be grouped as biological, hydro morphological, and physicochemical, and it can be concluded that methodical approaches to assessing the ecological state of surface waters using satellite data are based on established cause-and-effect relationships of processes affecting water objects.*

Key words: *surface water, ecological condition, satellite data, spectral indicators, databases, spatiotemporal changes*

Relevance of research. The problem of deterioration of the ecological condition of water bodies due to significant anthropogenic load and changes in climatic conditions is acute enough for all river basins of Ukraine. Therefore, in 2020, the Institute of Water Problems and Land Reclamation of the National Academy of Agrarian Sciences of Ukraine developed methodological recommendations for assessing the ecological state of water bodies and reclaimed land based on spatially distributed satellite data [1], which was proposed to assess the state of surface waters according to individual indicators determined based on multispectral satellite images. Over time, new developed indicators for assessing the ecological state of surface waters were added, and the methodology needed improvement, especially regarding the systematization of the indicators themselves. The basis of the improved methodology was the existing methodology, which is based on the use of ground information and was approved by the Order of the Ministry of Environmental Protection and Natural Resources of Ukraine dated January 14, 2019 No. 5 "On approval of the Methodology for classifying a body of surface water, as well as a significantly changed body of surface water to one of the classes of ecological potential of an artificially or significantly changed body of surface water" [2]. In the algorithm for determining the state of the surface water body, the ecologically-chemical state is considered. Ecological state indicators are: biological, hydromorphological, chemical, and physicochemical. However, in satellite data use, chemical analysis of water is not considered separately, but only physicochemical with selection for laboratory chemical analysis of water samples to confirm its spectral characteristics. Therefore, suggested to use the algorithm of the approved methodology as a basic one, and to attract and increase the number of indicators that can be determined by satellite data. This article is dedicated to solving this problem.

Analysis of recent research and publications. The domestic and international community pays considerable attention to the problems of creating an effective surface water monitoring system using satellite data. Among the domestic scientific developments of recent years, the work of V.I. Zatserkovny (2018) [3] stands out, in which the development of separate technologies in the form of a surface water quality monitoring database, which is intended for data storage, description of the parameters of the investigated substances, their maximum permissible limits, is considered concentrations that meet the requirements of the EU Directive 2000/60 (paragraphs 39, 40), description of observation posts, passport data of water bodies, data analysis and forecasting of the further impact of pollutants on the environment, detection of extreme situations on a water body after technogenic disasters. It is worth noting the published scientific work of R. Keklyu, A. Alkish (2021) [4] on the creation of a new trophic level index using water quality parameters. The use of water indices for the identification of water bodies in the Kyiv region is described in detail in the work of V. Belenko (2023) [5] and O. Apostolov (2020) [6] for determining the sufficiency or lack of moisture in the territory according to the ERS (Earth Remote Sensing) data.

Among the foreign works, it is worth noting the work of Polish scientists K. Dyba, S. Ermid and others. (2022) on the development of a method for remote monitoring of water temperature in lakes in a spatio-temporal context based on Landsat8 images [7]. A combination of the time series analysis method and a simplified algorithm based on the Planck equation was proposed by Italian scientists to determine and analyze the surface temperature in the lakes of Central Italy (De Santis D., 2022) [8]. The work of scientists from many countries around the world is devoted to surface water pollution, in particular, M. Golizade (2016) [9]; H. Adzhov Ebenezer (2023) [10], etc.

Special attention is paid to the examination of the Copernicus program of the European Union created in 2011, which is the best example of international observation and decision-making systems using remote sensing of the Earth for all components of the environment. Information services are provided free of charge and open access to authorized users of the Copernicus Program. Specialists of the Institute of Water Problems and Land Reclamation of the National Academy of Agrarian Sciences actively use Copernicus as part of Google Earth Pro when downloading high spatial resolution images and using archives of Landsat and Sentinel images, as well as Land Viewer and Crop Monitoring. An example of this is the research on the effect of the explosion of the protective dam of the Kyiv Reservoir on the Irpin River basin using remote sensing of the Earth.

Analytical studies have determined that with the development of technologies for processing and presenting the results of satellite information analysis, methodological approaches to assessing the ecological state of surface waters based on satellite data have also changed. The literature review shows that research is mainly conducted to identify the deterioration of ecological situations and for this purpose, certain informative parameters are considered, such as water temperature, the presence of surface formations (specular reflection), concentrations of various substances dissolved and suspended in water (diffuse reflection): transparency, turbidity, color, soluble iron. The use of various indicators requires systematization, which, in general, corresponds to the problem we have established, and a conclusion was drawn about the need to improve the existing methodology for assessing the ecological state of water bodies based on satellite data.

The purpose of the research is to improve the assessment of the ecological state of surface waters based on satellite data.

Research methods and materials. In the analysis of satellite data, the energy and polarization characteristics of the own and reflected radiation of water and vegetation surfaces and the atmosphere are determined in various ranges of the electromagnetic radiation spectrum. In conducting research with satellite data, the passive method of remote sensing of the Earth, analytical analysis of scientific works, spectral and geospatial analysis, and system analysis were used, and soil surveys and experimental studies were carried out using generally accepted and certified methods.

The research methodology included the following components:

- searching for publicly available satellite information and analyzing the possibility of its application to the task;

• analytical analysis of scientific works on the established problem;

• calculations of spectral water and vegetation indices, comparison of channel combinations;

• carrying out field observations, taking water samples, and measuring transparency, turbidity (the content of suspended substances), color, and temperature of water;

• analysis of the results obtained and determination of changes occurring in water bodies.

During the monitoring, biological and hydromorphological indicators were determined using satellite data and field surveys, and conclusions were drawn about the ecological state of surface waters.

Research results and discussion. The main attention was paid to identifying possible and systematizing tested indicators characterizing the ecological state of surface waters according to satellite data using the example of water bodies with different hydromorphological characteristics. At the beginning of the research, there was a search for satellite images of high spatial resolution in the Google Earth Pro and Land Viewer software products open to users. These typically include archival Landsat and Sentinel imagery, for which spectral empirical metrics can be obtained through indices or channel combinations, as well as high-resolution Aerbus and Maxar imagery. The studies used indicators such as the NDTI (Normalized Difference Turbidity Index) [11], which assessed the development and scale of distribution of blue-green algae ("blooming" of water), its turbidity; NDWI (Normalized Difference Water Index) [12–14], which at small values showed the absence of vegetation, and at large values (greater than zero) – the presence of water; GCI (Green Chlorophyll Index), which showed the content of green chlorophyll in areas of "blooming" of blue-green algae and the overgrowing of the reservoir with taller aquatic and surface vegetation; IO (Index of iron oxide content), according to which the presence of soluble iron in water was determined; NDSI (Normalized Difference Snow Index) [15], which made it possible to record the scale of floods when snow melts.

The indicators were obtained in 2023 during the study of the ecological state of the waters of Lake Verbne (Fig. 1) and Obolon Bay (Fig. 2) within the city of Kyiv using Landsat8 and Sentinel2 satellites.

The obtained results were verified by ground surveys (Fig. 3), during which the following were measured: water temperature with a standard water thermometer, which is used on the network of the hydrometeorological service; transparency using a Secchi disk, as well as color, suspended solids concentration (turbidity) and soluble iron, which were evaluated from water samples collected in laboratory studies.

The results of surveys based on satellite data according to the colors of the legend of their values show that the average values of the indices within the area of the water surface of a water body are:

• in Obolon Bay NDTI 0–0,25; GCI 0,25–0,5; NDWI 0,1–0,2; IO -0,75;

• in Lake Verbne NDTI 0,25–0,5; GCI 0,5–0,75; NDWI 0,3–0,6; IO-0,5.

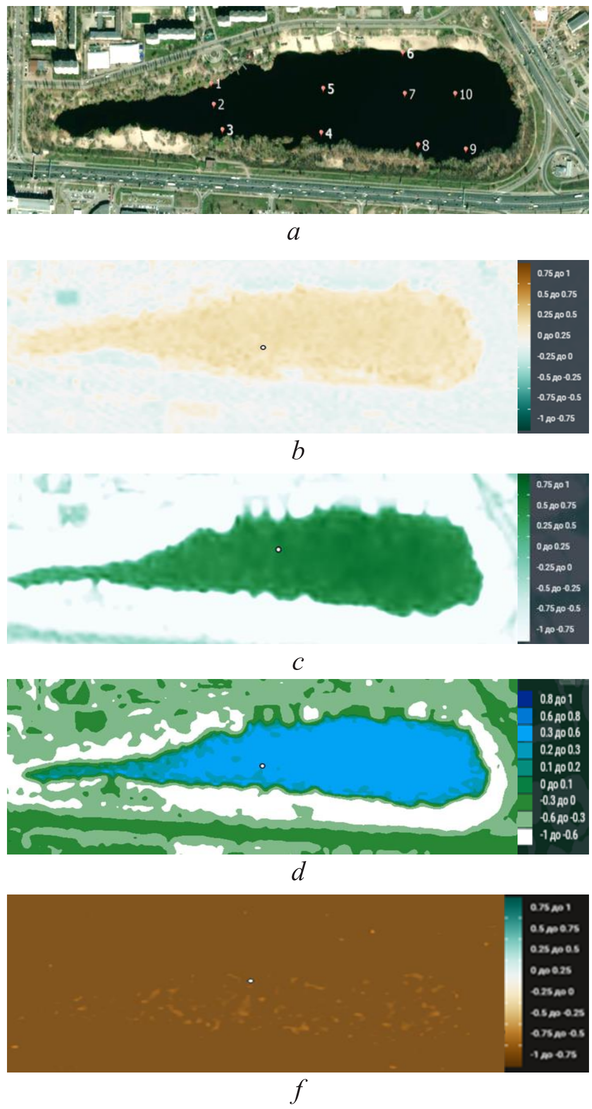
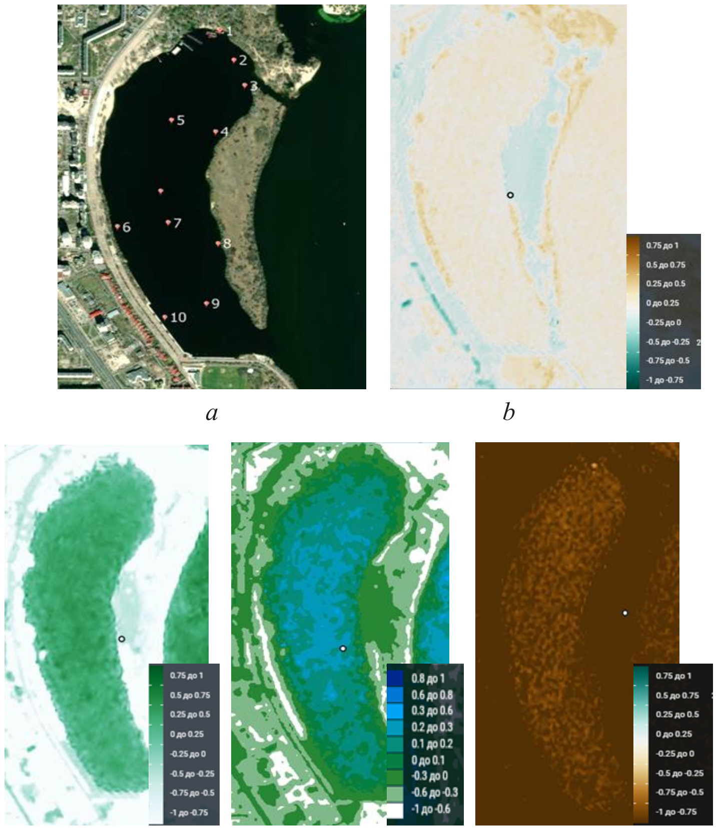


Fig. 1. Satellite image 07/04/2023 Sentinel-2 L2A of Lake Verbne with plotted ground observation points (*a*) and thematic maps of spectral indices:

b – NDTI, *c* – GCI, *d* – NDWI, *f* – IO



a *b*

c *d* *f*

Fig. 2. Satellite image 07/04/2023 Sentinel-2 L2A of the Obolon Bay with plotted ground observation points (*a*) and thematic maps of spectral indices: *b* – NDTI, *c* – GCI, *d* – NDWI, f – IO

Obolon Bay is located east of the Obolon residential area. This bay is connected to the Dnieper by a wide strait in its southern part, as well as a small strait in the northeastern part. The presence of two canals determines sufficient water exchange with the Dnieper. The length of the bay is 1,5 km, the maximum width is 430 m, and the depth is up to 17–19 m, because at one time sand was taken from it to wash the territory of the Obolon residential area. The area of the bay is 57,1 hectares. The shores of the bay are moderately gentle and sandy. It is used for recreational purposes (Fig. 3, a).

Lake Verbne (Fig. 3b) is located on the southern edge of the Obolon residential area. Non-flowing The length is 1070 m, the maximum width is 240-250 m. It is partly of artificial origin – it was a source of sand for washing the Obolon residential area. The area of the water mirror is 16.4 hectares. It is quite deep – up to 15 m. In 1994, by the Decision of the Kyiv City Council No. 14 dated February 17, 1994, Lake Verbne was declared an ichthyological and botanical reserve. In the lake there is a floating Salvinia fern – a species listed in the Red Book of Ukraine. There are also more than 20 species of lake-river complex fish here.

Since there are no standard indicators for comparison of spectral indices, during ground surveys the obtained indicators were compared with surveys of previous years. The results of ground-based surveys showed that in the studied water bodies over the summer period, the color of the water changed significantly and increased. Thus, compared to 07/08/2014, when the chroma in Obolon Bay was 33°, and in Verbne Lake – 13°, on 07/04/2023, the chroma in Obolon Bay was 132°, and in Verbne Lake – 89°. The main reason is the different types of algae, due to which the water acquires different colors, the presence of humic substances, compounds of ferric iron, as well as the influence of anthropogenic factors that can cause intensive coloring of the water. However, the transparency of the water has increased significantly. Thus, compared to July 8, 2014, when the transparency in the Obolon Bay was 14,5 cm, and in Lake Verbne – 9,2 cm, on July 4, 2023, the transparency in the Obolon Bay was 80 cm, and in Lake Verbne – 85 cm.

a *b*

Fig. 3. Photographs of places where ground-based surveys of water bodies were conducted: *a* – Obolon Bay, *b* – Lake Verbnoye

Based on the data of the calculated index and field surveys of Obolon Bay and Lake Verbne, graphs of the dependence of laboratory values of iron oxide and the IO index were constructed (Fig. 4). The coefficient of determination R2 for Verbnoy Lake is 0,898, and for Obolon Bay – 0,876.

The concentration of iron oxide should decrease as the volume of the water body increases, which is a natural phenomenon. But in Obolon Bay, the concentration is higher, which indicates an excess of iron coming from the upper reaches, that is, from the Kyiv Reservoir. Lake Verbne is non-flowing and has less soluble iron. It was established that the indicators of the ecological condition in Obolon Bay are worse compared to the indicators of Lake Verbne:

• the average temperature is lower by 1 °C;

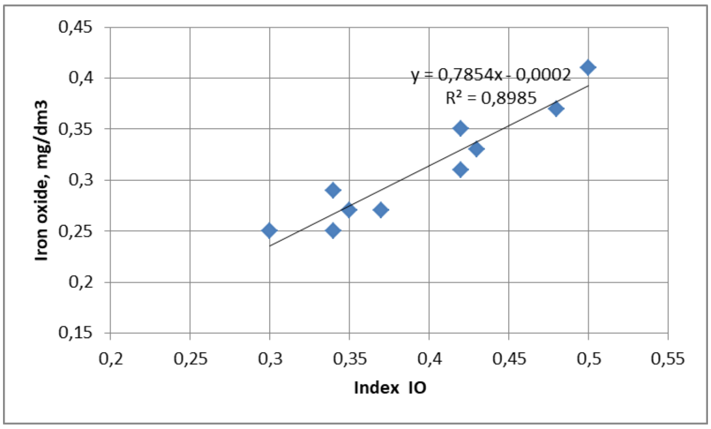
• chroma is higher on average – 147,06°/94,12°;

• turbidity is lower – 5,51/6,38 mg/dm^3, soluble iron is higher – 0,93/0,41 mg/dm^3.

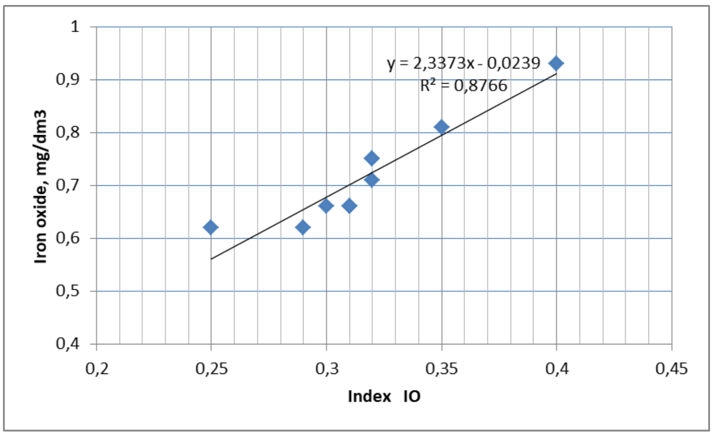
In addition to biological indicators, hydromorphological indicators were determined. Thus, according to the NDSI, NDWI indices and a combination of the red and infrared channels of the Sentinel-2 L2A satellite, the passage of the flooding of the floodplain of the Irpin River caused by the destruction of the hydrotechnical structure in the village of Kozarovichi was traced [16]. The research also studied the spatiotemporal transformation of the coastline of the Kaniv and Kremenchuk reservoirs. The reshaping of the shore occurs under the influence of natural and anthropogenic factors, which is a completely natural process, but it leads to the loss of a certain part of the land and ecological changes. To establish, observe and evaluate the process of reshaping the coastline, the method of determining spatio-temporal changes of the coastline as a result of its erosion was used, based on a combination of time-varying space images and topographic maps (Fig. 5). The assessment of spatio-temporal changes of the coastline should be carried out taking into account the water levels on the dates of the measurements.

Bank erosion was studied in the example of the Kanivskyi (Tsybli village) and Kremenchugsky reservoirs (Pronozivka village) using Landsat4, 1984 and Landsat8, 2016 satellite images (Figs. 5 and 6).

Analysis of temporal topographic maps and space images of the left bank of the Kaniv Reservoir in the area of Pereyaslav – p. Tsybli showed that intensive erosion of the coastal zone is observed only on the part of the coast that is located frontally to the line of maximum acceleration of wind waves, that is, from the estuary near the village of Tsybli to the mouth of the Trubizh River. Fig. 5 shows the dynamics of changes in the bankline of the entire 6,7 km long erosion-dangerous section. The red line shows the location of the bank on a topographic map at



a



b

Fig. 4. Graphs of the dependence of the value of iron oxide and the IO index in 2023:
a – Lake Verbne, *b* – Obolon Bay

a

b

c

d

Fig. 5. Pictures:
a – basic CNES/Airbus near the village. Tsybli, 2014; *b* – the dynamics of the bankline of the Kaniv Reservoir in the section of the village. Tsybli – the mouth of the Trubizh River; *c* – Landsat 5, 1985; *d* – Landsat 5 and Maxar composite, 2008

a *b*

Fig. 6. Erosion of the left bank of the Kremenchuk Reservoir:
a – dynamics of the shoreline of the Kremenchuk Reservoir near the village of Pronozivka for the period 1985–2022 (below in enlarged view); *b* – part of the shore

a scale of 1:100,000 as of 1983, that is, almost 10 years after the construction of the reservoir, when the reformation of the bank had already partially passed the stage of abrasion leveling. The green line shows the coastline as of 2023. The total area of bank erosion in this area was 51 hectares. The average erosion area for every 100 linear meters of shore is 7,6 thousand m^2. Upstream, in the area of Pereyaslav and to the north, the bankline is relatively stable.

Fig. 6 shows the erosion dynamics of the left bank of the Kremenchuk Reservoir south of the Sulsky Estuary, near the village of Diarrhea. The modern satellite image shows coastlines as of 1985 (red line) and 2009 (green line), which were determined from satellite images for the corresponding years. As the analysis of the data obtained shows, for the period 1985–2009, the maximum width of bank erosion in the area was 80 m, and over the next 13 years, it increased to 94 m.

Conclusions. Based on the results of our research, we found that it is advisable to improve the method of assessing the ecological state of surface waters based on satellite data by systematizing spectral indices, grouping them as biological (aquatic vegetation, cyanobacteria), hydromorphological (hydromorphological changes, processes of eutrophication, coastal erosion), physical chemical (concentration of various substances dissolved and suspended in water) and use them in an integrated manner.

In the studies of water bodies within the city of Kyiv, Obolon Bay and Lake Verbne, the optimal set of such indicators as spectral indices was determined, which made it possible to comprehensively assess the state of water bodies: NDWI – for distinguishing vegetation and water bodies, GCI – to assess the scale of blue-green algae distribution, NDTI – to determine turbidity, IO – to determine the presence of soluble iron in water.

It has been established that methodical approaches to the assessment of the state of surface waters with the use of data from ERS (Earth Remote Sensing) are based on the establishment of cause-and-effect relationships of processes affecting water bodies, the need to find evaluative informative parameters, and the development of methods for determining spatiotemporal changes that occur in within river basins.

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УДК 631.4:631.47

УДОСКОНАЛЕННЯ ОЦІНЮВАННЯ ЕКОЛОГІЧНОГО СТАНУ ПОВЕРХНЕВИХ ВОД ЗА СУПУТНИКОВИМИ ДАНИМИ

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Анотація. *У статті викладено результати досліджень екологічного стану поверхневих вод за новими розробленими науковими підходами, які ґрунтуються на використанні супутникових даних високого просторового розрізнення. Систематизація усіх наявних показників і розроблення нових методичних підходів істотно удосконалює існуючу методику визначення екологічного стану водних об'єктів, що є метою досліджень. У дослідженнях водних об'єктів у межах м. Києва затоки Оболонь і озера Вербне здійснено визначення оптимального набору таких показників, як спектральні індекси, які дали змогу комплексно оцінити стан водних об'єктів: NDWI – для розрізнення рослинності і водних об'єктів, GCI – для оцінювання масштабності поширення синьо-зелених водоростей, NDTI – для визначення каламутності, IO – для визначення наявності розчинного заліза у воді, NDSI – для оцінювання масштабу повені. За індексами NDSI, NDWI та комбінацією червоного і інфрачервоного каналів супутника Sentinel-2 L2A простежено проходження затоплення території заплави р. Ірпінь спричинено руйнацією гідротехнічної споруди біля с. Козаровичі. Хвильову абразію берегів досліджено на прикладі Кременчуцького водосховища біля сіл Пронозівка та Мозоліївка з використанням знімків супутника Landsat4 (1984 р.) та Landsat8 (2016 р.). Під час дослідження переформування берегової лінії біля с. Циблі у Київській області використано метод визначення просторово-часових змін берегової лінії в результаті її розмиву. Оцінювання просторово-часових змін берегової лінії повинно виконуватися з урахуванням рівнів води на дати виконання вимірювань. Проведеними дослідженнями встановлено, що всі визначені оцінювальні показники можна згрупувати як біологічні, гідроморфологічні та фізико-хімічні і зробити висновок, що методичні підходи до оцінювання екологічного стану поверхневих вод із застосуванням супутникових даних ґрунтуються на встановлені причинно-наслідкових зв'язків процесів, що впливають на водні об'єкти.*

Ключові слова: *поверхневі води, екологічний стан, супутникові дані, спектральні показники, бази даних, просторово-часові зміни*

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TECHNOLOGY OF STRUCTURAL REPAIR OF CONCRETE AND REINFORCED CONCRETE STRUCTURES OF WATERWORKS

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Abstract. *The assessment of the current state of the water and land reclamation engineering infrastructure facilities, which was carried out on the basis of the analysis of technical documentation, visual, and instrumental examination of the structures' technical condition, confirms that as a result of long-term operation of the waterworks without proper reparation and restoration measures, their technical condition has significantly deteriorated.*

The most promising for the repair of concrete and reinforced concrete structures are cement-based materials modified with polymers (polymer concrete), which are dry mixtures of cement, sand, re-dispersible polymer powder (RPP) and other modifying additives. The research results of the redispersing polymer powders influence on the adhesive properties of repair composites are presented. It is shown that the modification of cement-sand solutions of RPP leads to a significant increase in the adhesive properties of repair composites. The optimally effective concentration of RPP in repair compositions has been found.

The article highlights the technology of structural repair of concrete and reinforced concrete structures of the waterworks with the use of modern composite materials, which makes it possible to restore the design geometric indicators and the load-bearing capacity of the structures. The proposed technology and effective repair compositions help to carry out repair and restoration work on hydrotechnical structures of the water management and reclamation complex, in particular those destroyed or damaged as a result of the military aggression of the Russian Federation against Ukraine. The main principles of choosing the optimal technology for the structural repair of concrete and reinforced concrete structures of the waterworks, depending on the nature and degree of damage, the influence of technological and operational conditions on the structures' geometric indicators restoration during the modernization and reconstruction of reclamation systems in the post-war period, are revealed.

Key words: *hydraulic structures, composite materials, modifiers, compatibility, adhesion, structural repair*

Relevance of research. To ensure the efficient operation of irrigation systems in Ukraine, a large number of waterworks have been constructed and are in operation. The waterworks on canals make it possible to distribute and regulate the amount of water supplied to the reclamation system, to its individual sections, farms or fields; regulate water levels in canals; emergency discharge of water excess or emptying of individual sections of canals.

As a result of long-term operation of the waterworks without proper repair and restoration works, their technical condition has significantly deteriorated. On-site inspections of waterworks of irrigation systems, conducted in accordance with DSTU-NB V.1.2-18:2016 by scientists of the Institute of Water Problems and Land Reclamation of National Academy of Agrarian Sciences of Ukraine [1–3], testify to the progressive deterioration of their technical condition. Passive cracks with different opening widths on the surface of structures, peeling of the protective layer of concrete, sinks, chips, potholes, depressurized seams in prefabricated buildings are becoming more typical. These damages are the centers of further active structures destruction. The emergence of filtration zones and cavities in the body of the structures leads to a decrease in the carrying capacity of the waterworks, a decrease in the design indicators and the reliability of the structures as a whole, which causes water loss. Therefore, the restoration of reinforced concrete structures of the of reclamation systems' waterworks to the design operational indicators is an urgent problem today.

Analysis of recent research and publications. On-site inspections of water management and reclamation systems' waterworks showed that these structures simultaneously have a whole complex of damages, for the elimination of which there is no universal technology and material. Restoration is possible through the combined use of the most promising new technologies and materials. Depending on the nature of damage, concrete structures are restored using structural or non-structural repair methods. According to the nature of the impact on the bearing capacity, damages are divided into 4 categories:

1 – standardized, 2 – satisfactory;

3 – not suitable for normal operation;

4 – emergency.

Non-structural repair methods are used to eliminate concrete defects that are spread to a depth less than the surface protective layer. These defects include: shrinkage cracks, spalling of concrete, high porosity, insufficient thickness of the surface protective layer of the reinforced concrete structure, etc. Timely elimination of damage by methods of non-structural repair makes it possible to protect structures from the aggressive action of the environment and avoid their further destruction. The main technologies used for the restoration of concrete structures by methods of non-structural repair include surface impregnation, elastomeric sealing, penetrating waterproofing, pressure injection, coating waterproofing [4, 5].

Pressure injection technology is used to increase the waterproofing capacity and corrosion resistance of concrete and reinforced concrete structures of waterworks. The technological process of injection consists in injecting liquid waterproofing material under pressure into defective areas of concrete. The technology is used to restore the monolithicity and density of waterworks the concrete and to eliminate filtration through it.

Also, in order to increase the waterproofing capacity and corrosion resistance of concrete and reinforced concrete structures of waterworks, the technology of penetrating waterproofing is used in order to exclude the water filtration through the concrete structure, which has an extensive network of pores, capillaries and microcracks. Penetrating waterproofing is the gradual penetration of the waterproofing material into the base through the concrete capillary system and complete clogging of the concrete pores. The speed and depth of penetration of active chemical components depends on the chemical composition, humidity, concrete's density and porosity, and the ambient temperature. As a rule, for quality materials, the depth of penetration into concrete reaches 10–12 cm.

Coating waterproofing is used for external protection of structures from soil and atmospheric water and internal protection from capillary moisture. Coating waterproofing is a single-layer or multi-layer coating with a thickness from a millimeter to several centimeters.

To strengthen the protective layer of operational reinforced concrete structures, the technology of surface impregnation of concrete with low-viscosity compositions is used, followed by their polymerization (hardening) in concrete. After surface impregnation, the compressive and tensile strength of the original concrete increases by 3–4 times, waterproofness – by 1,5–1,6 times, frost resistance – by 3–6 times, impact strength – by 1,5–3 times.

For the repair and sealing of deformation joints and active cracks in concrete and reinforced concrete structures of reclamation systems' waterworks in order to increase their waterproofness and durability, repair technology with elastomeric compositions is used.

For fixing concrete and soil structures that have filtering zones of loose soil or concrete, destruction or mechanical damage in the form of caverns, sinks, wide-opening cracks on the structure's surface; for the repair of local structural damage of concrete and reinforced concrete structures for the purpose of their anti-filtration protection; to eliminate water filtration paths at waterworks of reclamation systems tamponage technology is used.

Structural repair technology is used to repair damage to reinforced concrete structures of waterworks, which during operation have suffered from the protective layer destruction or mechanical damage in the form of caverns, shells, chips, possibly with exposed reinforcement, or passive cracks with an opening width of up to 10 mm on the surface of the structures. Structural repair of concrete facilities is carried out in case of damage to the structures to a depth greater than the surface protective layer. The main purpose of carrying out structural repairs is to restore the parameters of the structures to the design indicators. For application of repair compositions for the structural repair of the waterworks, it is necessary to take into account the specific operating conditions of the structures. Such conditions are the location of the concreteof the structure relative to the water and the nature of the interaction with it. From this point of view, the concrete structure of facilities can be divided into three zones.

1. Underwater (underground) zone of the concrete structure. It is characterized by the fact that this zone is constantly in water and interacts with it and its components with varying intensity, which depends on the nature of the water action (under pressure or without pressure), the chemical composition (aggressiveness) of the water environment, as well as the composition and structure of facilities' material.

In this case, the stability of the structure's or facility's concrete is achieved by the correct choice of the raw material type, the increased density of the structure due to the rational selection of the concrete composition, in particular, the repair concrete, the reduction of the water-binding ratio, the introduction of modifying additives of synthetic and mineral origin.

2. Zone of variable water level. This zone is particularly tough to the action of a combination of natural factors, and the concrete of this zone has the highest requirements for corrosion resistance, wear resistance (abrasive and cavitation), frost resistance, mechanical strength under compression and tension, and water resistance. The stability of concrete in this case is achieved by a more careful selection of high-quality raw materials with increased physical and mechanical properties, an increase in the concrete density and mechanical strength, minimal intergranular voids, thanks to the rational selection of the concrete composition, the use of modifying additives, polymer materials.

3. Above water zone. The concrete of the above-water zone is subjected to episodic action of water (splashes), solar radiation, wind, etc. Therefore, in such conditions, the stability of concrete is achieved by complying with the specified class in terms of compressive strength and weather resistance.

In the case when it comes to restoring the load-bearing capacity of the structure to project indicators, structural repair technologies are used, which are aimed at restoring the structures geometric shapes, eliminating damage in the form of loosening of the concrete protective layer, chips, sinks, potholes, passive cracks with the width of the opening on the constructions' surface up to 10 mm and deconsolidation of butt joints.

The aim of the study. To determine technical and technological solutions for carrying out structural repairs of concrete and reinforced concrete structures of the waterworks.

Methods and objects of research. The research is based on the results analysis of the surveys of the technical condition of waterworks during the past years, the systematization of materials of experimental and field studies of the operation department of the Institute of Water Problems and Land Reclamation, the European standards requirements for the repair materials characteristics, as well as research materials of other authors published in open access. The research was conducted in laboratory conditions and at the facilities of the water management and reclamation systems of Ukraine.

The actual value of the parameters obtained as a result of the visual inspection was compared with the quantitative and qualitative criteria foreseen by the design, operational and regulatory documentation.

The survey methodology included the following operations:

– assessment of the actual operational conditions of facilities and their elements;

– detection of violations and deviations from normal operational conditions;

– inspection of engineering infrastructure objects to check compliance with the actual and design structural schemes;

– determination of the state of nodes connecting elements and structures;

– detection of poor performance of works during preliminary repairs;

– identification of places with damages and defects;

– determination of the damage degree and wear of equipment and metal structures.

The conducted surveys made it possible to reveal the presence of typical destructions on waterworks that are constantly in contact with water.

Research results and discussion. The assessment of the current state of the engineering infrastructure facilities of the water management and reclamation systems was carried out on the basis of the analysis of technical documentation, visual and instrumental examination of the facilities' technical state, their elements, control of material properties and estimated calculations.

As an object of research, the assessment of the technical condition of waterworks in the following Interregional Water Management Departments (IWMDs): Bortnytskyi, Irpin IWMD and Basin Water Management Department (BWMD) of the Tysa river were considered.

Bortnytskyi IWMD. During the inspection of the reinforced concrete waterworks of Bortnytska irrigation system, the following damages were found: cracks in the head of the water discharge into the main canal, violation of the structural integrity of the pumping station heads. The length of the cracks reached 120 cm, the depth – up to 4,5 cm (Fig. 1).

Fig. 1. Head on the canal of Bortnytska irrigation system

Irpin IWMD. Inspection of the pre-chamber technical condition of Kochurska pumping station revealed the following damages to the fixing panels: cracks, chips, shells, destruction of the concrete protective layer, violation of the coating geometric shape, exposure of the reinforces (Fig. 2).

BWMD of Tysa river. Similar to the pre-chamber panels damages were discovered during the inspection of pumping station No. 3/3A of the Latoritza polder system. Performing repair and restoration works on these objects requires analysis and development of fundamentally new technological methods and materials for their implementation.

Accordingly, the requirements for the characteristics of cement-based repair materials, which are the most common and intended for the structural repair of reinforced concrete facilities, were analyzed (according to the European standard EN 1504 "Materials and systems for the protection and repair of concrete") (Table 1) [6–8].

Additionally, taking into account the main operating characteristics according to EN 1504, actions and characteristics regarding the selection of repair material were determined. However, European regulations contain only functional requirements, there is no clear description of how to implement this or that technical solution. Thus, there is a need to work out technological solutions using the latest materials for structural repairs that would meet the functional requirements of European standards.

Fig. 2.Technical condition of the pre-chamber panels of the Kochurska pumping station of the Irpin IWMD

1. Requirements for the characteristics of cement-based repair materials intended for structural repair

Characteristics	Values	
	Class R4 (repair of main supporting structures)	**Class R3 (repair of fencing structures)**
Compressive strength, MPa	≥45	≥25
Bond strength with old concrete, MPa	2	1,5
Chloride content, % by mass	≤0,05	
Module of elasticity, GPa	≥20	≥15
Compatibility in freeze-thaw cycles. Adhesion after 50 cycles	≥2	≥1,5
Capillary sorption, kg/m^2 h	≤0,5	
Carbonation resistance, depth (dk)	≤ dk control concrete	

The literature analysis [9–13] shows that various materials and technologies are used as modern composites for the repair of reinforced concrete waterworks, depending on the type and nature of damages. One of the main requirements for choosing a composite is the characteristics of the binder. Binders are divided into three main categories according to operational, physical, and mechanical characteristics:

1st category – repair materials based on organic (polymer) binder (polymer concretes, polymer solutions);

2nd category – polymer-modified materials on a cement binder (polymer-cement concrete, polymer-cement solutions);

3rd category – repair materials on a cement binder (cement-sand solutions, concretes).

Based on the analysis of binders and repair materials, recommendations were developed for the use of different categories of materials for the repair of waterworks made from reinforced concrete (Table 2).

To ensure high-quality repair, a necessary condition in the creation or selection of repair compositions is the compatibility of the composition with the characteristics of the repaired concrete. Compatibility is the relationship between the physical, chemical, and electrochemical characteristics of the repair compositions components and the characteristics of the concrete surface of the existing facility [14–17]. These ratios of the characteristics of the repair layer (P) to the concrete base (C) and the general requirements for the properties of materials for repair work and the concrete base to ensure structural compatibility are shown in the table. 3.

Compatibility implies the nature of the behavior of the repair material both in the

2. Recommendations regarding the use of different categories of materials for the repair the waterworks made from reinforced concrete

Name of the material	Main properties	Recommendations for use
Cement mortars and concretes	Normal density and strength, normal concreting; low adhesion to old concrete. They require careful and long-term care during hardening, or the application of protective coatings.	Repair and strengthening of overall structures of waterworks elements; construction of reinforced concrete shirts, belts; construction of discharges; repair of the protective layer, which work only for constant load; repair of sinks, cavities, grouting of the cracks.
Polymer-cement mortars and concretes	Increased viscosity. Normal (compared to cement) density and strength, increased adhesion to concrete and crack resistance. Does not require careful care during hardening	Repair of damaged structures in areas where prestressed reinforcement is exposed; grouting of cracks; for the production of injection solutions; restoration of the concrete protective layer.
Polymer solutions and concretes	High strength, density and impermeability, resistance in an aggressive environment. Increased adhesion to dry concrete. Reduced shelf life of the prepared mixture (30–40 min)	Repair of concrete chips in areas where it is necessary to restore its calculated compressive and bending strength; achieving high chemical and mechanical resistance; for concreting prefabricated reinforcing structures; for the production of injection solutions; for the preparation of protective coatings.

3. General requirements for quality indicators of materials for repair work and concrete base for structural compatibility [14]

Quality indicators	The ratio of the characteristics of the repair layer (P) to concrete base (C)
Compressive strength, MPa	$P \geq C$
Module of elasticity, Pa	$P \sim C$
Coefficient of thermal expansion, K^{-1}	$P \sim C$
Adhesion, shear and tear strength, MPa	$P \geq C$
Expansion upon wetting, %	$P \geq C$
The ability to deform without breaking	$P \geq C$

hardened and in the hardening state. The efficiency of the repair is defined as the ratio of the stresses that the repaired structure can withstand to the stresses that the structure could withstand before the destruction and repair.

The main requirement in the selection of materials for the repair of concrete and reinforced concrete facilities is adhesive compatibility. Adhesion compatibility implies a sufficient amount of adhesion between the base concrete and the repair material. It was established that the insufficient adhesive property of the repair material to the restored concrete surface is observed when temperature deformations of the hardening repair composition and the base are detected. Adhesion also decreases with insufficient preparation of the damaged area of the facility surface before applying the repair material.

According to the research results, it was found that adhesively compatible characteristics are provided under the condition of equality of shear strength, tensile index between the base concrete and the repair material, as well as the contact zone of destruction, which can characterize the recovery process within three zones. Achieving the greatest adhesion compatibility and strength for repair materials occurs under the condition of optimal state of the concrete preparation surface, as well as the use of primers.

Under the conditions of temperature changes, the amount of deformation of the structure should be proportional to the coefficient of thermal linear expansion of the material. The introduction of polymers into the solutions causes an increase in the coefficients of thermal linear expansion of the repair composition by 1,5–5 times, which can lead to the appearance of significant stress in the contact zone and cause cracking, distortion and peeling of the repair material. In this case, there is a need to use modifiers. The brand of frost resistance of repair compositions must also correspond to the frost resistance of the concrete base.

Deformation compatibility ensures the ability of the repaired area to withstand changes in volume without loss of adhesion and delamination. It was established that in the absence of deformation compatibility, delamination occurs as a result of the following reasons:

– shrinkage deformation of the repair material (plastic shrinkage, drying shrinkage, changes in volume caused by internal shrinkage processes during carbonization);

– expansion in repair materials with shrinkage compensation;

– thermal expansion followed by cooling;

– thermal expansion of repair materials due to daily or seasonal temperature changes.

According to the indicator of structural compatibility, repair materials are divided into two areas of use:

– non-structural or cosmetic repair, for which the perception of stresses is not the main condition for the repair area;

– structural repair, during which the material of the repaired area accepts the load on the damaged area of concrete.

To ensure structural compatibility during the repair of individual areas, special attention should be paid to the following requirements for materials:

– the compressive, bending and tensile strength of the repair material must exceed the corresponding characteristics of the base concrete;

– the elasticity module and the thermal expansion coefficient of the repair material and the base concrete must be equal.

Repair objects include the following components: “old” concrete, transition layer (zones of contact between concrete and repair composition) and repair solution. At the same time, the arrangement of the transition layer – the primer – helps to improve the adhesion of the repair solution to the base by increasing its strength.

Considering the above, in the development of a multi-component composition of repair compositions, it is necessary to take into account at least the following conditions to ensure compatibility (in technological and physico-chemical terms) at all levels of the system “repair composition – primer – damaged surface”:

– rheological properties, which are determined by the instrumental research method;

– increase of adhesion to the concrete surface, in particular due to increase of penetrating capacity;

– reduction of shrinkage deformations, slowing of moisture migration and creation of normal hydration conditions.

For structural and non-structural repairs, mixtures are used, which, depending on the type of adhesive, can be divided into three groups: based on polymer resins; based on cements modified with active mineral additives; on the basis of cements modified with polymers (polymer cement).

According to research results, the following physical and mechanical properties of repair composites on different bases, which affect the operational reliability and durability of the “concrete – repair composite” system, were determined and are listed in table. 4.

4. Physical and mechanical properties of repair composites

Quality indicators	Composite based		
	polymer	cement	polymer-cement
Compressive strength, MPa	60–120	20–70	10–80
Module of elasticity under compression, MPa	$(2–10)10^3$	$(20–30)10^3$	$(15–40)10^3$
Bending tensile strength, MPa	25–50	2–5	6–15
Axial tensile strength, MPa	10–-20	1,5–3,5	2–8
Relative elongation at break, %	0–2	0	0–5
Coefficient of linear temperature expansion/ compression, mm/mm/°C	(25–30)10	(7–12)10	(8–20)10
Water absorption in 7 days at 25 °C, %	0,1–0,5	5–15	0,1–2
Adhesion to concrete, MPa	3,5	0,3–0,5	2,0–2,5

To increase the quality indicators of repair composites on a polymer or polymer-cement basis, modifying additives developed at the institute are recommended, which are able to influence technological, physical-mechanical and operational indicators and, in this way, increase the quality and efficiency of structural repair of concrete and reinforced concrete structures of reclamation systems' waterworks [18]. Redispersed polymer powders (RPP) are one of the most effective modifiers of the properties of building materials.

We investigated the effect of RPPs, differing in chemical composition, on the adhesive properties of repair composites (Table 5).

Determination of the adhesive strength of the cement-sand solution with RPP additives was carried out in accordance with ASTM C 190 by determining the tensile strength on samples in the form of figures of eight with a collapsible contact area of about 5,5 cm^2. For tests, cement-sand half-eights were made in special molds using a metal separation plate, to which half-eights

5. Components of redispersed polymer powders

Name of RPP	YT-8012	Elotex FLOWKIT 74	NEOLITH P 4400
Components of RPP	vinyl acetate, ethylene	vinyl acetate, ethylene acetate, ethylene, acrylate	vinyl acetate, versatile vinyl

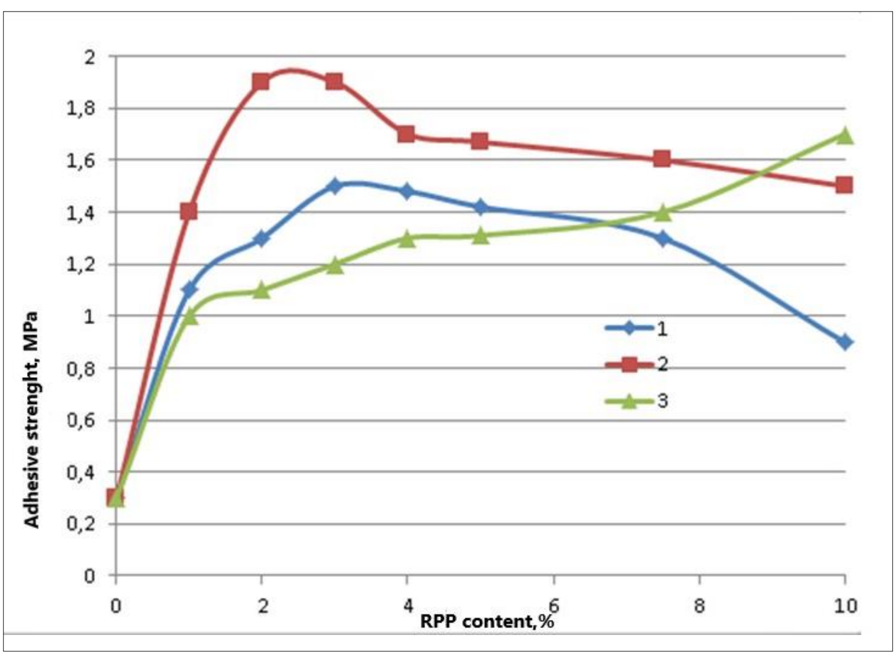

Fig. 3. Influence of RPP on adhesive strength:
1 – YT-8012; 2 – Elotex FLOWKIT 74; 3 – NEOLITH P 4400

were then formed from a modified solution with RPP additives. The redispersed polymer powder was introduced into a solution of 1 to 10 % of the mass of cement with a water-cement ratio (W/C) of 0,4. After 28 days of aging in normal humid conditions, the manufactured samples were tested on the RM-05 tearing machine. The obtained results are shown in Fig. 3.

As can be seen from the above data, the modification of cement-sand solutions of RPP causes a significant increase in adhesive strength. Concentration dependences of adhesive strength on the content of RPP have an extreme character. The most pronounced effect is achieved in the area of concentrations from 1 to 5 % of the RPP content in relation to cement. When 3 % YT-8012 is introduced into a cement-sand solution, the adhesive strength increases by 5 times, in the range of 2–3 % Elotex FLOWKIT 74 – by 6, and in the range of 4–5 % NEOLITH P 4400 by 4,3 times. The obtained results indicate the prospects of using RPP as part of repair composites.

Improving the physical and mechanical characteristics of cement-sand solutions by introducing modifiers of different chemical components into their composition makes it possible to create highly effective repair composites.

The properties of modified cement-sand solutions as heterogeneous multicomponent systems are the result of those changes in the physical properties and structure of the components, which are caused by the interaction at the phase interface. The change in the properties of the modified system compared to the original occurs as a result of the simultaneous action of many factors, but is not an additive value. Determination of the optimal ratio of components is carried out on the basis of the method of mathematical planning of the experiment. The obtained data are used for targeted regulation of the properties of modified cement-sand solutions.

Our research has found that with the complex use of superplasticizer (SP), microsilica (MC) and polypropylene fiber (F) in the composition of polymer cement dry construction mixtures in the area of concentrations of SP = 0,23–0,5 % (C), MK = 5–25 % (C), F=0 – 0,6 % (C), the following quality indicators are achieved [12]:

– compressive strength R_{cs} > 60 MPa,
– bending strength R_{bs} > 10 MPa,
– water absorption W_m < 5 %.

The results of research carried out at the institute indicate the possibility of increasing the strength indicators of cement-sand solutions modified with a powder superplasticizer of the polycarboxylate type Sika Viskocrete 225, amorphous microsilica (MK), polypropylene fiber (F) and redispersed polymer powder (RPP) [19].

The complex application enhances the effect of each individual modifying additive and makes it possible to obtain a composite material with high strength and performance indicators (R_{cs} = 12,5 MPa, R_{bs} = 65 MPa, Wm = 2,0 %) and is a relevant direction in the modification of cement-sand solutions for repair of reinforced concrete structures of the reclamation systems waterworks.

The institute developed a polymer-cement dry construction mix for structural repair of concrete of the waterworks. This mix as modifiers contains microsilica, polypropylene fiber, redispersed polymer powder and SVK 225 superplasticizer in the following composition, %:

Cement M500 ....22,04;
River sand 66,14;
SP SVK225 ....0,066;
Microsilica 3,307;
Fiber.............................0,066;
RPP 0,88;
Water............................7,49.

6. Technological, physical, and mechanical indicators of repair mix

Quality indicator	Mix, developed at institute	Rem-stream-T	Bud-Master TINK-93	Ceresit DM 25	Master Emaso C488C	Sika REPER	Siltek R-5
Ease of appication (blurring of the cone), sm	16,0	18,0	13,0	14,0	20,0	18,0	16,0
Compressive strength, MPa	65	60	45	25	60	45	35
Bending strength, MPa	10,5	7	8,5	8,0	8,0	9,0	8,0
Adhesion to concrete, MPa	2,2	2,0	2,0	1,5	2,5	2,0	2,0
Water resistance, W	14–16	16	12	12	12	18	15
Frost resistance, cycles, F	300	300	75	75	300	250	200
Viability, min	30	45	40	30	50	45	30

For practical use in the composition of the mix, a comparative analysis of the technical characteristics of the materials available on the market of Ukraine (according to the manufacturing companies materials) was carried out (Table 6).

The developed composite repair materials and technologies for their use have been successfully tested and implemented at the facilities of the State Water Agency of Ukraine: Bortnytska IWMD, Kochurska pumping station of the Irpin Interdistrict Water Management to restore waterproofing and monolithic reinforced concrete structures [20–22].

The repair of total concrete destruction, chips and shells was carried out by the method of monolithization based on the use of developed compositions of polymer cement mixes. Preliminary preparation of defective areas for repair consisted in cleaning the surface from debris, dust, removing destroyed concrete, overflows, treating cracks (creating a groove along the crack path for further sealing). To improve the adhesive properties of the repair compositions, preliminary surface impregnation of the site with epoxy isocyanate compositions was carried out. The structural repair of the head on the canel of the Bortnytska irrigation system is shown on Fig. 4.

In order to eliminate the detected damages of pre-chamber panrls of the Kochurska pumping station, a structural repair was carried out using fiber-polymer cement compositions.

The technology of carrying out repair and restoration works included the following operations:

– preparation of the defective area for repair;
– primer treatment of the repaired concrete surface;
– preparing the working composition of the repair composite material and applying it to the defect area.

The developed dry fiber-polymer cement mixtures were produced in laboratory conditions, and the necessary amount of the water was added at the place of repair and restoration works.

The liquidation of shells, chips, volume and surface destruction of the concrete protective layer was carried out by the method of structural repair with the restoration of the geometric shape of the facilities using fiber-polymer cement compositions, which were applied after careful preparation of the surface in the repair areas: weak and brittle concrete was removed; the surface of the site was washed with a stream water under high pressure and blown with compressed air to prepare the concrete surface for repair work. The thickness of the layer of repair compositions was from 5 to 30 mm, depending on the degree of damage (Fig. 5).

A visual inspection after hardening of the repair composite materials showed that the repair layers are dense, there is no delamination of the compositions, and there is no filtration during the pilot test using a filterometer. The general condition of the repaired areas is good, the monolithic adhesion of the laid repair materials to the concrete is high. The results of laboratory studies of physical and mechanical indicators of fiber-polymer cement composition samples, which were formed from a batch of material produced for repair, are given in table 7.

The obtained indicators correspond to the average values for repair mixes, given in the table 6 and correspond to class R3 of the European standard EN 1504 “Materials and systems for the concrete protection and repair” (Table 1).

a

б

Fig. 4. Head on the canel of the Bortnytska irrigation system after structural repair:
a – after restoration; b – in 2 years

Regular studies of the condition of restored sections of the waterworks after long-term operation have confirmed the absence of damages and the development of destruction and deformation of structures, which confirms the reliability and efficiency of the repair work.

Conclusions. The technology of structural repair of concrete and reinforced concrete structures of the waterworks with the use of modern composite materials has been developed, which ensures the restoration of the design geometric parameters and the load-bearing capacity of the facilities.

Repair composites on a polymer and polymer-cement basis have been developed, which are recommended and capable of influencing technological, physical-mechanical and operational indicators and, in this way, increasing the quality and efficiency of structural repair of concrete and reinforced concrete structures of reclamation systems' waterworks.

It was established that the modification of cement-sand solutions of RPP leads to a significant increase in adhesive strength. Concentration dependences of adhesive strength on the content of RPP have an extreme character. The most pronounced effect is achieved in the range of concentrations from 1 to 5 % of the RPP content in relation to cement. When 3 % YT-8012 is introduced into a cement-sand solution, the adhesive strength increases by 5 times, in the range of 2–3 % Elotex FLOWKIT 74 – by 6, and in the range of 4–5 % NEOLITH P 4400 by 4,3 times.

Fig. 5. The pre-chamber panels after structural repair

7. Results of research on the fiber-polymer cement composition used in the repair of panels

Indicator	**Compressive strength, MPa**	**Bending strength, MPa**	**Adhesion to concrete, MPa**
Value	45,6	8,3	1,58

Experimental and production testing, results of field studies and monitoring of the condition of repaired structures at the facilities of the Interregional Water Management Departments: Bortnytska, Irpinske Water Management Departments and BUVR of the Tysa region confirmed the high efficiency of the use of polymer-cement dry construction mixture in the repair and restoration of reinforced concrete water management facilities.

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ТЕХНОЛОГІЯ КОНСТРУКЦІЙНОГО РЕМОНТУ БЕТОННИХ ТА ЗАЛІЗОБЕТОННИХ КОНСТРУКЦІЙ ГТС

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Анотація. *Оцінка сучасного стану об'єктів інженерної інфраструктури водогосподарсько-меліоративного комплексу, що проводилась на основі аналізу технічної документації, візуального та інструментального обстеження технічного стану конструкцій підтверджує, що внаслідок багаторічної експлуатації ГТС без належного проведення ремонтно-відновлювальних робіт технічний стан їх значно погіршився.*
Найбільш перспективними для ремонту бетонних та залізобетонних конструкцій є матеріали на основі цементу, модифіковані полімерами (полімерцементні), які являють собою сухі суміші цементу, піску, редиспергуючого полімерного порошку (РПП) та інших модифікуючих добавок. Наведено результати досліджень впливу редиспергуючих полімерних порошків на адгезійні властивості ремонтних композитів. Показано, що модифікація цементно-піщаних розчинів РПП приводить до істотного зростання адгезійних властивостей ремонтних композитів. Встановлено оптимально ефективну концентрацію РПП у ремонтних композиціях.
У статті висвітлено технологію конструкційного ремонту бетонних та залізобетонних конструкцій ГТС із застосуванням сучасних композиційних матеріалів, що дає змогу відновити проєктні геометричні показники та несучу здатність конструкцій. Запропонована технологія та ефективні ремонтні композиції допомагають проводити ремонтно-відновлювальні роботи на гідротехнічних спорудах водогосподарсько-меліоративного комплексу, зокрема зруйнованих або пошкоджених внаслідок воєнної агресії російської федерації проти України. Розкрито основні принципи вибору оптимальної технології конструкційного ремонту бетонних та залізобетонних конструкцій ГТС залежно від характеру та ступеня пошкоджень, впливу технологічних та експлуатаційних умов на відновлення геометричних показників споруд під час модернізації та реконструкції меліоративних систем у повоєнний період.
Ключові слова: *гідротехнічні споруди, композиційні матеріали, модифікатори, сумісність, адгезія, конструкційний ремонт*

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APPROACHES TO ASSESSING THE STABILITY OF BANK PROTECTION STRUCTURES OF WATERBODIES: ANALYSIS OF CONSTRUCTIONS AND MODELS FOR THEIR CALCULATION

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Анотація: *The article analyzes the theoretical foundations for determining the stress state in a soil mass and the design of fastening the bank slope of reservoirs. Scientific research and theoretical principles on determining the forces that act on a bank protection structure have been systematized. Methodological approaches to the static calculation of bank protection for indirectly vertical structures are proposed, taking into account the relationship between the load on the structure and its deformation.*

The purpose of the research is to ensure the stability and reliability of bank protection structures and to substantiate directions for improving technical solutions in modern conditions.

The work analyzes the use of various types of slope fastenings for bank protection structures in accordance with the requirements of State construction standards. It is proposed to focus research on sheet piling shore fastenings, as a modern and progressive technology for bank protection. The "soil massif – fastening structure" system is considered as a calculation model in the form of a one-sided type, which is an elastic element, which makes it possible to apply the modern apparatus of the theory of elasticity in considering this problem. This makes it possible to accept a linear relationship between stress and strain and obtain sufficient accuracy, which is confirmed by the available results of domestic and foreign research. For calculations of deformations, and assessment of the strength and stability of soil massifs and foundations, it is proposed to pay direct attention to the characteristics of the mechanical properties of soils, while three stages of foundation deformation are considered.

The formulated differential equations of the equilibrium of the soil massif make it possible to solve a wide range of issues related to the limit equilibrium and to obtain the calculated parameters of the pressure of earth masses on the retaining walls of shore fortifications of the oblique-vertical type. The results of the research analysis are recommended for use in determining the main loads on hydraulic structures, substantiating technical solutions for the development and improvement of slope and slope-vertical types of bank protection of reservoirs.

Key words: *bank protection, stress state, theory of elasticity, soil mass, calculation model, stability*

Relevance of research. Bank protection structures as part of anti-slide and anti-landslide measures are used in areas where the bases of the slopes are placed in contact with the water mirrors of seas, lakes, reservoirs or rivers, to protect native shores or stabilize landslides, expand or preserve existing beaches. In connection with the change in the hydrological and geological situation, the increase in anthropogenic load and climate change, the conditions for ensuring the stability and reliability of the bank portection structures are an urgent task.

The spread of bank destruction processes, especially in the cascade of the Dnieper reservoirs, is the most representative of the objects, which requires the introduction of changes and renewal of the provisions of the existing methodological and regulatory documentation on the assessment of the processes of statics and dynamics of soil massifs and the calculation of bank fortification structures, their design, construction and operation. The accumulated experience in the operation of bank protection of reservoirs indicates the insufficient durability of the fastening structures used, both slope and vertical types. This is explained by the fact that during the design and construction of various types of bank protection structures, their stability and reliability were not sufficiently taken into account.

Determining the stress state of the interaction between the soil mass of the slope and the fasteners is a very complex statistically uncertain problem of structural mechanics. In practice, when determining the soil pressure on the construction of fasteners, the theory of limit equilibrium of granular bodies, proposed by C. Coulomb back in 1766, is used. This theory, as the practice of construction and operation of hydraulic structures shows, provides a solution with a certain margin of safety.

This is especially true for flexible fastening structures, both slope and vertical types, which under operating conditions are significantly different from the basic provisions laid down in the Coulomb theory. Therefore, there is a need to improve the methodology for calculating inclined-vertical structures, which would take into account the different rigidity and operating conditions of bank protection structures.

Purpose of research. Ensuring the stability and reliability of bank protection structures and substantiating directions for improving technical solutions in modern conditions.

Analysis of recent research and publications. The basis of Coulon's theory of the limiting equilibrium of granular bodies is the hypothesis that a granular body is a homogeneous continuous medium that perceives only compaction itself, and also that when the system is at "rest" (equilibrium), the resulting stress deviates by an angle less than – φ of the internal friction of the soil mass).

Coulon's theory reflects only one statistical side of the problem of pressure of a granular medium, and to a certain extent does not cover its kinematic side, that is, it excludes consideration of deformation and displacement from the processConsequently, the condition has been accepted that the movement of the fastener structure is sufficient for the occurrence of a state of limiting equilibrium of the backfill behind it. This means that the fastener structure and backfill are not in normal operating condition, but are in the initial stages of destruction. In 1840, Ponsele carried out scientific research and practical solutions to this problem, regarding the pressure on the retaining wall, graphic materials were proposed for determining the force acting on the structure of the fastener.

P.P. Argunov reduced the problem of determining the pressure on a vertical smooth wall to the problem of the theory of elasticity with the superimposition of solutions for two planes, one of which has a vertical plane and the other horizontal, which made it possible to determine the pressure on the structure depending on its displacement [1]. N.K. Snitko developed a method taking into account the joint movement of the retaining structure and its base [2]. I.E. Byaler obtained a general solution to the linear theory of elasticity for soil pressure on structures of any rigidity, including anchor and cantilever ones, taking into account their joint deformation of the backfill soil [3]. Later I.Ya. Beler, M.Ya. Borodyansky presented a new method for calculating retaining walls, based on the joint work of the retaining wall and soil backfill [4]. G.E. Lazebnyk, E.P. Chernysheva gave a solution for determining the influence of the shape of lateral soil pressure supports on forces in sheet pile anchor retaining walls [5]. A.I. Beleush outlined the basics of calculating retaining structures and the effectiveness of their operation in securing landslide slopes [6]. A.M. Ryzhev provided solutions to problems of nonlinear mechanics and physical modeling of the foundations of structures [7]. Yu.M. Kalyukh proposed modern information technologies, mathematical methods of studying and forecasting the evolution of processes in dangerous areas and objects [8, 9]. M.T. Kuzlo proposed calculation schemes and models for assessing the state of water-saturated soil massifs and foundations [10].

Based on the analysis of theoretical principles, it can be argued that the combined fastening of slopes of reservoirs is made in the form of a slope-vertical structure and has several advantages compared to classic fastening slopes, which are determined by hydraulic and static calculations. This design is widely used in hydraulic engineering. For example, strengthening the banks of the Dnieper reservoir cascade [11].

It is known that soils on the banks of reservoirs are a nonlinear elastic medium. Therefore, to obtain a more reliable solution for the selection and justification of calculations of slope-vertical structures of bank protection structures, it is necessary to develop new methodological approaches that would take into account both the rigidity of the structures and the nonlinear elasticity of the soil of the slopes and operating conditions.

Materials and methods of research. A slope is an artificially created surface that limits a natural soil massif, a recess, or an embankment. Slopes are formed during the construction of various types of embankments (roadbeds, dams, earthen dams, etc.), excavations (pits, trenches, canals, quarries), or during the repurposing of territories. On the sea and river coasts, hydraulic retaining walls and embankment shore fortifications are built to protect the slopes of enclosing dams or coastal slopes from the destructive effects of waves and storm currents [12].

It is allowed to use the following types of oblique fastenings of shore fortification structures in accordance with the requirements of State Construction Standard DBN V.2.4.-3:2010 [13]:

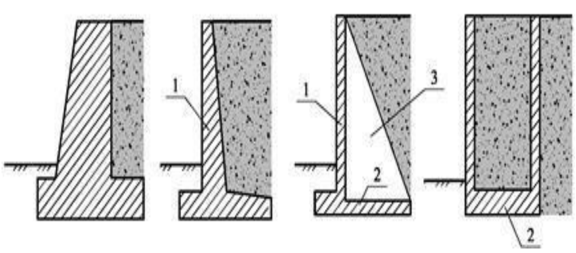
- impermeable concrete, reinforced concrete from prefabricated slabs or in the form of a continuous coating;
- permeable concrete, reinforced concrete from prefabricated elements in the form of a diagonal-stepped structure with a wave chamber;
- stacking from shaped or ordinary blocks;
- stone overlays and paving, including from mountain mass.

Depending on the design and purpose, hydraulic retaining walls are of the following types:

1. Gravity – erected on rock and non-rock foundations (Figure 1), made of monolithic or prefabricated concrete and reinforced concrete.

Retaining walls of this type, as a rule, are part of the structures of the pressure front of hydraulic units, mooring structures, and embankments;

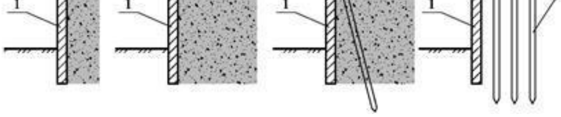
Gravity-retaining walls resist soil pressure due to their significant self-weight and the weight of the soil within the wall dimensions.



a *b* *c* *d*

Fig. 1. Types of gravity retaining walls:

a) massive, b) corner, c) buttress, d) shell;
1 – plate (face element), 2 – foundation plate,
3 – buttress (rib)



a *b* *c* *d*

Fig. 2. Types of sheet piling and pile retaining walls:

a) anchorless; b) anchored in the slab; c) anchored to the inclined pile; d) on a pile foundation;
1 – sheet pile, 2 – rod (rod), 3 – slab, 4 – piles

2. Sheet piling and pile retaining walls – are erected on a base that allows the deepening of sheet piles or piles (Figure 2). They are part of berth buildings, embankments and other hydraulic structures.

The strength of sheet piling and pile retaining walls is ensured by resistance to bending, and stability – mainly by resistance to bulging of the foundation soil.

Consequently, sheet piles generally act as flexible retaining structures. This means that they hold the soil, resist shifting and overturning due to embedding in the soil mass or the design of the fasteners (spacers, anchors). Thus, sheet piling structures operate either according to a cantilever design scheme or a beam design scheme (in the presence of spacers or anchors). Spacers and anchors should be used in cases where the operation of sheet piles according to the cantilever scheme does not provide the required durability, strength, rigidity, and deformability. As a rule, when the height of the retained difference is more than 5 m, fastening structures are required. In addition, it should be understood that the operation of a sheet pile using a cantilever scheme requires the presence of sufficiently strong soils into which the sheet pile can be deepened.

Calculation of sheet piling comes down mainly to determining its length and type, as well as the parameters of the anchor or spacer support, if necessary. Therefore, we are considering a problem of models for calculating sheet piling bank protection.

Models used for calculating natural slopes, bank protection slopes, combined into four groups:

- soils are considered as a continuous linear elastic medium that does not correspond to their natural state;
- soils in the form of a continuous incompressible single-phase medium, each point of which is in a state of maximum stress (theory of V.V. Sokolovsky);
- deformation-free models of the hardened compartment of the soil collapse, which is taken as an absolutely rigid body;
- soils as a solid, deformed, elastic-plastic, heterogeneous and strengthening medium, at each point of which it is possible to determine both stresses and strains from single positions.

The fourth nonlinear calculation model is complex, but it is the most progressive, both theoretically and in numerical implementation [14]. Compared to the other three models, it more fully reflects the natural soils' properties.

The paper presents approaches to the calculation of sheet pile fastening by the graph-analytical method – the Blum-Lohmeyer method. At the same time, the calculation is performed in the following order: the total soil pressure plot is divided into 10-12 layers. The areas of each layer are calculated, which are replaced by concentrated forces and laid in the center of gravity of the layers, taking into account the direction.

The stability of bank protection structures is checked using deep shear schemes using the K. Terzaghi method, in which calculations are reduced to determine the safety factor for the overall stability of the structure. When calculating the stability of slopes, it is important to establish the most dangerous position of the sliding surface, the stability of which is assessed by calculation methods, for example, the method of circular cylindrical surfaces of a leaning slope of horizontal forces.

Assessing the stability of a bank protection structure based on solutions to the elastic-plastic problem of nonlinear soil mechanics – establishing the relationship between the load and the deformation of the foundation. When calculating the stability of slopes based on deformations, the soil is considered as a structurally stable body, the deformation of which is assessed based on the theory of creep.

To calculate deformations, and assess the strength and stability of soil masses and foundations, we consider the characteristics of the mechanical properties of soils. By mechanical properties of soils, mean their behavior under the influence of external load or a change in their physical state. The mechanical properties of soil depend on the mineral and granulometric composition, physical state (density, humidity, temperature) and structural features.

Research results and their discussion.

The stability of bank protection slopes from the point of view of deformation development and offsets. Under natural conditions, the soil is affected by tension from its weight. Deformations usually occur upon completion of the processes of soil creation and diagenesis, external load, etc. If the soil is located in the base of massif then under the influence of the weight of the structure, stress arises, which leads to additional deformation of the soil. Soil deformations under load are accompanied by complex processes: compression of solid particles, compression of water and air that are in the pores of the soil, destruction of bonds between particles and their mutual displacement, changes in the thickness of water films, and squeezing out free water from soil pores [15]. Research by domestic and foreign scientists established stages of deformation of foundations, in which at each stage deformations of a certain type occur in the soil, affecting the nature of the dependence of subsidence on loading or pressure along the base of the foundation $p = F(A)$. The following stages of base deformation have been identified (Fig. 3):

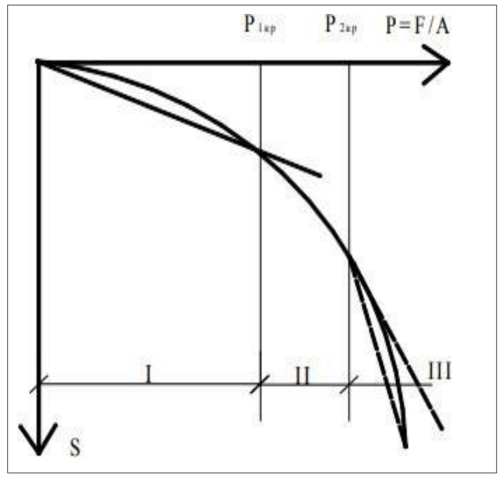


Fig. 3. Stages of base deformation:
I – compaction; II – shift; III – destruction

I – compaction stage;
II – shift stage;
III – stage of destruction.

In the first stage, the deformations are insignificant. The movements of soil particles are directed mainly vertically and a zone (core) of compacted soil is formed under the sole. The dependence $S = f/(p)$ in this section is close to linear. In the second stage, the nature of the deformation changes: the soil is squeezed out from under the edges of the foundation and areas are formed in which the strength of the soil is exhausted – shear zones. As they develop, the increment in subsidence increasingly outpaces the increment in pressure, which is described by the nonlinear relationship $S = f/(p)$.

The exit of the displacement areas to the soil surface leads to the beginning of the III stage – the destruction of the base with failure settlement.

Analyzing the graph (Fig. 3), it becomes necessary to theoretically determine the pressures (loads) that cause the transition of the base from one stage of deformation to another.

Taking into account deformation properties, and indicators of soil mechanics, which describe mechanical properties, the main regularities of soil mechanics are established, which are listed in Table 1.

1. The main regularities of soil mechanics

The law	Indicators	Note
Deformation characteristics		
Law of compaction	*m*0 – compressibility coefficient; *mv* – relative compressibility coefficient; *E*0 – modulus of total deformation	When calculating the foundation using the second group of limit states or deformations
Strength characteristics		
Coulon's law	φ – angle of internal friction; C – specific adhesion	When calculating the stability of the foundation, the first group of limit states
Water permeability		
Darcy's Law	*kf* – filtration coefficient; *cv* – consolidation coefficient	Calculation of base subsidence over time, other filtration calculations

Methods based on solving a system of equations of the theory of limit equilibrium with the construction of a grid of slip lines in the soil mass forming the slope. Quantitatively, the degree of slope stability is usually characterized by a stability or reliability coefficient, determined by the ratio:

$$C_{st} = F_{hodl} / F_{destr} \qquad (1)$$

where F_{hold} – a factor that takes into account the action of all forces that ensure stability;

F_{destr} – also, causing the slope to collapse.

The essence of the factors – forces or moments of forces – depends on the shape of the probable slope failure and, consequently, on the adopted design scheme.

By definition (1), when $C_{st} > 1$ the slope is stable, when $C_{st} < 1$ it is unstable, and when $C_{st} = 1$ there is a limiting equilibrium.

Having specified the value of C_{st}, you can determine the slope contour corresponding to it. The basis for assigning a stability coefficient can be regulatory recommendations (usually $C_{st} = 1,2–1,5$), as well as special pre-design studies. For the simplest but most common structures, methods for calculating the stability of slopes at limiting equiaction are often used.

Conditions for the limit equation of a granular body. In the case of hydraulic engineering constructions, a granular body (medium) includes solid homogeneous parts (soil, crushed stone), characterized by friction and adhesion coefficients. The amount of internal friction of a granular medium is estimated by the angle of internal friction – φ, and the amount of adhesion – by the adhesion coefficient – *C*.

The stability of a bulk body (medium) is ensured provided that at each point of it (the body) the following inequality is satisfied:

$$/\tau_n/ \leq \delta_n \, \mathrm{tg}\varphi + C, \qquad (2)$$

That is, with (2), the magnitude of the tangential stress in the massif, which causes displacement (sliding) of parts of the soil along any sliding plane, will be less than the sum of the friction and adhesion forces on the same plane. The condition for limiting equation in this case can be written in the form

$$/\tau_n/ = \delta n \, \mathrm{tg}\varphi + K, \qquad (3)$$

and the plane corresponding to this condition is the sliding plane.

The magnitude of the stresses and the coefficient of adhesion from the Coulon-Mohr circle are determined by the dependence:

$$/\tau_n/ = \frac{\delta 1 - \delta 3}{2}\cos\varphi$$

$$/\tau_n/ = \frac{\delta 1 - \delta 2}{2} - \frac{\delta 1 - \delta 3}{2} * \sin\varphi, \qquad (4)$$

$$K = \frac{\delta 1 - \delta 3}{2} * \frac{1}{\cos\varphi} - \frac{\delta 1 - \delta 3}{2} * \mathrm{tg}\varphi,$$

where $\delta 1 - \delta 3$ – normal stress.

Then the limit equilibrium condition can be expressed as a dependence:

$$(\delta_x - \delta_y)^2 + 4\tau^2_{xy} = (\delta_x + \delta_y + 2K \, \mathrm{tg}\varphi)^2 * \sin\varphi \qquad (5)$$

at $\varphi = 0$, that is, for a medium with perfect adhesion, the condition takes the form:

$$(\delta_x - \delta_y)^2 + 4\tau^2_{xy} = 4K^2. \qquad (6)$$

Which coincides with the plasticity condition (5).

The deformation equilibrium equation and condition (5) constitute the basic equation of statics of a granular mass (medium), which can be expressed by the equations:

$$\frac{d\delta_y}{d\delta_x} + \frac{d\tau_{xy}}{\delta_x} = 0;$$

$$\frac{d\delta_y}{d_y} + \frac{d\tau_{xy}}{\delta_x} = \gamma;$$

$$(\delta_x - \delta_y)^2 + 4\,\tau^2_{xy} = (\delta_x + \delta_y) + + 2K\,\mathrm{tg}\varphi^2) * \sin^2\varphi, \qquad (7)$$

where: γ, φ, К – volumetric weight, friction angle, specific adhesion of bulk medium.

Equation (7) allows for solving a wide range of issues related to the ultimate equilibrium of earth masses.

Discussion of the results. The results of the analysis of the stability of bank protection slopes and static calculations of bank protection structures indicate that the magnitude of the forces accepted by the structure varies widely depending on the physical and mechanical properties of the soil, the structure of the structure and the methods of construction work. It is impossible to take into account all factors. Therefore, it is proposed to exclude less important components from consideration and focus in the calculation theory on the components of the system – the interaction of fastener structures with the soil mass. The bank protection design, when interacting with the soil mass, absorbs part of the loading, thereby ensuring the stability of the soil mass, and also contributing to the equilibrium process. Consequently, the fastener structure and the earth mass are load-bearing components of a single system, and the stresses arising in the system are constantly interconnected. The above makes it possible to apply the modern apparatus of the theory of elasticity based on the linear relationship between stress and deformation through the use of differential equilibrium equations for the soil massif.

Conclusions. Methodological approaches are proposed for the static calculation of bank protection of sloped-vertical structures, taking into account the relationship between the load on the structure and its deformation.

The system "soil mass – fastener construction" is considered a one-sided calculation model, which is presented as an elastic element, which allows the use of modern elasticity theory. Accepting a linear relationship between stress and deformation simplifies the calculation of loads with obtaining stability indicators of bank protection structures with sufficient accuracy, which is confirmed by the available materials from the results of domestic and foreign research. Differential equations of equilibrium of the soil massif are formulated, which allows solving a wide range of issues related to limit equilibrium and obtaining calculation parameters of the pressure of soil masses on the retaining walls of shore fortifications of the slope-vertical type.

The research results are recommended for use in determining the main loads on hydrotechnical structures and justifying technical solutions for the development and improvement of oblique and oblique-vertical types of shore fortification of reservoirs.

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ПІДХОДИ ДО ОЦІНЮВАННЯ СТІЙКОСТІ СПОРУД БЕРЕГОУКРІПЛЕННЯ ВОДОЙМ: АНАЛІЗ КОНСТРУКЦІЙ І МОДЕЛЕЙ ЇХ РОЗРАХУНКУ

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Анотація. *У статті наведено результати аналізу теоретичних основ визначення напруженого стану в ґрунтовому масиві і конструкції кріплення берегового укосу водойм. Систематизовано наукові дослідження і теоретичні положення з визначення зусиль діючих на конструкції кріплень. Запропоновано методичні підходи до статичного розрахунку берегоукріплень укісно-вертикальних конструкцій з урахуванням взаємозв'язку між навантаженням на конструкцію та її деформацією.*

Метою досліджень визначено забезпечення стійкості та надійності конструкцій берегоукріплень та обґрунтування напрямів удосконалення технічних рішень у сучасних умовах.
У роботі проаналізовано застосовування різних типів укісних кріплень берегоукріплювальних споруд відповідно до вимог Державних будівельних норм. Запропоновано зосередити дослідження на шпунтових кріпленнях берегів, як на сучасній і прогресивній технології берегоукріплення. Система «ґрунтовий масив – конструкція кріплення» розглядається як розрахункова модель у вигляді одностороннього типу, який являє собою як пружний елемент, що дає можливість у розгляді цієї задачі застосувати сучасний апарат теорії пружності. Це дає можливість прийняти лінійну залежність між напругою і деформацією та отримати достатню точність, що підтверджується наявними результатами вітчизняних та закордонних досліджень. Для розрахунків деформацій, оцінювання міцності та стійкості ґрунтових масивів і основ запропоновано приділяти безпосередню увагу характеристикам механічних властивостей ґрунтів, при цьому розглянуто три стадії деформації основ. Сформульовані диференціальні рівняння рівноваги ґрунтового масиву, дають змогу вирішити широкий спектр питань, пов'язаних з граничною рівнодією та отримати розрахункові параметри тиску земляних мас на підпірні стінки берегоукріплень укісно-вертикального типу. Результати аналізу досліджень рекомендовано для використання у визначенні основних навантажень на гідротехнічні споруди, обґрунтуванні технічних рішень з розробки та удосконалення конструкцій укісного й укісно-вертикального типів берегоукріплення водойм.
Ключові слова: *берегоукріплення, напружений стан, теорія пружності, ґрунтовий масив, модель розрахунку, стійкість*

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