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

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CALCULATION AND VISUALIZATION OF WATER CONSUMPTION RATES OF CROPS WHEN USING INFORMATION TECHNOLOGIES

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Abstract. *The article analyzes existing approaches to determining water consumption rates of crops for irrigation in Ukraine. They were estimated at the level of weather stations and regions, in view of climate change and the need for their constant updating using the developed automated system and information technologies. It was found that water need for growing crops has increased significantly, especially in the southern regions of Ukraine. This work is a continuation of the study of evapotranspiration, its components and dynamics based on remote sensing data and calculations when using the Penman-Monteith-Leuning method. The obtained results are presented in an interactive database and as visualized cartographic information. The rate calculation was carried out based on the potential evapotranspiration for the period 2005–2024, when using the biophysical Shtoiko method, which allows determining water consumption rates taking into account a natural moisture deficit. Meteorological data from regional weather stations operating in automatic mod as well as the information systems developed at the Institute of Water Problems and Land Reclamation were used for calculations. Water consumption was estimated based on water balance equations and multi-year series of agricultural and meteorological observations.*

The average annual sowing dates and development phases of the main crops in the regions of Ukraine were also specified, with reference to weather stations, and the maps of water consumption spatial distribution were built. A database of crop water consumption rates was created with integrating geospatial parameters. Python software was developed using the Folium, Shapely, and Django libraries for data analysis and visualization. For geospatial presentation of the results, the zones of weather stations influence were calculated using the Thyssen-Voronyi polygon method. The study revealed a significant increase in water consumption rates for crops in Ukraine over the past two decades compared to the control climatic period of 1960–2000. In the Steppe zone, water consumption increased by 40 %, in the Forest-Steppe and Polissya zones – by 15 %. Data analysis for 2005–2024.

Analysis of data for 2005–2024 confirmed a further increase in water consumption in all climatic zones by an average of 18–25 %. Combining these data with web tools increases the availability of information and promotes its practical use in agriculture. Maps of water consumption deficits for the warm period of the year, water consumption rates for corn and wheat for the years of 50 %, 75 % and 95 % water supply deficit, which reflect regional variability in their distribution, were built. The study confirmed the need for constant updating of water consumption rates and their consideration in planning agricultural policy and water management.

Keywords: *evapotranspiration, water consumption rate, the Shtoiko method, information system, BBCH, development phases, Thyssen – Voronyi polygons, irrigation.*

Relevance of the research. Recent decades are characterized by a steady trend towards increasing aridity of the climate and maximum temperatures in the summer period [1, 2]. This has influenced the duration of crop vegetation period. Under these conditions, irrigation becomes key as one of the main measures for adapting agricultural production to climate change [3].

Effective adaptation involves the implementation of modern methods of water use planning and optimization of irrigation regimes taking into account the biological characteristics of crops, soil properties, irrigation technologies, as well as economic and environmental factors. Water consumption rates are a somewhat generalized criterion for assessing the suitability of the climate for crop growing under irrigation, since the same year, according to the assessment of water consumption deficits in the warm period, may be favorable for some crops and not favorable for others.

Water consumption rates are classified by various criteria: annual level of water supply by water consumption deficit, water losses, period, irrigation technologies, territorial relevance and optimality criteria.

Such rates are applied annually and in the long-term in water management planning, are used by project organizations to determine water supply volumes, calculate the capacity of irrigation networks and justify the water supply of systems being built or reconstructed. Management organizations use them to draw up annual water use plans and justify tariffs for water supply for irrigation, issue permits for special water use, etc. These indicators are necessary for agricultural producers for planning water intake volumes, calculating energy consumption and irrigation costs and assessing the economic efficiency of irrigation under various strategies of its use [4, 5].

Currently, studies of the mechanism of changing crop water consumption are very important for developing adaptation strategies and finding alternative solutions for water supply in agroecosystems. Determining the dependencies between climatic factors (temperature, precipitation, evaporation) and plant growth phases is the basis for optimizing water management, modernizing irrigation systems, and adapting agricultural technologies to new conditions. The study uses well-known methods for modeling crop water balance given regional climatic features of Ukraine.

Analysis of recent research and publications. Climate change is already having an impact and in the future, if current trends continue, it will cause an increase in demand for crop irrigation, and will affect the selection of sources and methods of irrigation in agriculture. This is evidenced by the studies conducted in Ukraine [6], the USA [7, 8], etc. Recent assessments conducted with the participation of the scientists from the Institute of Water Problems and Land Reclamation of NAAS [9] have shown that the restoration of irrigation will have significant potential for post-war reconstruction in war-affected regions, and play a significant role in supporting production, increasing productivity and ensuring the sustainability of agricultural crop cultivation.

Climate change will have a significant impact on all agricultural producers, but this impact will vary across countries and within individual territories due to different water requirements for irrigation, which are also changing.

The increase in the amount of moisture required during the season is already forcing agricultural producers to reconsider crop rotations in favor of more drought-resistant crops and technologies for their cultivation with minimizing unproductive moisture losses. Quantitative estimates of changes in seasonal water requirements have previously been obtained using agrometeorological yearbooks based on seasonal calculations.

The water consumption rates developed in the IWPLR [2] were based on the observations data from weather stations in the South of Ukraine, but progressive climate change caused the necessity to develop water consumption rates for the entire territory of Ukraine. In modern conditions, the assessment of water consumption deficits is also carried out using remote sensing and GIS [10–12], however, official data from ground-based weather stations are basic for comparison and development of regulatory documentation. This study focuses on the analysis of climate data and spatial visualization of water consumption rates based on weather station data, as well as clarification of the onset timing of the phenological phases of crop development based on the analysis of agro-forecast information and data from leading agricultural producers.

Effective water management requires irrigation planning, which in turn requires accurate measurement of crop water needs, namely accuracy in determining plant evapotranspiration.

In world practice, there are various approaches to calculating evapotranspiration, which have pros and cons [13–16]. Monitoring evapotranspiration by remote sensing when using satellites is becoming increasingly popular [17]. Ready-made solutions for measuring evapotranspiration are modern software products that automate all calculations necessary for its determination. [18–20]. In addition to numerical models based on using meteorological and remote sensing data as well as energy balance calculation algorithms, modern approaches involve the use of machine learning (ML) modeling methods [21].

There are a number of methods for calculating actual evaporation. According to the recommendations of the FAO, the Penman-Monteith method is used; however, in the case of limited climatic data, as in this work, the Shtoiko biophysical method was used, which is based on the correlative dependencies between air temperature, relative humidity, and total moisture evaporation from the soil. This method is called biophysical in the literature, since it enables us to calculate the total moisture evaporation from a field under a certain crop for any time period of the growing season.

The biophysical method is based on the fact that at optimal soil moisture, the evaporation process is practically not regulated by the plant and soil, since the supply of moisture to the plant or to the evaporation surface depends only on the state of the atmospheric surface layer.

The purpose of the research was to calculate and spatially visualize seasonal water consumption rates of crops, necessary for medium- and long-term irrigation planning.

The materials and research methods

The research was conducted from 2005 to 2024. To calculate evapotranspiration, when using the Shtoiko method, meteorological data from regional weather stations of Ukraine operating in automatic mode were used, as well as information systems developed by the IWPLR. The calculations were made in the warm period of the year [28] using daily data. They enabled us to determine the water consumption deficit of various crops when using standard calculation procedures.

The research algorithm can be presented in the form of the following stages:

- accumulation of daily climate data in the database;
- calculation of soil moisture consumption by the Shtoiko method;
- formation of data sets on phenological phases of crop development with reference to weather stations using the BBCH scale (an international system (scale) for describing the phenological phases of plant development in two-digit codes [29];
- ranking of data by weather stations in a multi-year series;
- development of software using the Folium, Shapely, Django, Voronoi package libraries [32];
- determination of the influence zone of weather stations by the Thyssen – Voronoi polygon method;
- visualization of calculated water consumption rates for a given level of annual water supply by the water consumption deficit of a certain crop.

The rationing of crop water consumption under irrigation is made based on zoning of the territory by a natural moisture coefficient and water balance calculations of the water consumption deficit. The water consumption rate is the estimated amount of water required during the growing season (irrigation season) per 1 ha of area to achieve the planned yield in specific natural, technical and economic conditions [22, 23].

Modern methods for determining water consumption rates include the use of the latest technologies, mathematical models and monitoring systems that allow for accurate calculation of the required water supply volumes. They take into account climatic conditions, crop development phases, soil type and irrigation methods [1, 2, 19].

The calculation of water consumption rates is based on determining the water consumption deficit when using a following water balance equation in the active soil layer:

$$D_i = E_i - \left(P_i - \Delta P_i\right), \quad \text{m}^3/\text{ha}, \quad (1)$$

where D_i is crop water consumption deficit the *i-th* decade of the growing season;

E_i is total evaporation;

P_i is precipitation;

ΔP_i is the part of precipitation that account for surface runoff and filtration.

Long-term series of meteorological observations (20–30 years) from representative weather stations, which allows obtaining reliable results for a specific territory [24, 2] are used.

To calculate the soil moisture losses, the biophysical method of Shtoiko was used in this work. The coefficient of soil moisture losses at different depths of groundwater was not used. Under these conditions, from sowing or germination to complete shading of the soil surface and during the ripening period, the total evaporation is determined by the formula [25]:

$$E_1 = \sum_{i=1}^{n} t_c^i * \left(0.1 * t_c^i - \frac{a}{100}\right). \quad (2)$$

And in other periods, when there is a complete soil shading by plants and more intense evaporation the total evaporation is determined by the formula:

$$E_2 = \sum_{i=1}^{n} t_c^i * \left(0.1 * t_c^i + 1 - \frac{a}{100}\right), \quad (3)$$

where – $\sum_{i=1}^{n} t_c^i$ is the sum of average daily air temperatures for *n* days;

t_c^i – average daily air tempeature for the period;

a – average daily relative air humidity for the period, %.

To calculate crop water consumption rates, the sum of water consumption deficits D_i for all decades of the irrigation period is reduced by the amount of readily available moisture in the active soil layer at the beginning of the growing season (W_0).

$$M_{j_n} = \sum_{i=1}^{i=J} D_i^{\kappa} - W_{0_j}, \quad \text{m}^3/\text{ha} \quad (4)$$

where M_{j_n} – crop water consumption rate;

D_i^{κ} – water consumption deficit in the i^{th} decade of the growing season;

W_{0_j} – starting moisture reserves in the active soil layer in the j^{th} period.

Based on crop water consumption deficits, net-field water consumption rates are determined. When calculating the water consumption of winter crops, autumn moisture-charging watering is also taken into in case it is performed.

Conversion into gross-field rates is made by dividing the net-field water consumption rates by efficiency coefficients of the irrigation network and sprinkling equipment. In this research, the net-field water consumption rate was determined.

The annual water consumption deficit is the probability in the estimated multi-year series of the number of years in which this deficit cannot be exceeded. When calculating crop water consumption deficit of agricultural crops based on a multi-year series of meteorological observations on air temperature, air humidity and precipitation, it is assumed that the patterns of D_i distribution observed in the past will be repeated in the future. To determine water consumption rates in irrigation of a given statistical water probability, the multi-year series of water consumption deficits D_i is ranked, and the water probability is determined by the Chegodaev formula [30, 31]:

$$p = \frac{n - 0.3}{N + 0.4} \cdot 100, \%, \quad (5)$$

where n is the serial number of the required rate by the deficit of the water balance;

N is the number of years in the series.

In the practice of irrigated agriculture, when designing, the most common calculation rates are 75 % of probability by water consumption deficit, which correspond to the average dry year and meet crop need in irrigation in approximately 3 out of 4 years. Therefore, the obtained probability p is reliable providing plants with water along many years of irrigation system operation, while $1-p$ characterizes unreliability, and is a risk characteristic.

The software developed in the Python programming language uses the Folium, Shapely, and Voronoi libraries for data analysis and visualization, and Django – for data storage [32].

To estimate the influence zone of weather stations, Thyssen-Voronoi polygons are used in calculations and visualization. They are built around a network of weather stations in such a way that the distance from any point to a weather station inside the polygon is always less than to any other point object within the existing weather station network. The data calculated for different degree of water consumption deficit probability (50 %, 75 %, 95 %) will be considered representative for the corresponding polygon. When visualizing crop water consumption deficits that are not typical for cultivation in a given region, the calculation results are not displayed, ensuring the correctness of the analytics.

Research results and their discussion. Based on the analysis of existing approaches to determining seasonal water consumption rates, assessments were made at the level of meteorological stations and regions. Water consumption rates, calculated based on estimates of potential evapotranspiration, are necessary for the development and implementation of state policies in the agricultural sector of Ukraine. They serve as an important source of information when forming integrated water resources management plans, agricultural sector development forecasts, setting restrictions on water use for irrigation, designing and reconstructing irrigation systems. Due to climate change, water consumption rates have to be constantly updated, and their trends have to be determined to assess the sustainability of current agricultural practices.

According to the research being conducted at the Institute of Water Problems and Land Reclamation, changes in modern climatic conditions and increasing aridity in almost all regions of the country have proven the need for developing water consumption rates not only for the southern, but also for the central and northern regions of Ukraine [12, 29].

Since 2005, climatic weather stations have been operating in automatic mode. The process of accumulating and analyzing climatic data, ranking years in series by the deficit of precipitation and water consumption, determining development phases and forming a ranked series with determined water consumption deficits has been automated. The results are collected in an interactive database on the website of the Institute of Water Problems and Land Reclamation [26].

Based on the assessment of potential evapotranspiration by the Shtoiko method when using modern climate data, updated crop water consumption rates were obtained and their trends were assessed. Water consumption rates were obtained for different levels of detail:

agro-climatic zone (Steppe, Forest-Steppe, Polissya), region, district, individual weather station, for crops under sprinkler irrigation, for dry (P = 95 %), medium-dry (P = 75 %) and medium (P = 50 %) years by water deficit.

Data on water consumption rates obtained in previous climatic periods are arranged in recommendations and reports [2, 24]. However, comparison of the water consumption rates obtained when processing the data for 2005–2024 has shown an increase in the impact of climate change. Table 1 shows the results of a selective comparison of normative values with data calculated when using the developed software [27]. As an example, a comparison of water consumption rates for winter wheat in different years of moisture supply when using normative data and meteorological data from the Kherson weather station is given. Data on the current water consumption rate are updated and arranged into series, automatically forming an annual current series and a list of observations for individual crops and meteorological stations, accumulating and replenishing the knowledge database.

The assessment of the results showed that with the onset of acute drought years (when natural moisture supply deficit is of 95 % probability and higher), water consumption rates in the Steppe zone of Ukraine increase on average by 15–40 %, in the Forest-Steppe zone by 9–67 %, and in Polissya by 2–58 %, depending on the crop grown.

Figure 1 shows the spatial distribution of water consumption deficits for years with different water probability, calculated when using the Shtoiko formula (3) based on the analysis of a series of data from May 1 to September 30 for 2005–2023. Using the formula (3) allows us to estimate the maximum values of water consumption deficits for years with different water probability.

Fig. 1 shows the degree of moisture deficit that occurs in years of different water probability. Thus, in medium-dry years (75 % water probability), that is, under conditions when natural moisture is insufficient, but not yet critical, there are regions where the natural moisture deficit is stably high, so there is a need to adjust water supply rates to obtain high yields. The greatest deficit is

1. Example of comparison of water consumption rates for winter wheat and mid-season corn in different years of water consumption deficit probability by weather station data

Kherson weather station, crop – winter wheat	**Probability the year by water consumption deficit,%**		
	95 %	**75 %**	**50 %**
Standard value, m^3/ha	2100	1500	1300
Calculated value (2005–2024), m^3/ha	2871	2553	2216
Deviation, %	36 %	70 %	70 %
Odesa weather station, crop – mid-season corn			
Standard value, m^3/ha	3900	3700	3500
Calculated value (2005–2024), m^3/ha	4890	4440	4145
Deviation, %	25 %	18 %	18 %

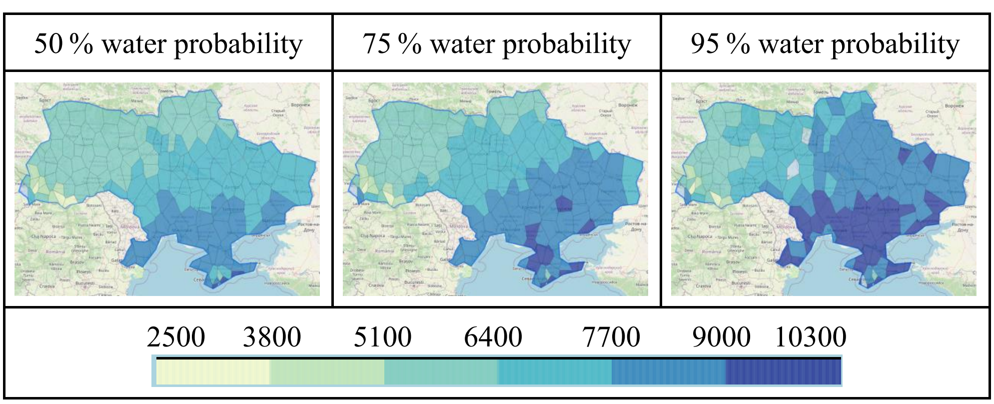

Fig. 1. Spatial distribution of water consumption deficits for years with different water probability by the Shtoiko E2 formula based on the analysis of a series of data from 01.05 to 30.09 for 2005–2023, m^3/ha

observed in the Steppe zone, especially in Odessa, Mykolaiv, Kherson and Zaporizhzhia regions. At the same time, in the Forest-Steppe and Polissya zones the moisture deficit is moderate.

In the driest years (95 % water probability), when natural moisture supply is extremely low, the need for additional irrigation becomes critical. Fig. 1 clearly shows that the most arid regions are the south of Ukraine – Odesa, Kherson, Zaporizhzhia regions, where soil moisture is insufficient even for drought-resistant crops. However, a high deficit of water supply is also observed in the Forest-Steppe zone, while based on spatial zoning this territory did not need additional moisture until 2005 [28].

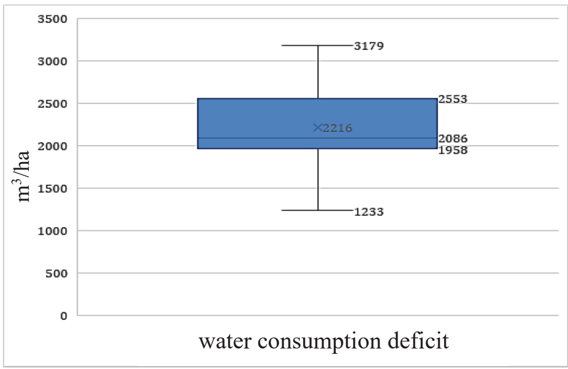

Fig. 2. Average ranked values of water consumption rates as a result of statistical analysis calculated by the Shtoiko method when using the data from the Kherson weather station, 2005–2024, m^3/ha

Figure 2 shows the results of the statistical analysis of the water consumption rate for a separate cell of the Thyssen-Voronyi polygon by the data of the Kherson weather station for the period 2005–2023 when growing winter wheat. According to this analysis, the average water consumption rate is 2216 m^3/ha – in the year of 50 % water probability, 2553 m^3/ha – in the year of 75 % water probability, 2871 m^3/ha – in the year of 95 % water probability and 1958 m^3/ha in the year of 25 % water probability by the deficit of natural moisture supply.

Climate change analysis shows that growing crops using the usual practices is already risky for Ukrainian agricultural producers. The high deficit of natural moisture supply shows that in the next 20–30 years, irrigation will be increasingly necessary to support crop production.

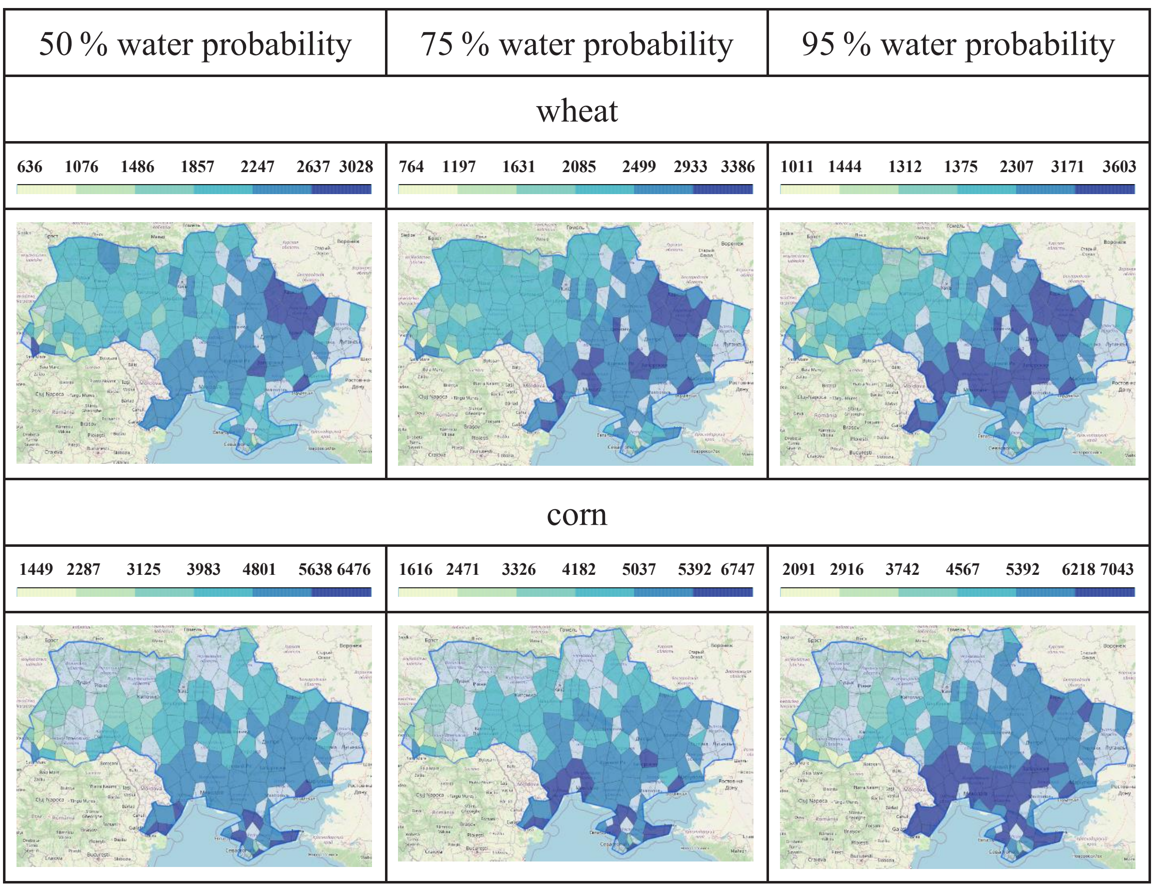

Fig. 3. Water consumption rates (m^3/ha) for growing crops in Ukraine in the years of different water probability with reference to weather stations

To calculate and specify natural moisture deficits, it is necessary to improve and replenish a database of agrometeorological parameters, data on crops given current trends in climate change: development phases, sums of active temperatures for the onset of phenological phases, lower limits of optimal moisture content in the root-containing soil layer and its depth, crop water consumption coefficients and their drought resistance depending on the development phases, etc.

In the course of conducted research, the phenological phases of crop development were assessed given the current trends in climate change, and crop databases were formalized and specified by the macrophases of the BBCH scale, both by regions and with reference to weather stations.

The analysis of phenological phases of plant development and their binding to weather stations in Ukraine was carried in the course of scientific research [29]. Based on the research results a database of the onset of crop development phases was formed. The study of crop development phases was carried given the data from agrometeorological yearbooks and the observation data obtained from leading producers of agricultural products. The database was digitized by the generally accepted BBCH scale for using in the information system. The calculation of water consumption deficits was made directly on vegetation days of each crop.

The calculation of water consumption rates for the main crops available in the database (early and mid-season soybean, spring and summer potato, mid-season corn, buckwheat, winter wheat, sugar beet, spring barley, oat, sunflower) for all natural-climatic zones of Ukraine was made given the phenological phases of their development, when using the available data from weather stations (Fig. 3).

The calculation of water consumption rates can be provided to the user both in paper form where there is information on water probability of the years (starting from 2005) and visualized information.

Further research will focus on comparing quantitative estimates of actual water consumption rates with similar estimates obtained from remote sensing data.

Conclusions

1. Comparison of the results obtained over the past two decades with the water consumption rates for 1960–2000, defined by the World Meteorological Organization as a reference climatic period, showed that the increase in water consumption in medium-dry years in the Steppe zone of Ukraine reaches 40 %, in the Forest-Steppe and Polissya zones – 15 %.

2. Comparison of accumulated data for 2005–2024 showed a continued increase in water consumption rates in all climatic zones (on average by 18–25 %) compared to the normative values and research data in the climatic period 1960–2000.

3. The practical use of updated water consumption rates will minimize environmental and economic risks when applying them due to their maximum compliance with the current climatic conditions.

4. Taking into account the specified phenological phases of crop development by the BBCH scale when determining water consumption rates allows us to specify the process of formation and accumulation of water consumption deficit during the growing season, depending on the phase of crop development.

5. Development of a database and visualization of water consumption rates, based on geospatial water deficits, creates a basis for medium- and long-term planning of agricultural activities. Combining this data with modern web tools will make the information accessible and practical for farmers and agronomists.

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

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

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МЕТОДОЛОГІЯ РОЗРАХУНКУ ТА ВІЗУАЛІЗАЦІЇ НОРМ ВОДОПОТРЕБИ СІЛЬСЬКОГОСПОДАРСЬКИХ КУЛЬТУР З ВИКОРИСТАННЯМ ІНФОРМАЦІЙНИХ ТЕХНОЛОГІЙ

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Анотація. *У дослідженні проаналізовано існуючі підходи до визначення та коригування норм водопотреби сільськогосподарських культур для зрошення в Україні. Коригування норм водопотреби здійснено по всім метеостанціям, для кожної з яких визначені дати настання фенологічних фаз сільськогосподарських культур. Виконано оцінку їх величини на рівні метеостанцій та областей, враховуючи сучасні кліматичні зміни та необхідність їх постійного оновлення з використанням розробленої автоматизованої системи та інформаційних технологій. Встановлено, що потреба у воді для вирощування культур значно зросла, особливо в південних регіонах України. Ця робота є продовженням дослідження евапотранспірації, її компонентів та динаміки за даними ДЗЗ за методом Penmann-Monteith-Leuning. Інтеграція до оцінювання евапотранспірації, розрахованої за різними методами залежно від наявних даних, дозволяє точніше враховувати зміни водопотреби* *сільськогосподарських культур, кліматичні зміни та регіональні особливості вирощування сільськогосподарських культур. Отримані результати впроваджено у вигляді інтерактивної бази даних та візуалізованої картографічної інформації. Розрахунок норм здійснено на основі потенційної евапотранспірації за період 2005–2024 рр. із використанням біофізичного методу Штойка, що дозволяє визначити оптимальні норми водопотреби з урахуванням дефіциту природного зволоження. Для розрахунків обирали метеорологічні дані регіональних метеостанцій, що працюють в автоматичному режимі та інформаційні системи розроблені в ІВПіМ. Оцінку водопотреби здійснювали на основі водно-балансових рівнянь та багаторічних рядів агро- та метеоспостережень. Проведена адаптація настання середньорічних дат сівби по основних сільськогосподарських культурах, здійснено уточнення настання фаз розвитку сільськогосподарських культур по регіонах України, з прив'язкою до метеостанцій, побудовано карти просторового розподілу норм водопотреби. Створена база даних норм водопотреби сільськогосподарських культур з інтеграцією геопросторових параметрів. Розроблено програмне забезпечення на Python із застосуванням бібліотек Folium, Shapely, Django для аналізу та візуалізації даних. Для просторового розподілу і аналізу поширення результатів розраховані зони впливу метеостанцій за методом полігонів Тиссена-Вороного. Дослідження встановило значне зростання норм водопотреби сільськогосподарських культур в Україні за останні два десятиліття порівняно з контрольним кліматичним періодом 1960–2000 років. У степовій зоні водопотреба збільшилася до 40 %, у лісостеповій та поліській – на 15 %. Аналіз даних 2005–2024 рр. підтвердив подальше зростання водопотреби у всіх кліматичних зонах в середньому на 18–25 %. Удосконалення методів розрахунку норм водопотреби з урахуванням фенологічних фаз розвитку культур за шкалою BBCH, дозволяє точніше оцінювати накопичення дефіцитів вологи протягом вегетаційного сезону. Поєднання цих даних із веб-інструментами підвищує доступність інформації та сприяє практичному використанню її у сільському господарстві. Побудовано карти розповсюдження дефіцитів водопотреби для теплого періоду року, норм водопотреби для кукурудзи та пшениці для років 50 %, 75 % та 95 % за дефіцитом водозабезпеченості, що враховують регіональні мінливості їх розподілу. Дослідження підтвердило необхідність постійного оновлення норм водопотреби та їх врахування при плануванні аграрної політики та управлінні водними ресурсами.*

Ключові слова: *евапотранспірація, норма водопотреби, метод Штойка, зміни клімату, інформаційна система, BBCH, фази розвитку, полігони Тиссена – Вороного, зрошення*

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STUDY OF THE POTENTIAL USAGE OF ANOLYTES ANK TO REMOVE BIOLOGICAL FOULING FROM DRIP IRRIGATION SYSTEMS

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Abstract. *The prospects for using neutral anolytes ANK of Ukrainian producers for cleaning emitters and pipelines of drip irrigation systems from contaminants of biological origin have been studied. The relaxation characteristics of the neutral anolytes ANK were determined, changes in their main characteristics (TDS, ppm, pH; ORP, mV) were established depending on the degree of dilution with water, and an assessment of the market and production capacities of anolytes ANK in Ukraine was performed. The laboratory, laboratory-analytical, field, and mathematical-statistical comparative research methods were applied to determine the effectiveness of flushing the emitters and drip irrigation pipelines with environmentally safe neutral anolytes ANK of Ukrainian manufacturers ("AQUA SALIS", "Krystal", and "Secobren") and environmentally hazardous 15 % sodium hypochlorite produced in the People's Republic of China (PRC). The presence of a biological component of contaminants was determined using the Biuret reaction. It has been found that obtaining effective solutions for flushing emitters and pipelines of drip irrigation systems from contamination of biological origin, with an ORP of not less than +750 mV, is possible by diluting the anolytes ANK produced by "Aquasalis", "Krystal", and "Secobren" with irrigation water in a 1:40 ratio; produced by "Sterilox", "Vitalmix" and "Allsteril" – in a 1:20 ratio.*

Visual and quantitative indicators of the quality of flushing the emitters and drip irrigation pipelines from contaminants of biological origin were obtained. In laboratory, it was determined that the flow rate of drip pipelines with 20 emitters clogged with biological contaminants after washing with hypochlorite "AquaDoctor", depending on the pressure, increased by 17.6…52.3 %, with anolyte "Krystal" – by 23.7…92.0 %. Field flushing of 136 m long drip irrigation pipelines with 340 emitters with anolytes ANK resulted in an increase in the flow rate of one pipeline by 8 l/h, and the other – by 13 l/h.

It has been found that neutral anolytes ANK produced in Ukraine are an effective and environmentally safe alternative to chemicals (chlorine, 15 % sodium hypochlorite, chlorine dioxide, and hydrogen peroxide), which are currently used to flush emitters and drip irrigation pipelines from contaminants of biological origin. It was determined that Ukrainian production capacities for anolytes ANK are capable of meeting the needs of Ukrainian farmers for flushing emitters and drip irrigation pipelines.

Keywords: *drip irrigation systems, drip water emitters, biological pollution, flushing, electrochemically activated low-concentration salt solutions, anolyte, sodium hypochlorite*

Relevance of the research. The problem of biological contamination of pipelines that transport water for various purposes is not the new, but the need to solve it is becoming increasingly urgent in different countries [1, 2]. For the drip irrigation systems, this issue has become one of the main reasons for the decrease in the reliability of their operation in recent years [3, 4]. It is associated, on the one hand, with the use of emitters (drip water outlets), the diameters of water supply pipelines (labyrinths) and holes of which are from 0.5 to 1.4 mm (to ensure flows from 0.5 to 8 l/h), and, on the other hand, with the increasing intensity of reproduction and growth of various microbiota in water supply sources due to the increase in solar radiation and average daily air and soil temperatures during the irrigation period as a result of climate change. It should be noted that emitters of drip irrigation systems, due to the very small diameters of their labyrinths, are vulnerable to contamination of mechanical and chemical origin in addition to biological contamination [5]. To prevent mechanical contamination, filter stations with coarse and fine filters are placed at the beginning of drip irrigation systems, which prevents mechanical particles that are larger in size than the diameters of the emitter labyrinths (50…150 microns) from entering the system. As a result, and while maintaining a turbulent water flow regime in the emitters, the risk of mechanical contamination is significantly minimized, but the threat of chemical and biological contamination remains high.

Chemical contamination of emitters occurs as a result of the formation of solid deposits in the labyrinths or at the emitter outlet due to the deposition of salts, metals, or mineral compounds under the influence of changes in pH, pressure, temperature, or mixing of fertilizers with water. The main mechanisms of chemical pollution are the contamination from carbonates $CaCO_3$, MgCO when using "hard" water, as well as phosphates and sulfates $Ca_3(PO_4)_2$ or $CaSO_4$ when fertilizers are improperly mixed during their application with irrigation water [6]. Another source of chemical (partially biological) pollution is the presence of Fe^{2+} or Mn^{2+} ions in water, which, upon contact with oxygen, are oxidized to insoluble forms of $Fe(OH)_3$ or MnO_2. These compounds form rusty-brown or black deposits that settle in pipelines and emitters and are often combined with biological deposits (iron bacteria). The main methods for combating chemical pollution are regular acid washing of systems with nitric, phosphoric, sulfuric, or citric acids [7]. Despite the fact that research is constantly being conducted to improve the means and methods of cleaning emitters of drip irrigation systems from contamination of mechanical and chemical origin, it can be considered that the problem of combating them has been generally solved today. But this cannot be said about the issue of combating biological contamination of emitters of drip irrigation systems.

Biological contamination of emitters of drip irrigation systems is a complex biochemical process, in which microorganisms create a biofilm, and within it, redox and sedimentary reactions occur, which lead to a decrease in the permeability of the emitter labyrinths and, as a result, a decrease in their flow rates and the reliability of the systems. The main groups of organisms involved in bio-fouling are bacteria (*Pseudomonas, Bacillus, Flavobacterium, Leptothrix, Sphaerotilus* – the most active initiators of biofilm); micro-algae *Chlorella, Oscillatoria*, and *Anabaena* that photosynthesize and produce mucus enriching the system with organic substances; fungi *Aspergillus, Penicillium,* and *Fusarium*, whose mycelium intertwines particles and enhances the mechanical strength of the biofilm; iron and sulfur bacteria (*Gallionella, Thiobacillus*), which oxidize Fe^{2+} or S^{2-} creating additional solid deposits (hydroxides, sulfates) [6]. The mentioned groups of microorganisms in the form of embryos, spores, and larvae practically freely pass through all filters, only partially slowing down on their working surfaces, penetrate with irrigation water into the distribution and irrigation pipelines of drip irrigation systems and emitter labyrinths, and, attaching to the walls, develop to sizes that subsequently significantly exceed the diameters of the labyrinths. In addition, growing in the housings and filter elements of the filters, they completely disable them. In coarse sand and gravel filters, algae and other microbiota form various colonies weighing up to several kilograms. E.g., during our audit on October 8, 2025, sand and gravel filters on the drip irrigation system of the FG "GRASS AVENUE" of the Zhytomyr district of the Zhytomyr region (near the village of Zabilochchya) of Ukraine, a significant amount of algae similar in appearance and consistency to river's Badyaga (*Ephydatia fluviatilis*) was discovered (Fig. 1).

Analysis of recent research and publications. Since the emergence of the problem of biological fouling of drip irrigation systems (late 1990s – early 2000s) and to this day, methods for cleaning drip irrigation pipelines and emitters from such contamination have followed similar methods for cleaning drinking water supply pipelines. The main method for a long time was chlorination [8]. Chlorination is quite effective in terms of destroying microbiota, but extremely dangerous from an ecological point of view. The disadvantages of chlorination of drip irrigation systems are the formation of toxic by-products: trihalomethanes, haloacetic acids, and chloramines. These compounds are toxic to plants, soil microbiota, and can pollute the environment [9]. In addition, chlorine causes corrosion of metal elements of the system (fittings, valves, pumps; elements of pressure control systems, etc.), and also leads to degradation of polymers, gradually destroying polyethylene and rubber parts (emitters, seals, tubes). Further searches for an effective cleaner

a

b

Fig. 1. Biological contamination of sand and gravel filters:
a – small particles of algae in water drained from the filter; b – large conglomerates of algae

for drip irrigation systems follow similar ways to overcome this problem in water supply: the use of sodium hypochlorite (NaOCl), chlorine dioxide (ClO_2), and hydrogen peroxide (H_2O_2) [10, 11, 12]. All of these substances are quite successful in destroying biological contamination (biofilms, bacteria, algae, fungi, etc.) also in drip irrigation systems. However, sodium hypochlorite can cause corrosion of system elements (which reduces their service life) and form harmful by-products, such as trichloromethanes. The use of chlorine dioxide, compared to chlorination and the use of sodium hypochlorite, reduces the risks of the formation of some organochlorine by-products, but does not guarantee their complete elimination, and, in addition, it has higher cost and more complex application technology. Hydrogen peroxide does not leave a chlorine residue, but it is quite corrosive and has a short life period, which makes it practically impossible to flush drip irrigation pipelines longer than 20…30 m.

The shortcomings of the existing methods for cleaning drip irrigation systems from biological contaminants necessitate the search for new, more effective and environmentally friendly methods for their cleaning. In the process of such a search, the authors drew attention to anolytes – electrochemically activated (ECA) low-concentrated salt solutions with high oxidation-reduction potential (ORP).

The history of the invention and development of electrolyzed water is associated with the Japanese company FUJIIRYOKI, which in 1931–1950 initiated scientific research into the production of such water and the study of its impact on the development of agricultural plants [13]. In the territory of the former USSR, work on the study of ECA water began in the 1970s in Uzbekistan by a group of scientists led by Ph.D. in Technical Sciences V. Bahir. The influence of the components of ECA water (catholyte and anolyte) on the properties of drilling fluids was studied, and high bactericidal properties of one of these components – anolyte – were discovered by chance. That was when the names "living water" appeared – for the catholyte – the alkaline component, and "dead water" – for the anolyte – the acidic component of ECA water. Catholytes, in addition to high alkalinity (pH 10 and above), are characterized by a negative ORP: −400 mV. The effect of catholytes on biological organisms, both of plant and animal origin, is manifested in their regenerative (antioxidant) and stimulating effects: seed germination improves along with plant growth and development; for humans and animals, catholyte promotes cell regeneration, but excessive or prolonged use can disrupt the acid-base balance. At the same time, the effect of catholytes on living organisms is less predictable than the effect of anolytes.

Anolytes, unlike catholytes, have high acidity (pH 5 and below) and high ORP values (+500 and above). The acceptor properties of anolytes determine their high bactericidal activity against almost all types of microorganisms. Anolytes destroy bacteria, viruses, fungi, and spores by destroying cell walls and membranes, oxidizing enzymes and DNA, and in plants at low concentrations they can stimulate germination, growth, and disease resistance. Anolytes are safe for animals and humans when properly diluted, but highly concentrated solutions can irritate mucous membranes. In general, catholyte and anolyte are paradoxical liquids, since their properties cannot be explained in terms of the normal physics and chemistry of water solutions. Being highly active substances, they are environmentally safe, and the ultra-low salt content in them (from 0.01 to 0.5 %) cannot explain their high activity. With the time that has passed since the discovery of the phenomenon of ECA water, many studies have been conducted on the influence of ECA water components on the processes of development and vital activity of plants and animals. Summarizing the research results, including the results of the authors of the paper [14], on the assessing the influence of ECA water components on plant development, we can state that irrigation with water solutions of catholytes (or their mixtures with anolytes) accelerates the germination and the development of vegetable crops and increases their yield. At the same time, it should be noted that this effect is quite differentiated and significantly depends on both the parameters of irrigation solutions (pH, ORP), and on the type of plants and stages of their development. In addition, one of the properties of catholytes is their rapid relaxation – the loss of biologically stimulating properties within a short time (several hours), which requires their production directly in the field – near the pumping stations of irrigation systems. All this significantly complicates and reduces the potential effectiveness of the use of catholytes in irrigated agriculture.

Unlike catholytes, the results of using anolytes are much more predictable and can be achieved much more easily technologically. Acting as universal, environmentally friendly and powerful antiseptics, anolytes have been used in the agricultural sector as environmentally safe disinfectants in the food industry and livestock farming since the middle of the first decade of this century [15, 16]. An important advantage of anolytes over catholytes is also their sufficiently long life period. These properties were acquired by neutral anolytes ANK, which began to be produced on advanced installations for the generation of ECA water starting from the end of the last – beginning of this century. Anolytes ANK are characterized by pH 6.5…7.2 and ORP +800…+900 mV with a guaranteed life period of at least 1 year.

Aim of the research is to determine the main characteristics of Ukrainian neutral anolytes ANK and to substantiate the possibility of their use for cleaning emitters and pipelines of drip irrigation systems from contaminants of biological origin, as well as the ability of Ukrainian manufacturers of anolytes ANK to meet the needs of the users of drip irrigation systems.

Research methods and materials. Analytical, laboratory, field, mathematical-statistical, and comparative research methods were used. Analytical methods were used in planning and summarizing laboratory and field research, assessing the market for Ukrainian anolytes ANK, etc. Laboratory, field, and comparative studies were conducted to determine the effectiveness of flushing emitters and drip irrigation pipelines with environmentally safe neutral ANK anolytes of Ukrainian manufacturers (“AQUA SALIS”, “Krystal”, and “Secobren”) and environmentally hazardous 15 % sodium hypochlorite produced in the PRC. Mathematical and statistical research methods were used in processing the results of laboratory and field studies. The presence of a biological component of pollution was determined using the Biuret reaction. Laboratory studies of the action of anolytes ANK on the cleaning of drip water emitters of a drip tape manufactured by “Metzer” (Ultra Lin W.T. – 0.15–5 F mil, with a diameter of 16 mm and a number of emitters of 20 pcs. with a distance between emitters equal to 20 cm) from contamination by organic compounds were carried out on a stand for testing drip irrigation pipelines (Fig. 2) in the Laboratory for Testing Irrigation and Drainage Means of the Institute of Water Problems and Land Reclamation of the National Academy of Agrarian Sciences of Ukraine (IWP&LR of NAAS) (Certificate of Measurement Capabilities No. PT-8/24 dated 01/11/2024). The flow rates of the emitters were determined by the volumetric method using 25 ml measuring cups and a stopwatch. The determination time at each pressure was 60 s. The pressure was created by the test bench pump, controlled by a manometer, and the pressure was regulated by a valve. The studies were conducted according to the microirrigation technical equipment testing methodology developed at the IWP&LR of NAAS [17].

Field research (tests) were conducted on drip irrigation systems of POA “UKRAINE” of Boryspil district, Kyiv region, Ukraine, and FG “GRASS AVENUE” of Zhytomyr district, Zhytomyr region (village Zabilochchya), Ukraine. The research was conducted on drip irrigation pipelines manufactured by the Spanish company AZUD, 136 m long and with a nominal passage diameter of 16 mm, equipped with adjustable (compensated) emitters with a nominal flow rate of 1 l/h and a distance between emitters equal to 40 cm.

The testing procedure included:

- emptying the irrigation pipelines (in turn) through the end taps followed by rinsing them with irrigation water for 5 minutes;
- measurement of pipeline flow rates with irrigation water supply at a nominal pressure of 0.17 MPa;
- filling pipelines with anolyte ANK flushing solution diluted with irrigation water in a ratio of 1:30;

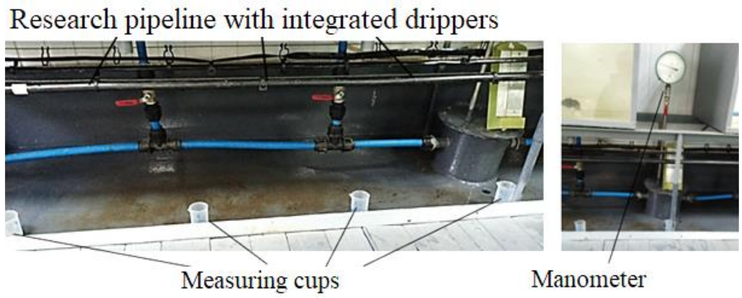


Fig. 2. Laboratory stand for testing water emitters and irrigation pipelines

- keeping the flushing solution in the pipelines for 48 hours;
- draining the flushing solution through the end taps and flushing the pipelines with irrigation water during 5 minutes;
- measurement of pipeline flow rates after flushing with irrigation water at a nominal pressure of 0.17 MPa.

The supply of irrigation water to the pipelines, as well as the preparation of flushing solutions, was carried out withdrawing water from the distribution pipeline of the pumping station. The preparation of the flushing solution was carried out in a mixing tank with a volume of 100 dm^3 (Fig. 3a), from which it was then pumped into the pipelines. Pressure was maintained using taps and controlled by a manometer with a measurement range of 0…0.6 MPa and a division value of 0.01 MPa of a portable measuring stand (Fig. 3b). The flow rates were determined using a volumetric water meter with a division value of 0.1 dm^3 as part of the stand (Fig. 3c) and a stopwatch.

Research results. Analysis of the Ukrainian market of anolytes ANK revealed the presence of 6 varieties: “Aquasalis”, “Krystal”, “Secobren”, “Sterilox”, “Vitalmix”, and “Allsteril” (Fig. 4). The production capacity of these anolytes ranges from 0.3 to 0.8 m^3/h.

a b c

Fig. 3. Technical means of research:
a – container with a pump inside for preparing the flushing solution and a line for pumping the solution into the pipeline; b – portable test stand with taps, a pressure gauge, and a water meter (also serves as a line for pumping the working solution into the pipeline); c – volumetric water meter

a b c d e f

Fig. 4. Neutral anolytes ANK of Ukrainian production:
a – “Aquasalis”; b – “Krystal”; c – “Secobren”; d – “Sterilox”; e – “Vitalmix”; f – “Allsteril”

Studies of the changes in the physicochemical properties of anolytes produced in Ukraine at different degrees of dilution with water allowed us to conditionally divide them into two groups according to the similarity of the main parameters (TDS, ppm, pH and ORP, mV) both in the initial state and after dilution with water in ratios from 1:5 to 1:50.

Table 1 shows changes in TDS, ppm, pH and ORP, mV of anolytes "Aquasalis", "Krystal", and "Secobren" (first group), Table 2 shows changes in anolytes "Sterilox", "Vitalmix", and "Allsteril" (second group).

As can be seen from the data presented in Table 1, despite the significant difference in the initial TDS values, the anolytes of this group have a pH close to neutral and an ORP exceeding +800 mV. It is especially important that even at high dilution rates with water (1:40), their ORP exceeds +750 mV, which will positively affect the bactericidal activity of their solutions.

1. Change in TDS, pH and ORP parameters of anolytes "Aquasalis", "Krystal", and "Secobren" depending on the degree of their dilution with water (water characteristics: TDS, ppm = 211 pH = 7.5; ORP, mV = 256 mV; T. deg. C° = 23.4)

Name	**"Aqua Salis"**			**"Krystal"**			**"Secobren"**		
Dilution	**TDS, ppm**	**pH**	**ORP, mV**	**TDS, ppm**	**pH**	**ORP, mV**	**TDS, ppm**	**pH**	**ORP, mV**
0	236	6,5	890	512	6,3	914	311	8,1	822
1:5	568	7,0	835	378	6,6	862	524	7,9	803
1:10	403	7,1	819	283	6,8	823	440	7,7	802
1:20	317	7,3	805	251	7,1	805	340	7,7	792
1:40	268	7,5	763	242	7,2	763	283	7,7	774
1:50	258	7,5	767	239	7,3	651	271	7,7	748

2. Change in TDS, pH and ORP parameters of anolytes "Sterilox", "Vitalmix", and "Allsteril" depending on the degree of their dilution with water (water characteristics: TDS, ppm = 226 pH = 7.4; ORP, mV = 251 mV; T. deg. C° = 24.5)

Name	**"Sterilox"**			**"VITAMIX"**			**"Allsteril"**		
Dilution	**TDS, ppm**	**pH**	**ORP, mV**	**TDS, ppm**	**pH**	**ORP, mV**	**TDS, ppm**	**pH**	**ORP, mV**
0	446	6,2	892	492	6,3	850	211	6,0	845
1:5	270	6,6	856	969	7,2	772	512	6,4	763
1:10	239	7,0	801	632	7,4	732	365	7,3	679
1:20	228	7,2	770	443	7,5	618	296	7,4	553
1:40	225	7,2	691	342	7,6	520	260	7,5	472
1:50	223	7,2	482	312	7,6	480	231	7,5	428

From the analysis of the data given in Table 2 it is clear that, despite the similar initial TDS, pH and ORP indicators when compared to the anolytes of the first group, in the anolytes of the second group, when diluted with water in proportions higher than 1:20, the ORP decreases to +770 mV in ("Sterilox") and lower – to + 618 mV in "VITAMIX", and to + 553 mV in "Allsteril", which will negatively influence the bactericidal properties of their solutions. Therefore, the dilution of anolytes of the second group when used for washing emitters and irrigation pipelines of drip irrigation systems should not be more than 1:20, while for the anolytes of the first group, the dilution can be carried out in a ratio of 1:40.

The study of changes in the main characteristics (TDS, ppm, pH and ORP, mV) of the anolytes ANK "Krystal", "Sterilox", and "Allsteril" over time showed that they retain their properties for a fairly long time (20 days) (Fig. 5). Fig. 5a shows that with a significant difference in the total salt content of the studied anolytes (from 200 to 1000 ppm), the nature of changes in this indicator over time is almost unchanged. Changes in the pH and ORP values for the anolytes (Fig. 5b, 5c) are more significant compared to the salt content, but these changes not only do not worsen, but on the contrary, due to the increase in ORP, improve the bactericidal effect of the anolytes. This gives reason to believe that it is possible to store anolytes for a relatively long time and deliver them to drip irrigation systems directly from manufacturers, which significantly improves the possibilities of using anolytes ANK to clean emitters and pipelines of drip irrigation systems from contaminants of biological origin.

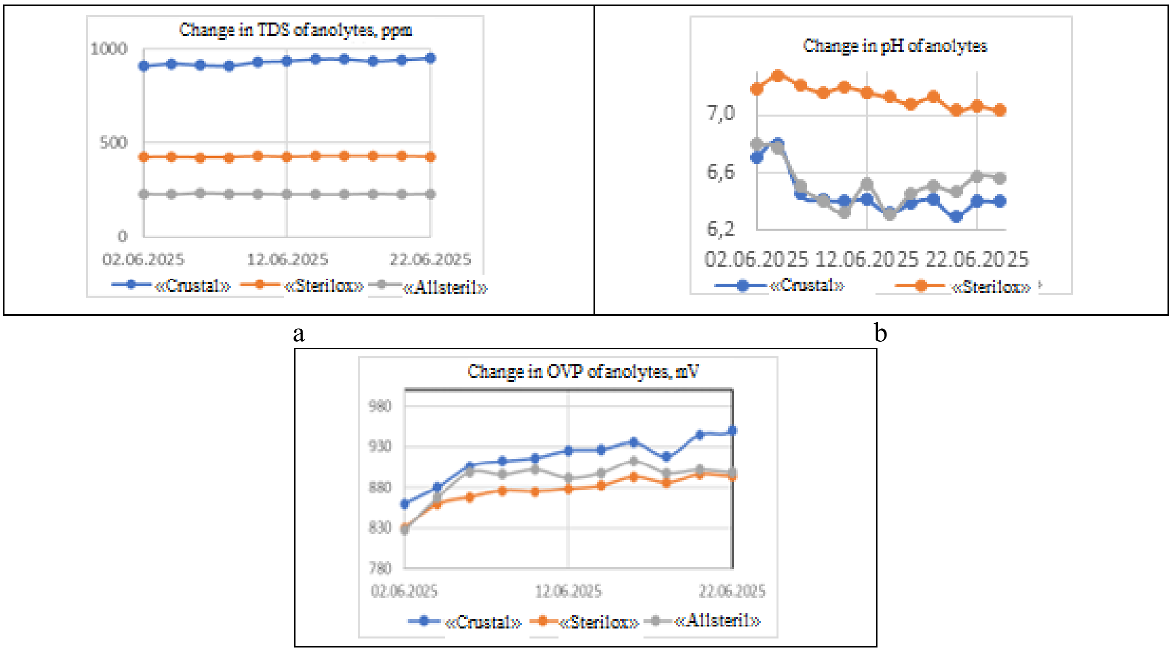


Fig. 5. Time-dependent changes in TDS, ppm (a); pH (b) and ORP, mV, of the anolytes ANK "Krystal", "Sterilox", and "Allsteril"

The feasibility of using anolytes ANK to clean emitters and pipelines of drip irrigation systems from contaminants of biological origin was substantiated based on the results of laboratory and field studies conducted in 2024–2025.

Laboratory studies in 2024 included a comparison of the effectiveness of flushing drip tape emitters with sodium hypochlorite "Akvador" (PRC) with an active chlorine content of 15 %, and anolytes "Krystal" and "Secobren". Flushing was carried out in two stages: in the first stage, the concentration of the solutions was 1 % at pressures from 0.025 to 0.1 MPa, in the second stage, the concentration was 5 % at pressures from 0.15 to 0.3 MPa. Before flushing, one of the samples was filled with "Akvador", the second one – with "Krystal", and the third one – with "Secobren". All samples filled with these substances were kept for 48 hours, after which they were flushed with water at pressures from 0.025 to 0.3 MPa. The results of laboratory studies confirmed high flushing ability of environmentally safe anolytes "Krystal" and "Secobren", which is not inferior to the washing effect of environmentally dangerous hypochlorite "Akvador" (Table 3) [19].

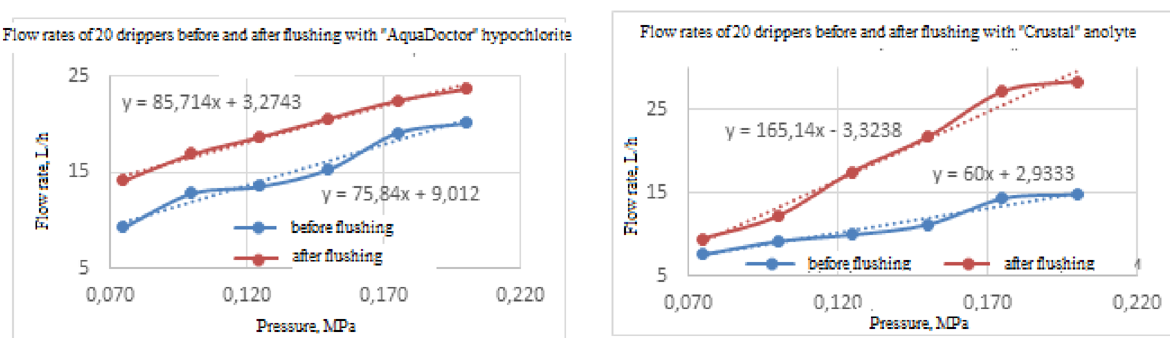
These results were confirmed by laboratory studies conducted in 2025 on the pressure-flow characteristics of pipelines with 20 emitters "before" and "after" flushing with 15 % sodium hypochlorite "AquaDoctor" (Fig. 6a) and anolyte "Krystal" (Fig. 6b). The flow rate of the pipeline after flushing with hypochlorite "AquaDoctor", depending on the pressure, increased by 17.6–52.3 %, and with anolyte "Krystal" – by 23.7–92.0 %. In this case, the pressure-flow characteristics of pipelines with 20 emitters before and after flushing in the pressure range of 0.075–0.2 MPa are approximated by the dependencies shown in Fig. 6.

The results of field research conducted in 2024 in the POA "UKRAINE", Boryspil district, Kyiv region, Ukraine, on the quality of flushing the pipelines of the subsurface drip irrigation system with anolytes ANK "Krystal" and "Secobren" and 15 % hypochlorite "AquaDoctor" showed comparable results of the quality of flushing with all three tested substances. Visual analysis of the condition of the inlet filters of the emitters of the drip irrigation pipelines "before" and "after" flushing showed a high degree of cleaning of the emitters with anolytes (Fig. 7) [19].

During field research in 2025 on the subsurface drip irrigation system of the "GRASS AVENUE" FG, Zhytomyr district, Zhytomyr region, Ukraine, the flushing effect of anolyte ANK diluted with irrigation water in a ratio of 1:30 was determined by the changes in the flow rate of two pipelines at a nominal pressure of 0.017 MPa "before" and "after" flushing. The flow rate of both pipelines before flushing was 382 l/h. After flushing the pipelines with anolyte,

3. Assessment of changes in the flow characteristics of drip water emitters depending under the influence of different types of detergents

Active ingredient	%, drip water emitters	Pressure, MPa											
		0,15			0,2			0,25			0,3		
		Flow rate depending on pressure, ml/60s											
		before	after	%, changes from nominal	before	after	%, changes from nominal	before	after	%, changes from nominal	before	after	%, changes from nominal
Aqua Doctor	33	0	7	50	0	11	79	0	14	100	12	14	100
	33	0	0	0	0	0	0	0	0	0	0	0	0
	34	1	0	0	2	0	0	4	0	0	3	0	0
Secobren	25	8	10	71	13	13	93	12	13	93	12	13	93
	25	7	8	57	10	10	71	10	11	79	10	12	86
	25	6	8	57	9	9	64	10	10	71	11	10	71
	25	5	1	7	4	4	29	12	12	86	13	13	93
Krystal	20	7	7	50	9	10	71	11	11	79	12	12	86
	20	7	8	57	6	10	71	9	10	71	7	8	57
	20	6	7	50	8	10	71	11	11	79	11	12	86
	20	7	7	50	8	10	71	11	12	86	12	13	93
	20	0	0	0	0	0	0	0	0	0	0	0	0



a b

Fig. 6. Pressure-flow characteristics of pipelines with 20 emitters before and after flushing with sodium hypochlorite “AquaDoctor” (a) and anolyte ANK “Krystal” (b)

a b c

Fig. 7. The emitters from the side of the inlet filter:
a – before washing; b, c – after washing

the flow rate of one of the pipelines increased to 390 l/h (an increase by 2 %), of the other one – to 395 l/h (by 3.5 %). At the same time, as in 2024, a high degree of cleaning of the inlet filters of the drip water emitters was visually observed (Fig. 8a), as well as a significant increase in the contamination of the drained water "before" and "after" flushing with anolyte (Fig. 8b, 8c).

As a result of the research, an assessment was made on the ability of Ukrainian producers of anolytes ANK to meet the needs for cleaning emitters and pipelines of drip irrigation systems in Ukraine from pollution of biological origin. The following initial data were adopted in the calculations: the total area of drip irrigation systems in the country is 50 thousand hectares; the required volume of anolyte to fill irrigation pipelines on an area of 1 hectare, depending on their diameters and provided that the anolyte is diluted with irrigation water in a ratio of 1:30 – 0.45…0.7 m^3. Accordingly, for a single flush (provided that 50 % of drip irrigation systems need to be flushed) about 11.250…17.500 m^3 of anolyte ANK is required per year. The existing total capacity of Ukrainian production of anolytes ANK per day can reach 60 m^3, which significantly exceeds the annual need for them for the purposes of cleaning drip irrigation systems from contaminants of biological origin.

a b c

Fig. 8. a – view of the emitters at the heads of both pipelines; b – drained water before flushing with anolyte; c – drained water after flushing with anolyte

Conclusions. It has been proven that neutral anolytes ANK of Ukrainian production are an environmentally safe and effective alternative to the chemicals – chlorine, 15 % sodium hypochlorite, chlorine dioxide, and hydrogen peroxide, which are currently used to flush emitters and drip irrigation pipelines from contamination of biological origin. It has been established that from the point of view of maintaining bactericidal activity and economic efficiency, the rational proportion of dilution with irrigation water of anolytes "Aquasalis", "Krystal", and "Secobren" is 1:40, of anolytes "Sterilox", "Vitalmix" and "Allsteril" – 1:20. It has been determined that the capacities of Ukrainian producers of anolytes ANK are able to satisfy the needs of farmers in the country for carrying out measures to flush emitters and drip irrigation pipelines from contamination of biological origin.

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

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

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ДОСЛІДЖЕННЯ МОЖЛИВОСТІ ЗАСТОСУВАННЯ АНОЛІТІВ АНК ДЛЯ ОЧИЩЕННЯ СИСТЕМ КРАПЛИННОГО ЗРОШЕННЯ ВІД ЗАБРУДНЕНЬ БІОЛОГІЧНОГО ПОХОДЖЕННЯ

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Анотація. *Досліджено перспективи використання вітчизняних нейтральних анолітів АНК для очищення емітерів і трубопроводів систем краплинного зрошення від забруднень біологічного походження. Визначено релаксаційні характеристики вітчизняних нейтральних анолітів АНК, встановлено зміни їх основних характеристик (TDS, ppm; pH; ORP, mV) залежно від ступеню розведення водою, виконано оцінку ринку та потужностей вітчизняного виробництва анолітів АНК. Застосовано лабораторні, лабораторно-аналітичні, польові та математико-статистичні порівняльні методи досліджень з визначення ефективності промивки емітерів і трубопроводів краплинного зрошення екологічно безпечними нейтральними анолітами АНК вітчизняних виробників (“AQUA SALIS”, «Кристал» та «Секобрен») і екологічно небезпечним 15 % гіпохлоритом натрію виробництва КНР. Наявність біологічної компоненти забруднень з'ясовувалась за допомогою Біуретової реакції. Встановлено, що отримання ефективних розчинів для промивки емітерів і трубопроводів систем краплинного зрошення від забруднень біологічного походження, з ОВП не меншим, ніж +750 мВ , можливо за розведення поливною водою вітчизняних анолітів АНК “Aquasalis”, «Кристал» і «Секобрен» в пропорції 1:40; “Sterilox”, “Vitalmix” та «Allsteril” – в пропорції 1:20.*

Отримано візуальні і кількісні показники якості промивки емітерів і трубопроводів краплинного зрошення від забруднень біологічного походження. В лабораторних умовах визначено, що витрата краплинних трубопроводів з 20-ма емітерами, засмічених біологічними забрудненнями, після промивки гіпохлоритом “AquaDoctor”, залежно від тиску, зросла на 17,6…52,3 %, анолітом «Кристал» – на 23,7…92,0 %. Промивка в польових умовах трубопроводів краплинного зрошення довжиною 136 м з 340 емітерами анолітами АНК призвела до збільшення витрат одного трубопроводу на 8 л/год, іншого – на 13 л/год.

Встановлено, що нейтральні аноліти АНК вітчизняного виробництва є ефективною і екологічно безпечною альтернативою хімічним речовинам (хлору, 15 % гіпохлориту натрію, діоксиду хлору і пероксиду водню), які сьогодні використовуються для промивки емітерів і трубопроводів краплинного зрошення від забруднень біологічного походження. Визначено, що вітчизняні потужності виробництва анолітів АНК спроможні забезпечити потреби українських аграріїв для промивки емітерів і трубопроводів краплинного зрошення.

Ключові слова: *системи краплинного зрошення, краплинні водовипуски, забруднення біологічного походження, промивки, електрохімічно активовані низькоконцентровані сольові розчини, аноліт, гіпохлорит натрію*

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SOIL WATER REGIME AND POTATO YIELD UNDER DIFFERENT IRRIGATION METHODS IN THE POLISSYA REGION OF UKRAINE

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Abstract. *In this scientific study, the parameters of irrigation regimes, evapotranspiration (ETc) values, and potato yields were experimentally determined depending on irrigation methods and water supply regimes. To conduct the study, a short-term (2023–2025) field experiment, analytical and statistical methods of experimental data processing were used. It has been proven that the method of laying irrigation pipelines for drip irrigation systems, the method of irrigation, and the water supply regime have a significant impact on evapotranspiration, soil water regime, and potato tuber yield in the Polissya region of Ukraine. Thus, the amount of evapotranspiration of plantings varied depending on the water regime: 2,20–2,51thousand m³/ha in non-irrigated conditions; 4,47–5,31 thousand m³/ha in the case of underground placement of irrigation pipelines (at a depth of 0,30 m), 4,72–5,61 thousand m³/ha for drip irrigation with periodic water supply, and 4,30–5,17 thousand m³/ha for drip irrigation with pulsed water supply. Under sprinkler irrigation, evapotranspiration was highest, ranging from 5,80 to 6,24 thousand m³/ha over the years of the study. It is natural that without irrigation, the lowest yield of marketable tubers was obtained – 43,4 t/ha, and the factor of "irrigation" in combination with fertigation increased this indicator by an average of 1,5 times – to 65,15 t/ha. The increase in tuber yield with drip irrigation with periodic and pulsed water supply was statistically significant: up to 66,4 t/ha and 70,4 t/ha, respectively. Under conditions of sprinkler and subsurface drip irrigation, 60,8 t/ha and 62,7 t/ha were obtained, respectively. The minimum specific irrigation water consumption was obtained with drip irrigation with a pulsed water supply mode – 67,6 m³/t, respectively. The highest water consumption coefficient was for sprinkler irrigation – 100,4 m³/t. Thus, when growing potatoes in the Polissya region of Ukraine, it is more expedient to use drip irrigation, preferably with a pulsed water supply mode, and in conditions of acute water shortage for irrigation, drip irrigation with underground installation of irrigation pipelines.*

Keywords*: irrigation methods, soil water regime, pulsed water supply, evapotranspiration, water consumption coefficient, yield, potatoes*

Relevance of the research. Potato (*Solanum tuberosum L.*) is traditionally one of the main agricultural crops in Ukraine in terms of acreage and consumption. During 2023–2025, the area under this crop ranged from 1,05 to 1,33 million hectares, and the gross annual harvest of tubers ranged from 17,54 to 21,36 million tons. On the one hand, these volumes are sufficient to cover the domestic market, but due to the lack of sufficient modern vegetable storage facilities, Ukraine is forced to import potatoes from EU countries (Poland, Lithuania, Germany, the Netherlands) and Egypt every year [1].

Given the physiological characteristics of potatoes, namely, the cessation of tuber growth at air temperatures above +27–29 °C, the most favorable soil and climatic zones for their cultivation in Ukraine are Polissya and Forest-steppe zone of Ukraine. For example, about 75 % of all potato acreage is located here. Another critically important feature of potato physiology is its demanding water requirements. The average water consumption coefficient of potatoes is over 90–100 m^3/t. At the same time, the amount of effective (over 5 mm) precipitation during the growing season within 200–300 mm ensures a potato yield of no more than 20–30 tons/ha. Therefore, irrigation is a mandatory element in modern technologies for growing this crop in all soil and climatic zones of Ukraine [2]. Practice shows that today, the implementation of various methods of potato irrigation, such as sprinkling and surface drip irrigation, provides relevant efficiency. For Ukrainian conditions, subsurface drip irrigation and drip irrigation with a pulsed water supply mode are relatively new methods of potato irrigation [3, 4]. The principle of pulsed water supply, unlike periodic irrigation, involves the discrete supply of irrigation water to the area of plant root system concentration in short cycles (pulses) of fixed or variable duration in accordance with the actual transpiration of plants.

Thus, applied scientific research on determining the parameters and effectiveness of irrigation methods and water supply modes for potatoes in the Polissya region of Ukraine is new and quite relevant today.

Analysis of recent studies and publications. Over the years, the issue of optimizing the water regime of potato soil in Ukraine has been most thoroughly researched at three scientific institutions: the Institute of Irrigated Agriculture of the National Academy of Agrarian Sciences (now the Institute of Climate-Oriented Agriculture of the National Academy of Agrarian Sciences), the Institute of Hydrotechnics and Land Reclamation of the NAAS (now the Institute of Water Problems and Land Reclamation of the NAAS), and the Institute of Southern Vegetable and Melon Growing of the NAAS (currently located on the temporarily occupied territory of the Left Bank of the Kherson Region, in the city of Hola Prystan). At the first stage (1970s-1990s), Ukrainian scientists established the optimal parameters of the water regime for potatoes under sprinkler irrigation. The greatest contribution in this regard was made by scientists from the Institute of Irrigated Agriculture – E.M. Gorbatenko, V.A. Pysarenko, M.S. Boiko, P.V. Matsko, G.S. Balashova, and others [5, 6, 7]. Since the 2000s, domestic scientists (V.A. Pysarenko, I.P. Bugayeva, V.S. Snigovyi, M.I. Chernichenko, Yu.O. Lavrinenko, P.V. Pysarenko, O.I. Golovatskyi, S.M., Romashchenko M.I., Shatkovsky A.P., Yatsyuk Z.F., Kapelyukha T.A., Lymar V.A., Shabunin I.M.) studied both the effectiveness of drip irrigation in potato cultivation and compared different irrigation methods in the conditions of the Ukrainian Steppe [2, 8–14]. The general conclusion of these scientific studies is that drip irrigation (compared to sprinkler and micro-sprinkler irrigation) is proven to be effective for growing potatoes in the southern region of Ukraine.

At the same time, there have been almost no studies on potato irrigation in the Polissya region of Ukraine to date. Against the backdrop of drip irrigation, research was conducted under the leadership of Veremeyenko S.I., but the main subject of study was the effect of fertigation on potato yield [15]. The need for such research is further emphasized, on the one hand, by the increasing aridization of the climate [16] and, on the other hand, by the actual gradual introduction of irrigation in the Polissya region of Ukraine, especially in the Zhytomyr, Kyiv, and Chernihiv regions. In this context, the most relevant are the studies conducted by Polish scientists from the Faculty of Agriculture and Biotechnology at the University of Science and Technology in Bydgoszcz during 2011–2013 [17]. Based on the results of a two-factor experiment, they determined the water requirements of potato plants and found that drip irrigation increased the marketable yield of tubers by 55 %. The effectiveness of fertigation compared to the application of mineral fertilizers was also confirmed. Other comprehensive studies in Poland (2007–2009) have proven the positive effect of drip irrigation and fertigation on the yield and some quality elements of potato tubers [18].

The aim of the study was to prove and evaluate the impact of irrigation methods and water supply regimes on soil water regime, evapotranspiration, and potato yield in the Polissya region of Ukraine.

Materials and methods. Field experiments were conducted under production conditions on irrigated lands of Agrofirma Kyivska LLC (Makovysche village, Bucha district, Makariv territorial community, Kyiv region, Polissya zone of Ukraine, Google maps coordinates 50.465494, 29.855753) during 2023–2025. The two-factor field experiment included the following options: sprinkler irrigation, drip irrigation with periodic water supply, drip irrigation with pulsed water supply, and subsurface drip irrigation with irrigation pipes laid in the center of the ridge at a depth of 0,30 m. The control option was natural moisture supply without irrigation. The study was conducted using standard methods: systematic plot placement, four repetitions, and a plot area of 32 m^2 [19, 20]. The Granada potato variety (early maturing table variety, originator – Solana GmbH & Co. KG, Germany) was used. The planting pattern was 75+75 × 15 cm with irrigation pipes laid in the center of the ridge. The predecessor crop was field peas (*Pisum sativum*).

The soil of the experimental plot was gray podzolized sandy loam on loess. The density of its 40-centimeter layer was 1,49 g/cm^3 , humus content – 0,51 %, pH = 4,1, soil nitrogen content is very low, mobile forms of phosphorus are high, potassium – average. The minimum moisture content of the arable soil layer (0–30 cm) is 20,15 % of the mass of absolutely dry soil, and that of the 0–100 cm soil layer is 18,33 %.

The amount of productive precipitation during the growing season (May-first ten days of September) for potatoes varied over the years of research. In 2023, it was 188 mm, which is 71,8 % of the climate norm, in 2024 – 198,3 mm or 75,0 %, and in 2025 – 211.6 mm or 80,9 % of the climate norm. The pre-irrigation moisture level in a 30 cm layer of soil was −18 kPa. To determine the timing of irrigation, we used the mMetos Base digital internet station with Watermark 200 SS sensors [21], as well as AQUAMETER PRO tensiometric sensors [22]. Statistical analysis of the results was performed using dispersion, correlation, and regression methods with the Statistica 8.0 program.

Research results and discussion. The study experimentally confirmed the direct influence of the irrigation method, and in fact, the method of distributing irrigation water within the field and the transformation of water flow into soil moisture, on the formation of the soil water regime. In particular, the irrigation method had a significant effect on the irrigation regime (timing, amount, and frequency of irrigation), evapotranspiration, yield, and water consumption coefficient of potatoes (Table 1).

The largest number of vegetative irrigations were carried out using pulse drip irrigation – 237 with an average rate of 10–12 m³/ha. These parameters correspond to the principle of pulse water supply (discrete irrigation in short cycles (pulses) of fixed or variable duration in accordance with the actual transpiration of plants). Under conditions of periodic water supply, 38 irrigations were carried out using drip irrigation at a rate of 80 m³/ha. Potatoes required fewer irrigations with sub-soil irrigation – 27 with an average rate of about 100–105 m³/ha. The smallest number of irrigations was with sprinkler irrigation – 13, but this method resulted in the maximum irrigation rate: 283 m³/ha due to the need to moisten the entire area and moisture losses due to evaporation during irrigation.

The total volume of irrigation water (irrigation rate) required to maintain the pre-irrigation threshold (−18 kPa) was close in value for subsurface and drip irrigation with a pulsed water supply mode –2,76 thousand m³/ha and 2,66 thousand m³/ha, respectively. A significantly higher rate was observed for drip irrigation with periodic watering – 3,05 thousand m³/ha. In turn, sprinkler irrigation increased the irrigation rate by 1,3–1,5 times – up to 3,96 thousand m³/ha. The parameters of evapotranspiration (ETc) of potato plants varied similarly. Lower values were characteristic of drip irrigation options (4,77–5,18 thousand m³/ha), and the maximum ETc was for sprinkler irrigation – 6,08 thousand m³/ha. On average, irrigation increased evapotranspiration by 2,25 times compared to non-irrigated conditions, where ETs was limited by productive precipitation and soil moisture reserves and amounted to 2,33 thousand m³/ha.

The minimum specific irrigation water consumption was obtained when implementing the drip irrigation option with a pulsed water supply mode – 67,6 m³/t, respectively. The relevant water consumption coefficient was for drip irrigation with periodic watering and subsurface drip irrigation – 78,0 m³/t and 78,2 m³/t, respectively. The highest water consumption coefficient was for sprinkler irrigation – 100,4 m³/t. In the control group, this indicator averaged 53,7 m³/t over three years.

It has been proven that irrigation is a key factor in intensifying potato productivity in the Polissya region of Ukraine. It was found that irrigation combined with fertigation (compared to the control – without irrigation, 43,4 t/ha) increased the yield by an average of 1,5 times – to 65,15 t/ha (Fig. 1).

The yield of tubers in non-irrigated conditions varied greatly over the years of the study, depending on the regime and amount of productive precipitation: from 37,1 t/ha in 2024 to 53,7 t/ha in 2023. In turn, irrigation ensured consistent productivity, and this indicator varied within narrow limits over the years of the study: 57,9–64,3 t/ha for sprinkler irrigation, 61,4–64,5 t/ha for subsurface drip irrigation, 66,3–68,7 t/ha for drip irrigation with periodic water supply, and 68,5–72,25 t/ha for drip irrigation with pulsed water supply.

1. Irrigation regime, evapotranspiration, and water consumption coefficient (WCC) of potatoes depending on the irrigation method (average for 2023–2025)

Irrigation method	**Water supply regime**	**Number of watering**	**Irrigation rate, m³/ha**	**Evapotranspiration (ETc), m³/ha**	**WCC, m³/t**
Subsurface drip	Periodic	27	2765	4902	78,2
Drip	Pulse	237	2663	4746	67,4
	Periodic	38	3048	5179	78,0
Sprinkling	Periodic	14	3962	6079	100,0
Control	–	–	–	2329	53,7

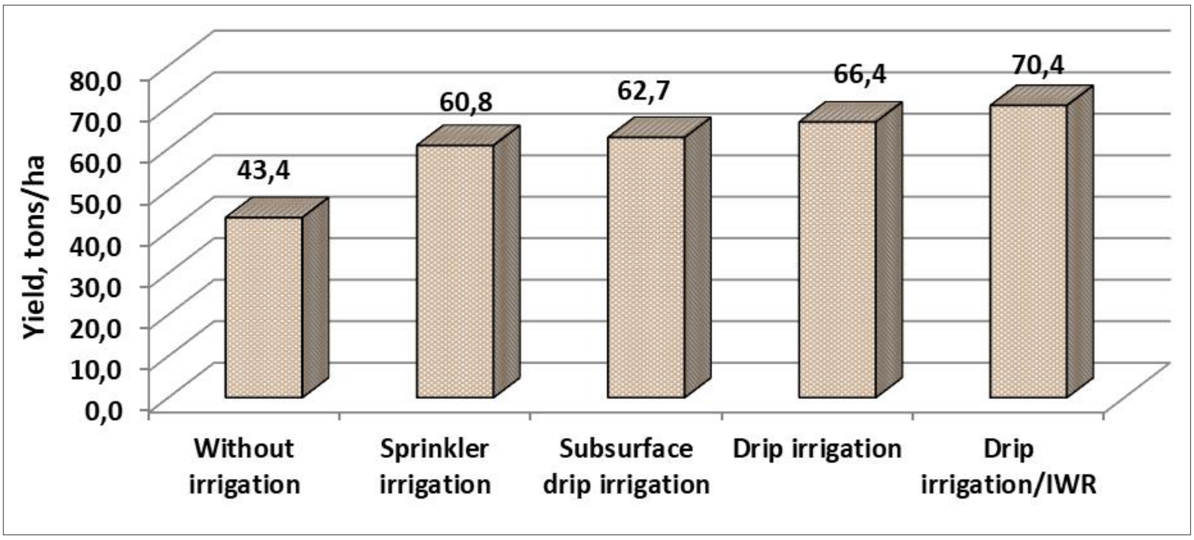

Fig. 1. Yield of marketable potato tubers depending on the irrigation method (average for 2023–2025) $MDD_{.5}$ = 3,15 t/ha

A statistically significant ($MDD_{.5}$ = 3,15 t/ha) increase in tuber yield was observed with drip irrigation with periodic and pulsed water supply: up to 66,4 t/ha and 70,4 t/ha, respectively. Under conditions of sprinkler and subsurface drip irrigation, 60,8 t/ha and 62,7 t/ha were obtained, respectively.

Based on averaged experimental data on evapotranspiration and potato yield, a statistical relationship between evapotranspiration and yield was obtained. This relationship is actually a response curve to a single-factor field experiment and consists of three parts: limiting, stationary (optimal), and inhibitory (excessive). The coefficient of determination R^2 = 0,764 indicates a stable relationship between these values. It has been established that the limiting area of the curve corresponds to the control variant of the experiment – without irrigation; the stationary part (optimum zone) corresponds to three variants with drip irrigation (subsoil, surface, and impulse drip), and the inhibitory part (excess zone) corresponds to sprinkler irrigation (Fig. 2).

The established statistical dependence between evapotranspiration and yield is not

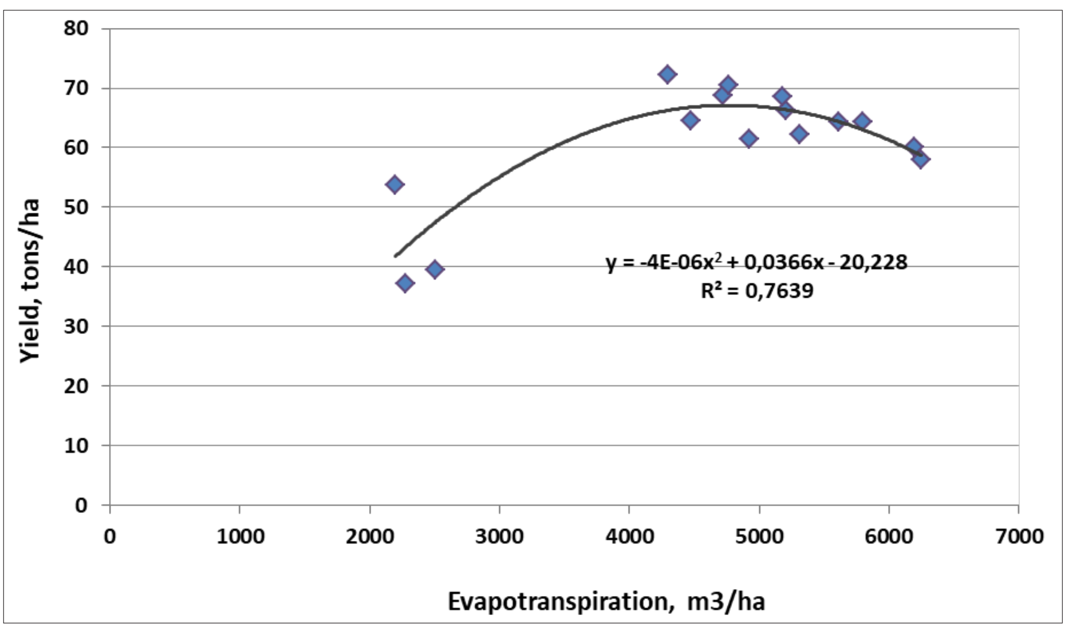

Fig. 2. Dependence of “Evapotranspiration – Yield” for potato cultivation in the Polissya region of Ukraine

stable from an agrobiological point of view, since there are agrotechnological and breeding-genetic possibilities for increasing potato yield with the same plant evapotranspiration values. Therefore, the main task of future research on evapotranspiration processes is to reduce unproductive water consumption (for physical evaporation and infiltration into lower soil horizons) while increasing the productivity of potato plants.

The results obtained are generally consistent with the data obtained in a study by Polish scientists [17]. In particular, drip irrigation increased the marketable yield of potato tubers by 55 %, and the water requirement for irrigation during the growing season was 2,2 thousand m^3/ha.

Conclusions. It has been proven that the method of laying irrigation pipelines for drip irrigation systems, the method of irrigation, and the water supply regime have a significant impact on evapotranspiration, soil water regime, and potato tuber yield in the Polissya region of Ukraine. The most optimal for potatoes in these conditions is the introduction of drip irrigation with a pulsed water supply regime. This ensures minimum specific irrigation water consumption and a yield of marketable tubers of over 70 t/ha. The option with underground irrigation pipelines provided almost identical irrigation water consumption parameters during the growing season, but the yield decreased by 10,9 % or 7,7 t/ha. This irrigation method is advisable to implement as a strategy for integrating potatoes into field crop rotation.

Conflicts of interest: the authors declare no conflict of interest.
Use of artificial intelligence: the authors confirm that they did not use artificial intelligence technologies during the creation of this work.

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ВОДНИЙ РЕЖИМ ҐРУНТУ І ВРОЖАЙНІСТЬ КАРТОПЛІ ЗА РІЗНИХ СПОСОБІВ ЗРОШЕННЯ В УМОВАХ ПОЛІССЯ УКРАЇНИ

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Анотація. *У науковому дослідженні експериментально визначено параметри режимів зрошення, величини евапотранспірації (ETc) та врожайність картоплі залежно від способів зрошення та режиму водоподачі. З метою реалізації дослідження використано короткотерміновий (2023–2025 рр.) польовий дослід, аналітичні і статистичні методи обробки експериментальних даних. Доведено, що спосіб укладання поливних трубопроводів систем краплинного зрошення, спосіб зрошення та режим водоподачі достовірно впливають на евапотранспірацію, водний режим ґрунту та врожайність бульб картоплі в умовах Полісся України. Так, величина евапотранспірації насаджень варіювала залежно від водного режиму: 2,20–2,51 тис. м³/га у незрошуваних умовах; 4,47–5,31 тис. м³/га у разі внутрішньоґрунтового розміщення поливних трубопроводів (на глибині 0,30 м), 4,72–5,61 тис. м³/га за краплинного зрошення з періодичним режимом водоподачі та 4,30–5,17 тис. м³/га – за краплинного зрошення з імпульсним режимом водоподачі. За умови зрошення дощуванням евапотранспірація була найвищою і становила від 5,80–6,24 тис. м³/га за роками дослідження. Закономірно, що без зрошення отримано найнижчий рівень врожайності товарних бульб – 43,4 т/га, а фактор «зрошення» у поєднанні з фертигацією збільшував цей показник в середньому у 1,5 рази – до 65,15 т/га. Статистично достовірним було збільшення врожайності бульб за краплинного зрошення з періодичним та імпульсним режимом водоподачі: до 66,4 т/га і 70,4 т/га відповідно. За умов дощування та внутрішньоґрунтового краплинного зрошення отримано 60,8 т/га і 62,7 т/га відповідно. Мінімальні питомі витрати зрошувальної води отримано за реалізації варіанту краплинного зрошення з імпульсним режимом водоподачі – 67,6 м³/т відповідно. Найвищим коефіцієнт водоспоживання був для умов дощування – 100,4 м³/т. Таким чином, за вирощування картоплі в умовах Полісся України доцільніше впроваджувати краплинне зрошення, переважно – з імпульсним режимом водоподачі, а за умови гострого дефіциту водних ресурсів для зрошення – краплинне зрошення з внутрішньоґрунтовим укладанням поливних трубопроводів.*

Ключові слова: *способи зрошення, водний режим ґрунту, імпульсний режим водоподачі, евапотранспірація, коефіцієнт водоспоживання, врожайність, картопля*

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MODELING OF THE OPERATING MODES OF THE EJECTOR-CAVITATOR TO DETERMINE ITS OPTIMAL DESIGN AND TECHNOLOGICAL PARAMETERS

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Abstract. *The article presents the results of the development and scientific substantiation of the technology of cavitation activation of natural zeolites of the Sokyrnytske deposit (Transcarpathian region) and the Nyzhnohrabovetske deposit (Slovakia) to significantly increase their sorption capacity for heavy metal ions (Pb, Cd, Zn, Cu, etc.), radionuclides (^{137}Cs, ^{90}Sr) and nitrogen compounds (nitrates, ammonium). The use of hydrodynamic cavitation in a Venturi tube and a modified ejector-cavitator is proposed as an environmentally safe, energy-efficient and reagent-free method of modifying sorbents, which fully complies with the principles of green chemistry and the objectives of the Water Strategy of Ukraine until 2030.*

A comprehensive CFD modeling (Ansys Fluent 2023 R2) with a multiphase VOF+URANS approach, a Schnerr-Sauer cavitation model, and a discrete-phase model for estimating trajectories and collapse of cavitation cavities was performed. The independence of the solution from the computational grid was verified with more than 100 thousand elements. Single-phase and multiphase modelingswere compared. The multiphase approach provides physically realistic values of pressure (up to 215 atm) and temperature (~800 K) of cavity collapse, while the single-phase approach significantly overestimates these parameters, but is suitable for quick qualitative assessment and preliminary optimization of geometry and operating modes.

The optimal inlet pressure of 7 bar was established, having which the maximum intensity of the cavitation effect is achieved with minimal energy costs. A hybrid optimization strategy was developed, which consists of the initial rapid screening of promising designs by single-phase modeling with subsequent detailed multi-phase analysis of the best options.

Based on the results of modeling the operating modes of the ejector-cavitator, its optimal design and technological parameters were obtained. Using the obtained data, a laboratory recirculation unit (volume 20 l, pump 1,1 kW, pressure regulation up to 10 bar) and an ejector-cavitator design for manufacturing by 3D printing from cavitation-resistant Spectrum PP polypropylene will be created. The obtained results are a scientific and technical basis for making highly efficient sorption materials and water purification technologies with high potential for industrial scaling.

Keywords: *cavitation, zeolites, sorption, heavy metals, radionuclides, nitrogen compounds, Venturi tube, adsorption isotherms, Langmuir model, CFD modeling, particle size analysis*

Relevance of the research. Pollution of natural and wastewater with heavy metals (Pb, Cd, Zn, Cu, etc.), radionuclides (137Cs, 90Sr) and nitrogen compounds (nitrates, ammonium) remains one of the most acute environmental problems of Ukraine, especially in regions of intensive agriculture, industry and prone to the consequences of the Chernobyl disaster. Natural zeolites of Ukraine have significant potential as affordable and environmentally safe sorbents. However, their sorption capacity in the natural state is often insufficient. Modification of zeolites by cavitation allows to significantly increase the surface activity, porosity and selectivity without the use of expensive chemical reagents, which corresponds to the principles of green chemistry and the objectives of the Water Strategy of Ukraine until 2030.

Analysis of recent research and publications. The issue of sorption water purification with zeolites is actively studied both in Ukraine and all over the world [1–4, 13]. High efficiency of zeolites for Cesium-137, Strontium-90, heavy metal ions and ammonium has been established. At the same time, chemical (acid, alkaline), thermal and mechanical activation are used to increase the capacity [5, 6, 15]. Cavitation technologies for water purification are being developed separately [7, 14], however, the use of hydrodynamic cavitation specifically for the modification of natural zeolites has been almost not studied yet. CFD modeling of cavitation flows in Venturi tubes and ejectors is presented in the works [8–12], but without connection to sorbent modification.

Research objective. To develop a scientifically based technology for cavitation activation of natural Ukrainian zeolites using a Venturi tube and a modified ejector-cavitator to increase their sorption capacity for heavy metals, radionuclides and nitrogen compounds, as well as to create a laboratory unit and CFD models for further optimization of the process.

Research objective. To develop a scientifically based technology for cavitation activation of natural Ukrainian zeolites using a Venturi tube and a modified ejector-cavitator to increase their sorption capacity for heavy metals, radionuclides and nitrogen compounds, as well as to create a laboratory unit and CFD models for further optimization of the process.

Materials and methods of research. The object of research is natural zeolites of the Sokyrnytske deposit (Transcarpathian region) and the Nyzhniy Grabovets deposit. The Ansys Fluent 2023 R2 software was used for modeling (k-ω SST turbulence models, Schnerr-Sauer cavitation model, VOF+URANS multiphase approach, discrete-phase model for cavity trajectories). Venturi tube geometryis the following: neck diameter is 2 mm, tube diameter is 20 mm, narrowing/expansion angles are 22б61°/6б4°. A laboratory recirculation unit has been developed (tank volume 20 l, three-cylinder pump 1.1 kW, pressure regulation up to 10 bar, cavitation Venturi tube in the main line). An ejector-cavitator for 3D printing made of Spectrum PP polypropylene has been designed.

Research results and discussion. For the study of modification methods, the flow through a cavitation Venturi tube was considered the most promising. The chosen geometry is shown in Fig. 1. Several experiments were conducted using this Venturi tube to verify the CFD model.

The diameter of the venturi tube orifice is 2 mm and the diameter of the tube is 20 mm. The convergence angle of the venturi tube is 22,61° and the divergence angle is 6б4°. The walls of the converging and diverging sections are straight. An additional length of 60 mm before the inlet and 200 mm after the outlet was added to the CFD model to obtain a fully developed flow and to avoid any inlet or outlet effects.

When determining mesh dependencies the modeling was performed when using different mesh sizes to provide an independent solution. The geometry was divided into meshes with 14 k, 40 k, 60 k, 70 k, 100 k and 200 k elements. A representative mesh is shown in Fig. 6 (a) below.

For a mesh with 70 k-elements and higher, the average value was below 1, which is sufficient for the resolution of the viscous sublayer. A comparison of the velocity profiles in the Venturi orifice is shown in Fig. 2(b). It was found that the solution was not mesh dependent beyond 100 k-elements, hence this mesh is a discrete-phase model. After the turbulence model was completed, steady-state modeling was performed for a range of venturi inlet pressures considering single-phase flow. The cavitation model was not included in the modeling. It was noted that the single-phase

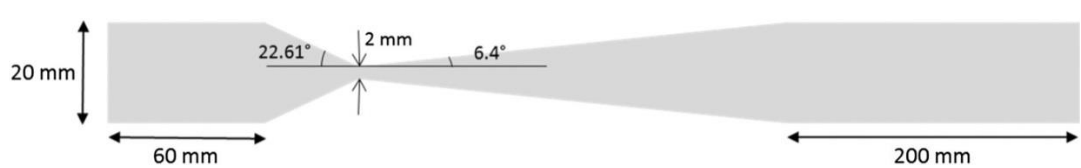
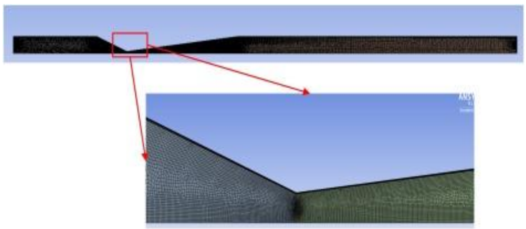
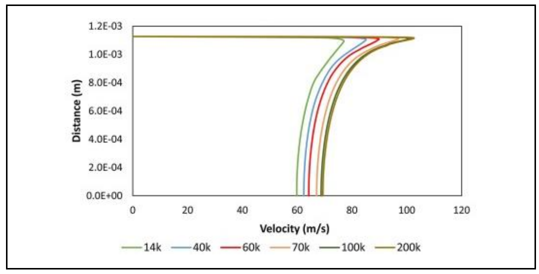


Fig. 1. Schematic diagram of a venturi tube

(a) (b)

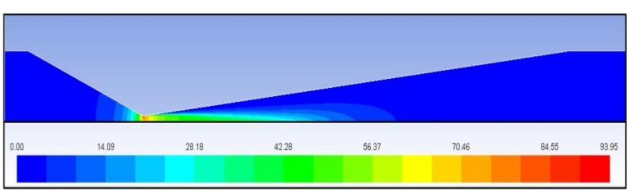
Fig. 2. Typical mesh for a Venturi tube (a), Comparison of velocity profiles in the orifice for different mesh sizes (b)

model significantly overestimated the flow rate for the corresponding inlet pressure.

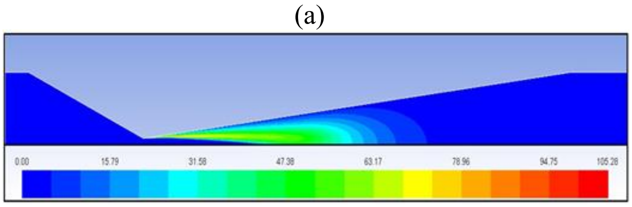
The maximum velocity and turbulent kinetic energy in the flow area were high. Fig. 2(a) and (b) show the velocity and turbulent kinetic energy plots for an inlet pressure of 7 bar. Since the cavitation model is not included, the predicted pressure in the orifice is lower than the vapor pressure and even reaches negative values, which is unrealistic. In the single-phase model, the phase transition is not considered, and since there is no energy loss during the phase transition, the pressure energy is completely converted into kinetic energy, which leads to high velocities and therefore high flow rates. Thus, it is necessary that the cavitation model matches the mass flow rate and pressure drop relationship.

The multiphase CFD modeling was performed using the URANS (finite difference method for convergence) approach. The time step size was 10^{-6} s. It was observed that the flow in Venturi tube initially fluctuated and stabilized after some time, as shown in Fig. 3. (d) The Y-axis indicates the normalized average flow rate through the orifice of Venturi tube as a function of time. The modeling was considered complete when the inlet and outlet flows were stabilized and no fluctuations in flow rate were observed with respect to flow time. This damping of flow fluctuations could be a result of the URANS modeling approach, and what is obtained as a stable result is the average flow through the orifice of Venturi tube. There may be some changes in the cavity dynamics at the lowest and highest flow through the orifice due to flow fluctuations, which are not considered in this study. However, the average behavior of the cavity dynamics is expected to be similar to that predicted one by the current model. Typically, the flow was found to stabilize after 0,5–0,7 s. The fluctuation frequency ranged from 30 to 100 Hz, depending on the inlet pressure. The fluctuation frequency gradually decreased and the fluctuation amplitude increased as the inlet pressure increased.

The modeling data were also validated using measured pressure drop and flow rates. The flow velocity in the multiphase model is much lower compared to the single-phase model, so the



(a)



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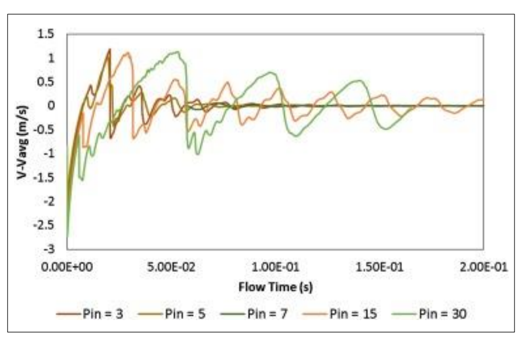


(c)

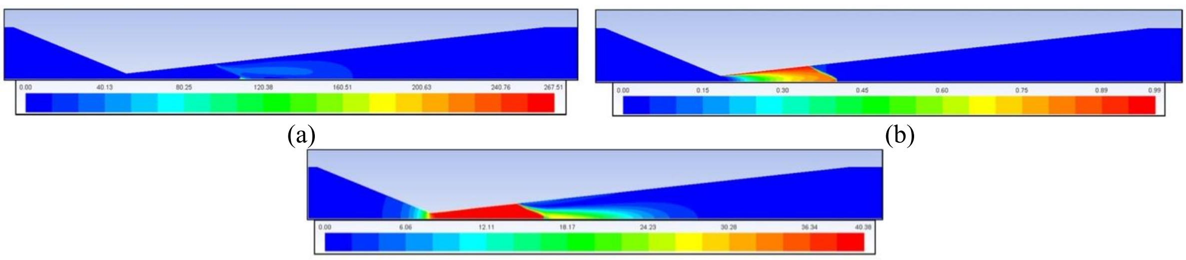
Fig. 3. Plots of (a) velocity, m/s and (b) turbulent k2inetic energy, m^2/s^2 for single-phase CFD modeling when having P_{in} = 7 bar, (c) oscillatory flow in the orifice

velocity and kinetic energy in the flow area are also lower. Cavitation is observed in the diverging section of Venturi tube, just downstream of the orifice, with maximum vapor fractions observed near the orifice wall. The velocity plot contours, turbulent kinetic energy, and vapor volume fraction are shown in Fig. 4.

After obtaining convergent results in the CFD modeling, about 75 particles was introduced onto the isosurface, at the distance of 2 mm before Venturi orifice. The trajectory plot is shown in Fig. 5. The pressure data depending on the particle flow time were plotted along these trajectories. These data were used as the volume pressure (p^t) surrounding the cavity at time *t*. The initial cavity radius (R_0) when $t = 0$ was previously assumed to be 1 μm.

Fig. 6 (a)–(c) shows the results of the cavity dynamics model for the case when $P_{in} = 10$ bar. The cavity gradually contracts through multiple volume fluctations as it passes through the flow area, and the maximum collapse pressure was about 215 atm. The corresponding maximum collapse temperature was about 800 K.

Similar studies were also conducted for DHM introducing under single-phase flow modeling conditions. In this case, the predicted collapse pressure and temperature трawere very high compared to the multiphase case. The results are shown in the form of plots in Fig. 6 (d)–(f). These values are unrealistic and should be considered



(a) (b) (c)

Fig. 4. (a) turbulent kinetic energy, m^2/s^2, and (b) vapor volume fraction for multiphase CFD modeling when having $P_{in} = 7$ bar, and (c) velocity contours, m/s

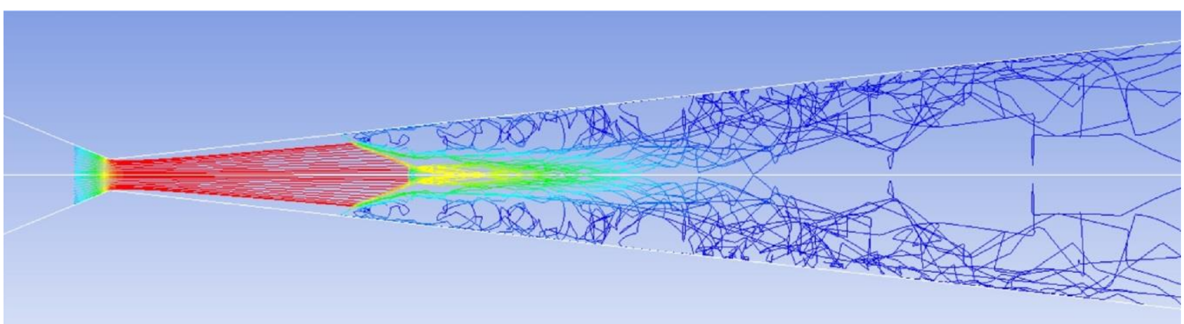


Fig. 5. DPM trajectories in the flow area, representing the paths of cavities

for qualitative comparison only. Such high values of collapse pressure and temperature can be explained by the very high pressure difference at the inlet and in the orifice of the Venturi tube. This means that the bubble in such a flow will have a higher velocityin the orifice compared to the multiphase modeling, and therefore higher turbulence levels, which further contributes to the unrealistic growth of a parameter (R/R0) and more intense bubble collapse temperature and pressure.

The collapse pressure values for all trajectories were averaged. The average collapse pressure was used to estimate the cavitation efficiency coefficient (CEC). Since CEC is directly proportional to the collapse pressure value of the cavity, the CEC values for the single-phase modeling are unrealistically higher than those observed in the multiphase simulation. CEC is a parameter for comparing the theoretical efficiency of a cavitation device. In this case, the effect of the operating condition, i.e., the inlet pressure, on CEC is shown in Fig. 7. A comparison of the trends of CEC as a function of inlet pressure for the single-phase and multiphase cases was made. Due to the difference in the scale of the values, the CEC values are normalized using the volumetric flow rate (Q).

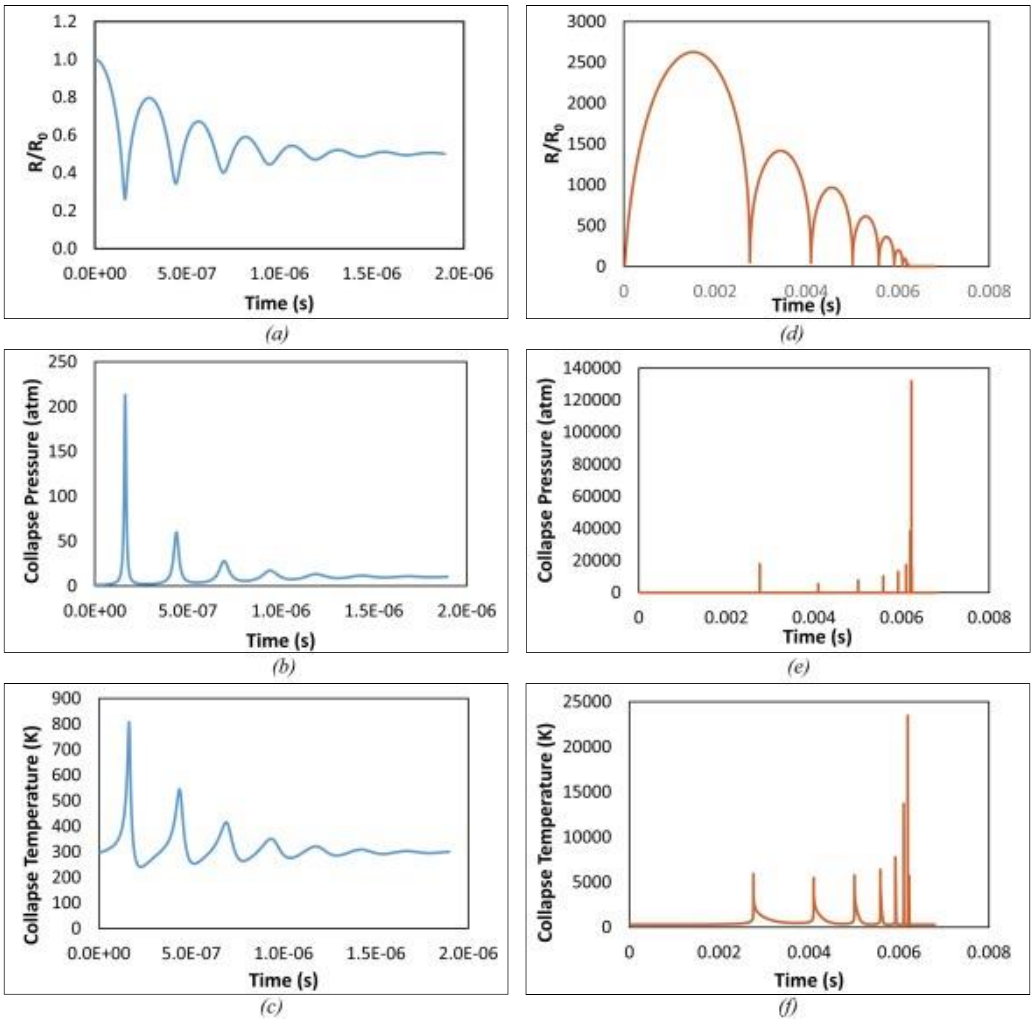


Fig. 6. (a)–(c) The results of the cavity dynamics model showing the change in relative cavity size, cavity collapse pressure, and cavity collapse temperature for multiphase simulation; (d)–(f) – the results of the cavity dynamics model for single-phase modeling

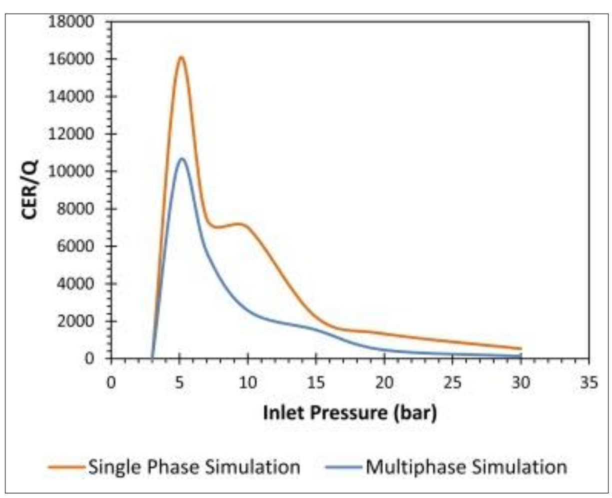


Fig. 7. Comparison of flow-normalized CEC values depending on inlet pressure (P_{in}) for single-phase and multiphase cases

Although the CEC values for the single-phase modeling are unrealistically high, the trend for the normalized CEC for both the single-phase and multiphase cases is qualitatively similar, indicating a correct representation of the physics of cavitation flow.

Considering the multiphase case, it can be concluded that an inlet pressure of 7 bar is the optimal operating condition. The fact that the results of the single-phase and multiphase models are qualitatively similar, single-phase modeling is much faster and numerically less expensive compared to multiphase one. However, it is necessary to properly account for the damping and the lower value observed in multiphase flow. Single-phase modeling can be used to qualitatively determine the optimal design or optimal operating conditions, and the multiphase model can be run only for these optimal conditions to obtain more accurate quantitative results.

Conclusions

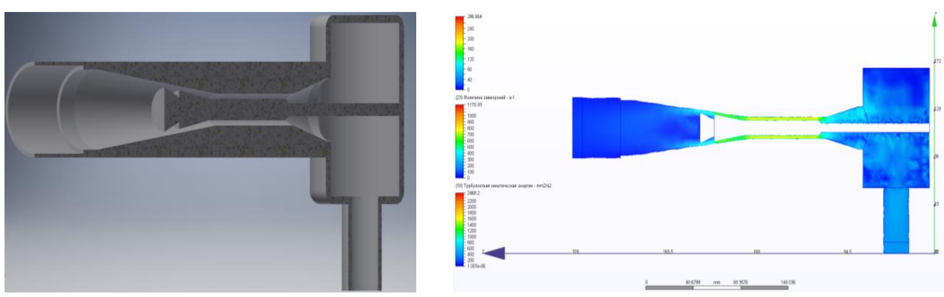
1. Cavitation activation when using a Venturi tube and a modified ejector-cavitator is a promising, environmentally safe and energy-efficient method of increasing the sorption activity of natural zeolites of the Sokyrnytske and Nyzhnohrabovetske deposits in Ukraine, which allows to significantly increase the porosity, surface activity and selectivity of sorbents without the use of chemical reagents, contributing to the implementation of green chemistry principles and compliance with the Water Strategy of Ukraine until 2030. It also opens up opportunities for industrial scaling in wastewater and natural water purification systems from heavy metals, radionuclides and nitrogen compounds.

2. The optimal inlet pressure to achieve the maximum intensity of the collapse of cavitation cavities is 7 bar, when the cavitation efficiency coefficient (CEC) reaches its peak value, ensuring a balance between high pressure and collapse temperature (up to 215 atm and ~800 K in multiphase modeling) and minimal energy consumption, which was confirmed by a comparison of single-phase and multiphase CFD modeling, as well as flow stabilization without significant flow fluctuations.

3. Multiphase CFD modeling in view of the phase transition (VOF+URANS, Schnerr-Sauer model) is mandatory for accurate quantitative estimation of cavitation flow parameters, such as pressure and cavity collapse temperature, while simplified single-phase modeling, despite overestimation of velocity and turbulent kinetic energy values, can be effectively used for initial qualitative optimization of the geometry and operating modes of cavitation devices, allowing to reduce computational costs before conducting detailed multiphase calculations.

Prospects for further research. Based on the results of the modeling, it was decided to use single-phase modeling of the modified ejector-cavitator for the activation and modification of zeolite. To select the cavitation modes, a virtual model of the modified ejector-cavitator was created, and hydrodynamic modeling is currently being conducted using Autodesk CFD Simulation software.

For laboratory studies on improving zeolite, a schematic diagram of a laboratory unit was developed, shown in Fig. 9. The unit has a 20-liter tank attached to the suction line of a three-cylinder positive displacement pump (to reduce flow pulsations). There are baffles inside the tank to avoid the formation of vortices and to entrain air bubbles into the flow. The pump power is 1.1 kW. The pump discharge line is divided into a main line and a bypass line, which after a while merge and are connected back to the tank, which is under atmospheric pressure, forming a recirculation circuit. The bypass line in the unit is mainly used as a safety device to avoid excessive back pressure on the pump. A cavitation Venturi tube is placed in the main line. The flow rate through the main



(a) (b)

Fig. 8. (a) – Simplified model of the ejector-covitator for hydrodynamic modeling; (b) – Flow velocity distribution diagram of the hydrodynamic calculation of the ejector-covitator; number of calculation cells is 913; inlet velocity of 7 atm and turbulent kinetic energy of 160,000 mm^2/s^2

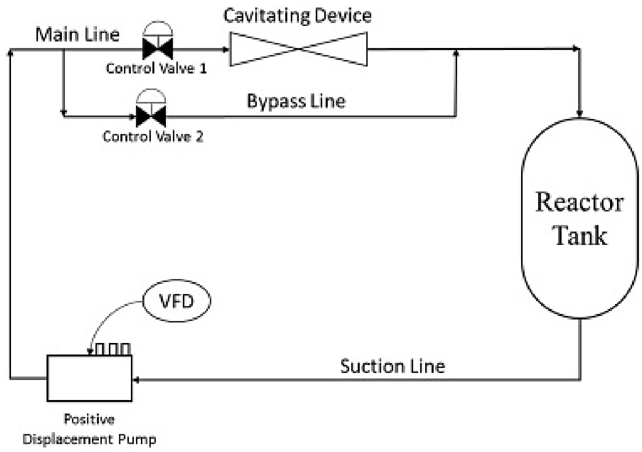


Fig. 9. Schematic representation of the experimental unit

and bypass lines is controlled by three control valves. Pressure gauges are provided before and after the cavitation device to measure the pressure drop. The pump is equipped with a flow controller in the VFD system. Water was passed through Venturi tube at different inlet pressures and the corresponding flow rates were measured.

It is planned to make a modified ejector-covitator when using 3D printing from Spectrum PP polypropylene using the FDM printing method. Spectrum PP is a new material with good mechanical properties, capable of effectively resisting cavitation effects and abrasion effects.

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

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

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МОДЕЛЮВАННЯ РЕЖИМІВ РОБОТИ ЕЖЕКТОРА-КАВІТАТОРА ДЛЯ ВИЗНАЧЕННЯ ЙОГО ОПТИМАЛЬНИХ КОНСТРУКТИВНИХ І ТЕХНОЛОГІЧНИХ ПАРАМЕТРІВ

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Анотація. *У статті представлено результати розробки та наукового обґрунтування технології кавітаційної активації природних цеолітів Сокирницького родовища (Закарпаття) та Нижньограбовецького родовища (Словаччина) з метою суттєвого підвищення їх сорбційної ємності щодо іонів важких металів (Pb, Cd, Zn, Cu тощо), радіонуклідів (^{137}Cs, ^{90}Sr) та сполук азоту (нітрати, амоній). Запропоновано використання гідродинамічної кавітації в трубці Вентурі та модифікованому ежектор-кавітаторі як екологічно безпечний, енергоефективний і безреагентний метод модифікації сорбентів, що повністю відповідає принципам зеленої хімії та завданням Водної стратегії України до 2030 року.*

Проведено комплексне CFD-моделювання (Ansys Fluent 2023 R2) з багатофазним підходом VOF+URANS, моделлю кавітації Schnerr-Sauer та дискретно-фазовою моделлю для оцінки траєкторій і колапсу кавітаційних порожнин. Верифіковано незалежність розв'язку від розрахункової

сітки при кількості елементів понад 100 тис. Порівняно однофазне та багатофазне моделювання: багатофазний підхід забезпечує фізично реалістичні значення тиску (до 215 атм) і температури (~800 К) колапсу порожнин, тоді як однофазний значно переоцінює ці параметри, але придатний для швидкої якісної оцінки та попередньої оптимізації геометрії й режимів роботи.
Встановлено оптимальний вхідний тиск 7 бар, за якого досягається максимальна інтенсивність кавітаційного впливу при мінімальних енергетичних затратах. Розроблено гібридну стратегію оптимізації: первинний швидкий скринінг перспективних конструкцій однофазним моделюванням з подальшим детальним багатофазним аналізом найкращих варіантів.
За результатами моделювання режимів роботи ежектора-кавітатора отримані його оптимальні конструктивні і технологічні параметри. Використовуючи отримані дані, буде створено лабораторну рециркуляційну установку (об'єм 20 л, насос 1,1 кВт, регулювання тиску до 10 бар) та конструкцію ежектор-кавітатора для виготовлення методом 3D-друку з кавітаційно-стійкого поліпропілену Spectrum PP. Отримані результати формують науково-технічну основу для створення високоефективних сорбційних матеріалів і технологій очищення води з високим потенціалом промислового масштабування.
Ключові слова. *кавітація, цеоліти, сорбція, важкі метали, радіонукліди, сполуки азоту, трубка Вентурі, ізотерми адсорбції, модель Ленгмюра, CFD-моделювання, гранулометричний аналіз*

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PROBLEMS AND DIRECTIONS FOR IMPROVING THE METHODOLOGY FOR ASSESSING THE IMPACT OF CLIMATE RISKS ON THE SUSTAINABILITY OF MELIORATIVE AGRICULTURE

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Abstract. *Global climate change drives aridization and instability of soil-moisture conditions, which threatens sustainable development in agriculture and creates preconditions for accounting for these changes in the design of irrigation and drainage (land reclamation) systems and their operating regimes. Existing methods for designing irrigation and drainage often do not account for current climate trends (seasonal shifts, increased duration of rainless periods, changes in temperature regime), which creates a need for their systematic improvement. The article presents an approach to assessing the impact of climate risks on irrigated agriculture that integrates up-to-date indicators (moisture-supply deficit, reference evapotranspiration, crop coefficients, soil water-holding capacity and field capacity, the frequency and intensity of droughts, heat waves and precipitation intensity) with scenario analysis to forecast different moisture regimes under expected climate conditions. The concept of a methodology adapted to the regional diversity of Ukraine is outlined. For testing, pilot regions with contrasting climate-soil characteristics are proposed: the arid South, the moderately arid Center (periodic temperature stress, high inter-annual variability of precipitation), and the West, which is excessively humid in spring and slightly arid in summer (risks of waterlogging, the need for effective drainage at the beginning of the growing season and additional moisture supply during the rest of the period). A monitoring and validation program is proposed, including regular collection of meteorological data (daily temperatures, precipitation, radiation, wind, humidity), biometric indicators of plant growth and development (development stages, leaf-area indices, actual yield), soil characteristics (moisture, structure, nutrient content), as well as performance indicators of irrigation and drainage networks. Based on these data, crop coefficients and modelling parameters are refined, which makes it possible to perform hourly–daily calculations of water deficit, to develop adaptive irrigation and moisture-supply schedules, and to test SSP-based climate scenarios. The use of modern digital and automated tools (local weather stations, soil-moisture sensors, etc.) forms the basis for the digitalization of irrigation and water-regulation management in line with impact indicators. The improved methodology will make it possible to increase water-use efficiency in existing reclamation systems, incorporate updated climate parameters into new designs, reduce the vulnerability of agro-systems to droughts and other extreme weather events, minimize yield losses, and ensure production stability under climate change. An additional advantage is the possibility of ranking investment options according to economic efficiency indicators.*

Keywords: *climate risks, irrigation, meliorative agriculture, water deficit, scenario analysis, sustainable development*

Relevance of the research and problem statement. Global climate change is causing aridization of territories and instability of moisture regimes, which threatens the sustainable development of agriculture and creates an additional need for irrigation [1–8]. In particular, according to the Fifth National Climate Assessment [9], rising temperatures and changes in rainfall patterns lead to more frequent droughts and generally lower soil moisture, increase evapotranspiration and the need for irrigation, which raises the risks of reduced yields and agricultural productivity. For example, according to projections of current warming trends, by the end of the 21st century in California and Nevada an increase of reference evapotranspiration by

13–18 % is expected, which will accelerate soil drying and increase the risks of droughts and wildfires. This, in turn, will significantly increase the need for irrigation water [10]. Already now, in traditionally arid regions of the world, there are simultaneous decreases in precipitation and increases in temperature, which is reflected in the growth of the water stress index (the ratio of water use to available water resources) [11, 12].

Similar trends are recorded in Ukraine. In the period 2010–2020 the climate was characterised by increasing aridity (especially in the South and Centre) and moisture deficit during the growing season [13–17]. The current climate of most of Ukraine is classified as semi-arid, except for the western regions with sufficient moisture [13, 14]. Estimates show that about 46 % of the country's agricultural land cannot provide adequate yields without irrigation, about 43 % requires irrigation for high water-consuming crops, and only about 11 % has sufficient natural moisture [18–20]. Since the existing systems were not adapted to current conditions at the design stage [21, 22], and taking into account the current state and the continuous trend towards worsening climate conditions, the question arises of the need to revise water requirements and irrigation regimes, with consideration of methodological approaches to assessing climate risks and the vulnerability of the agricultural sector [23]. According to research estimates, ignoring the new climate conditions will lead to yield reductions of up to 69 % in the most arid regions (under a pessimistic scenario) [9, 13, 14]. In some dry years, the volumes of irrigation water use in the South of Ukraine exceed the average indicators of wet years by 50 % [18, 20], whereas in wet periods the need for irrigation significantly decreases. Such variability of climate conditions requires the use of more flexible approaches to maintain sustainable agricultural production.

In addition, a practical problem is that the design of land-reclamation systems was carried out according to historical climate norms, equipment energy-efficiency norms and typical operating conditions, while current temperature regimes and shifts in the seasonality of precipitation affect both crop water requirements and peak loads on water supply and drainage. Accordingly, without taking into account these changes and the methods of climate-risk assessment when defining design parameters, the modernization of even individual technical elements of irrigation systems may not ensure their proper adaptation to new climate conditions [13, 18, 19].

Thus, climate change has created an urgent need to adapt land-reclamation systems to new climate realities and to develop and implement scientifically based approaches that take climate risks into account in the practice of designing modernization projects for existing systems and constructing new land-reclamation systems. This will make it possible to increase the efficiency of water use, minimise yield losses and ensure food security [21, 22]. Improving the methodology for assessing the impact of climate change on irrigated agriculture is an important component of developing an adaptation strategy for agricultural production to new climate realities.

Analysis of recent studies and publications. The issue of assessing and mitigating the negative impact of climate risks by improving and expanding the use of land reclamation (melioration) attracts considerable attention from researchers worldwide. In particular, a climate risk management system for irrigation systems in arid regions was introduced in 2023 [8], and in 2021 researchers implemented concepts of "climate-smart" agriculture and intelligent irrigation systems based on digital solutions [25]. In the U.S. National Climate Assessment, the consequences of global warming for the agricultural sector are especially emphasised and described in detail [9]. Studies carried out in Ukraine, including with the participation of the authors of this article [26], have shown that there is a "hot phase" of climate change in Ukraine, which started in the late 1980s – early 1990s and continues today. It is characterised by the highest rate of increase of the mean annual air temperature in Europe (more than 0,45 °C per 10 years), with almost unchanged, and in the last decade slightly lower, mean annual precipitation. This has caused a significant increase in total evaporation and in the deficit, both annual and monthly, of the climatic water balance and, as a result, a progressive development of the process of drying of the territory of Ukraine, which has led to a significant deterioration of natural soil moisture conditions and a reduction in the volume of water resources available for use. The same studies, using climate change projections for 2050 and 2100 developed at the Ukrainian Hydrometeorological Research Institute under different scenarios, carried out a zoning of the territory of Ukraine by the value of the annual climatic water balance. The results made it possible to justify the need to use irrigation and water regulation by drainage systems as one of the most effective tools for adapting agriculture to climate change, and to determine the demand and main directions for improving the design of reclamation systems and technologies of irrigation and water regulation. The studies showed a significant mismatch between existing volumes of irrigation and water regulation and the current level of aridity [20] and became the basis for the "Strategy for Irrigation and Drainage in Ukraine for the Period until 2030" approved by the Cabinet of Ministers of Ukraine [21] and its Action Plan [22]. The above results were later confirmed by the conclusions of the World Bank Analytical Report (2024) taking into account climate trends [18].

Modern studies also emphasise the change in the conditions of use and parameters of irrigation systems under the influence of climate change: a 2024 study [27] notes a shift in phenological phases of vegetable crops and corresponding changes in crop coefficients (Kc) under different warming scenarios. Therefore, the issue of revising the basic conditions and guidelines for calculating water demand is important, where the FAO-56 Penman–Monteith method can be applied [28]. In the field of adaptation to droughts, a number of strategies have been developed, including for the conditions of Ukraine [29], to mitigate their impact on agricultural production, including for farms. To take into account the uncertainty of the climate future, a scenario approach is widely used: in particular, a set of global development scenarios, the so-called Shared Socioeconomic Pathways (SSP), has been formed to model trends in climate and related indicators [30]. The effectiveness of scenario analysis in irrigation planning has been confirmed in studies on optimisation of system management strategies, where multi-criteria optimisation of irrigation regimes for winter wheat was performed based on the combination of the AquaCrop-OSP model with the NSGA-III evolutionary algorithm. The obtained results showed that the scenario approach makes it possible to increase water productivity and yield stability at the same time under different projected water-resource constraints due to the advance optimisation of the system for forecast scenarios [31].

The basic approaches to planning and operation of irrigation traditionally rely on:

(1) calculation of reference evapotranspiration and transfer to crop water demand through crop coefficients (Kc) (as in FAO approaches) [28, 32];

(2) planning of irrigation schedules and regimes according to irrigation management methods [33];

(3) design based on historical climate norms or a limited set of "typical" years. These elements are necessary, but they are not sufficient to assess climate risks for the stability of irrigated agriculture under climate change.

The problem is that current methods do not ensure the integration of key indicators for the full chain "climate–water–soil–engineering infrastructure–yield", namely:

– the deficit of water supply is not considered as a risk metric (no transition from calculating water demand to assessing the risk of water under-supply);

– the frequency and intensity of droughts, the duration of rainless periods, and the combination of droughts with heatwaves are not included in the analysis (temperature stresses) [9, 10];

– the intensity of precipitation and the risks of extreme wetting are not included in the analysis (which is also important for drainage systems in overly wet zones) [2, 17];

– indicators of soil water-holding capacity and field capacity are not included as a "buffer" against drought, although they define the resilience of the system and the feasibility of irrigation under different conditions [35];

– the dynamics of Kc and phenological shifts of crops under warming, which change the seasonal profile of water consumption, are not taken into account [27];

– there is no scenario analysis of future conditions as a basis for stress-testing water infrastructure and agricultural production [30, 31].

Thus, the improvement of the methodology should consist in moving from a normative, calculation-based approach under average conditions to a risk-oriented approach with stress-testing and the inclusion of melioration-specific indicators that reflect both climate impacts and the limitations of infrastructure and the soil component of the water balance [38–40].

Goal of the research. The goal of this research is to improve the methodology for assessing the impact of climate risks on the sustainability of meliorative (irrigated) agriculture. To achieve this goal, the methodology proposes integrating updated climate indicators, applying scenario analysis of years with different rainfall availability, and using modern monitoring tools. The updated methodology should ensure the adaptive capacity of irrigation to changing climate conditions, increase the efficiency of energy and water use in agro-systems, and ensure the sustainable development of meliorative agriculture.

Materials and methods of the research. For a comprehensive assessment of the influence of climate factors on agro-systems, a list of indicators has been defined that should be included in the risk-assessment methodology:

– Water-supply deficit – an integral indicator of the water balance that reflects the lack of available water for plants over a certain period.

It is calculated as the difference between the crop's water requirement (reference evapotranspiration adjusted by the crop coefficient, ETc) and the incoming moisture (effective precipitation, soil moisture) [33]. The value of the deficit characterises the level of aridity: a higher deficit corresponds to a higher risk of drought and, accordingly, to an increased need for irrigation. This indicator is a basic one for calculating the level of climate risk for agriculture.

– Crop coefficients (Kc) – indicators representing the ratio of the actual evapotranspiration of a crop to the reference evapotranspiration (ET_0). They take into account the biological characteristics of plants (for example, growth stages) and are used for calculating water consumption. This indicator depends on the type of crop and reflects the dependence of yield on the level of water availability. Among crops vulnerable to water deficit are rice and alfalfa, compared with, for example, chickpea [28]. Climate change affects the development of crops during the season through changes in evaporative demand, because with increasing air temperature the growing period may become shorter, and total water consumption may increase due to higher daily water requirements [10][9]. Accordingly, the methodology should take into account updated crop coefficients for major crops and projected changes of these indicators under different climate scenarios, in order to assess risks in a differentiated way [27].

– Soil water-holding capacity – an indicator that characterises the ability of the soil to retain a certain amount of water available for plants between rainfall or irrigation events. It depends on soil texture and organic-matter content and serves as a buffer during drought, from which the crop satisfies its water needs [35]. Soils with higher water-holding capacity (clayey soils, soils rich in humus) can support plants longer without rainfall, whereas light sandy soils lose moisture more quickly. Including this indicator allows assessing the regional specificity of soil conditions and the feasibility of agricultural production under certain conditions (in some regions, adaptation measures may be economically impractical due to low water-holding capacity and high operational irrigation costs).

– Frequency of dry years – a statistical indicator that reflects the probability of extreme precipitation deficit in a region. The indicator characterises the probability of acute (that is, intensive) climate risks [41–44].

– Temperature regime (during the growing season) – mean and extreme air temperatures during the crop's growing season. Temperature affects evapotranspiration and plant development. High temperatures increase water demand and may suppress photosynthesis, raising the risk of yield loss during drought [9, 10]. Accordingly, the methodology should consider the temperature background: mean monthly temperatures, the number of extremely hot days, the sum of effective temperatures, and other parameters. This will help adjust the assessment of water requirements and determine periods when the combination of heat and drought is especially dangerous for crop cultivation.

– Monthly ET_0 values – the reference evapotranspiration indicator for each month of the growing season, which reflects the seasonal dynamics of water demand. Maximum ET_0 values usually occur in summer, and minimum values occur in spring and autumn. Including monthly ET_0 values in the methodology is important for identifying critical periods with the highest likelihood of water deficit. For example, if in peak summer months ET_0 reaches 200 mm and rainfall during this period is only 50 mm, water deficit will inevitably arise without additional irrigation. Climate change affects not only the annual total but also the monthly distribution of ET_0: with rising temperatures, reference ET_0 is expected to increase, with peak values in summer [10, 33]. Accordingly, the methodology should analyse the monthly water balance and compare ET_0 with monthly rainfall norms. This will make it possible to determine the volume of irrigation required for each month and to predict the technical capacity of the system to provide peak water supply [28, 36, 37].

The indicators listed above are interconnected and together make it possible to comprehensively assess potential climate risks for irrigated agriculture [21]. Their inclusion in the methodology increases its accuracy and allows compiling integrated risk ratings for different regions or agro-systems, where climate, soil conditions and crop characteristics are taken into account. This creates a scientific basis for defining the priority of implementing adaptation measures and refining design decisions in meliorative practice.

Scenario analysis of climatic conditions. The improved methodology proposes including the application of a scenario approach. Such an approach makes it possible to consider the realisation of potential risks under different projected conditions. In particular, for the purposes of improving the methodology, it is advisable to implement this approach through projected conditions of agro-system functioning in years with different levels of rainfall availability (from a conditionally worst – dry year, to a conditionally best – wet year) [30, 31]. This approach makes it possible to test the resilience of land-reclamation systems across the full range of climate changes. In particular, it is proposed to include two basic scenarios consistent with modern projections developed by the Intergovernmental Panel on Climate Change (IPCC):

– an extremely dry scenario (analogous to scenario SSP5 – economic development based on fossil fuels with minimal actions to counter climate change), which serves as a stress test for the irrigation system under minimal precipitation, and

– an excessively wet scenario (analogous to scenario SSP2 – a moderate pathway to achieving climate neutrality, in which significant resources are allocated for mitigation and adaptation), when precipitation exceeds the norm [45–48].

In the first case, the analysis makes it possible to assess the maximum water deficit and the ability of the system to meet the needs of the agricultural sector under extreme drought; in the second case – to check whether the system can cope with excess water drainage and use favorable conditions (accumulating soil moisture for future periods, etc.) [18, 45]. Designing only for an average year does not take into account peak extremes and relies solely on historical trends, while designing for the worst year for all crops may be economically impractical due to high capital and operational costs of maintaining such systems [21]. Scenario analysis in stress-testing and risk-management practices is widely applied and helps find a balance between the level of resource availability and an acceptable level of risk by quantitatively assessing yield losses or water deficit for each option [31]. This approach is an international practice for planning reliable strategies not only in business operations but also in the functioning of irrigation systems [49][50]. Including two polar scenarios in the methodology makes it possible to conduct a full assessment of the resilience of land-reclamation systems, justify design parameters under different conditions consistent with reality, and plan mitigation measures for negative consequences [21], minimising the impact of climate variability on yields.

Selection of pilot regions. Practical testing and improvement of the methodology is proposed in several pilot regions of Ukraine with different climatic conditions. In particular, three contrasting regions in terms of water-resource availability may be covered:

(1) a dry southern region (semi-arid climate, chestnut and southern chernozem soils with moderate water-holding capacity, a developed network of main irrigation canals). This is a zone of risky agriculture where most crops depend on irrigation (up to 60 % of all irrigated lands of Ukraine are concentrated here) [18, 24];

(2) a central forest-steppe region (close to a dry subhumid climate, heavy chernozem soils with high water capacity, mainly local sprinkler and drip irrigation systems). Traditionally, this is a rainfed zone, but recent aridization trends increase the relevance of irrigation for this region as well [18, 21];

(3) a western Polissya/foothill region (humid subhumid climate, in some areas heavy gley soils, high groundwater levels in drained zones, land reclamation functions mainly as drainage). In this region droughts are rare, but there are risks of both over-wetting and over-drying of the soil [13, 51].

The selected regions cover a range of conditions from extreme water deficit to excess moisture, which makes it possible to test the applicability of the methodology under different moisture conditions. Pilot testing in real farms with long-term data will make it possible to identify which climate-risk indicators are the most critical for each zone and ensure that the methodology adequately accounts for both drought risk and excessive moisture risk. It is advisable to involve existing land-reclamation systems in the research, where long-term observations are available and there is technical capability to implement the recommendations [21].

Programme for methodology validation. The improved methodology will require testing under real conditions. Trials are planned to be conducted at selected pilot sites over several years in order to cover weather variability. During each growing season, regular monitoring of the following indicators will be carried out on the experimental plots:

– meteorological data (amount of precipitation for the period, average daily and extreme temperatures, humidity, wind speed, etc.) [52–56];

– soil conditions (soil texture, hydro-physical characteristics, moisture in the root zone, depth of wetting after rainfall/irrigation, groundwater level in drainage zones);

– irrigation and moisture regimes (dates and rates of irrigation/moisture application);

– plant development (dates of growth-stage onset);

– yield and product quality.

Collecting these data will make it possible to compare the indicators predicted by the methodology with actual ones and quantitatively assess the accuracy of forecasts. If systematic discrepancies are identified, model calibration will be carried out – adjustment of the methodology parameters to real conditions [27, 21]. After that, validation will continue using independent data from subsequent years or regions. Field validation followed by adjustment is a widely accepted practice in the implementation of agro-ecosystem models [21] and will ensure reliability and credibility of the improved methodology before its large-scale application.

Material and technical support. For the practical implementation of the proposed methodology, modern instrumental and software support is required. It is envisaged to use the following tools (if available):

– data from the national network of meteorological observations as a basic source of information on temperature, precipitation, humidity, wind and other parameters (with unified data series and quality-control procedures), as well as, if available, local sensors/devices installed in farms [35];

– software tools for calculating ET_0 using the Penman–Monteith formula (the official FAO ETo calculator) for the purpose of automating computations [28];

– computer models and algorithms for forecasting the water balance, which, with the involvement of artificial intelligence methods, will predict moisture deficit and irrigation needs in advance [31, 66,67];

– geographic information systems and remote-sensing data (satellite images of NDVI, EVI indices, thermal field scanning) for spatial analysis of risks and crop conditions [57–65].

The integration of these components into a single decision-support system corresponds to the concept of so-called "smart agriculture" and will allow automation and increased accuracy of irrigation management [25]. Adherence to standard methods will ensure unification and the possibility of comparing risk-assessment results in different regions [28].

Conclusions. Existing methods for planning irrigation systems, their operation and design have faced challenges under climate change and require updating. International studies confirm that rising temperatures and changes in precipitation regimes lead to increased water deficit and drought risk; therefore, the integration of climate indicators is a necessary condition for assessing melioration needs under current conditions and for the effective operation of land-reclamation systems [28, 10, 68]. At the same time, to bring the methodology in line with the content of the task of assessing climate risks in irrigated agriculture, it is necessary to take into account not only basic calculations of water requirements and irrigation planning, but also specific risk-oriented indicators and scenario uncertainty, which determine system resilience under extremes and seasonal shifts [69, 70, 71]. It is proposed to include widely accepted approaches of scenario analysis of extremely dry and wet conditions, which cover a wide range of possible impacts on systems and increase the reliability of management decisions in accordance with modern principles of risk management [40, 79]. The developed methodology will be tested in different climatic zones of Ukraine – from the arid steppe to the humid Polissia. The use of modern software will simplify the process of assessing and modelling climate risks and will allow effective management of them. The implementation of the improved methodology will contribute to increased efficiency of water-resource use, reduced vulnerability of the agricultural sector to droughts and extreme weather events, and the sustainable development of irrigated agriculture under global climate change. This is consistent with the goals of national food security and the recommendations of leading international organisations regarding adaptation of agricultural production to climate change [1, 2, 6, 7]. A scientifically grounded methodology for assessing climate risks will become the foundation for making effective management decisions and for investing in land-reclamation infrastructure [72–78].

Prospects for further research. Further research should be aimed at adapting the methodology to different types of land-reclamation systems, taking into account practical aspects and operating conditions, improving the module for forecasting climate indicators, developing digital platforms for real-time risk assessment, and integrating economic indicators into the analysis. In addition, the methodology may become a scientifically grounded basis for implementing support policies in agriculture aimed at introducing resource- and energy-saving technologies and ensuring financial mechanisms for infrastructure modernization [80].

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

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ПРОБЛЕМИ ТА НАПРЯМИ УДОСКОНАЛЕННЯ МЕТОДИКИ ОЦІНКИ ВПЛИВУ КЛІМАТИЧНИХ РИЗИКІВ НА СТАЛІСТЬ ВЕДЕННЯ МЕЛІОРАТИВНОГО ЗЕМЛЕРОБСТВА

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Анотація. *Глобальна зміна клімату зумовлює аридизацію та нестабільність умов зволоження ґрунтів, що ставить під загрозу сталий розвиток у сільському господарстві, а також формує передумови щодо її врахування при проектуванні меліоративних систем та режимів. Існуючі методики проектування зрошення та дренажу часто не враховують поточні кліматичні тренди (зміщення сезонів, збільшення тривалості бездощових періодів, зміна температурного режиму), тому виникає потреба в їх системному удосконаленні. У статті представлено підхід до оцінки впливу кліматичних ризиків на зрошуване землеробство, який передбачає інтеграцію актуальних показників (дефіциту вологозабезпечення, еталонної евапотранспірації, коефіцієнтів культур, водоутримувальної здатності та вологоємності ґрунтів, частоти та інтенсивності посух, теплових хвиль і інтенсивності опадів) зі сценарним аналізом для прогнозування різних режимів зволоження відповідно до очікуваних кліматичних умов. Розкрито концепцію методики, адаптованої до регіонального різноманіття України. Для апробації запропоновано пілотні регіони з контрастними кліматично-ґрунтовими характеристиками: посушливий Південь, помірно посушливий Центр (періодичні температурні стреси, висока міжрічна мінливість опадів) та надмірно зволожений весною і легко посушливий влітку Захід (ризики перезволоження, потреба в ефективному дренажі на початку вегетації і додатковому зволоженні в решту часу). Запропоновано програму моніторингу й валідації: регулярний збір метеоданих (добові температури, опади, радіація, вітер, вологість), біометричних показників росту та розвитку рослин (фази розвитку, показники листкової поверхні, фактична врожайність), характеристик ґрунтів (вологість, структура, вміст поживних речовин) а також показників роботи зрошувальних і дренажних мереж. На базі цих даних уточнюються коефіцієнти культур і параметри моделювання, що дає змогу здійснювати погодинно-добові розрахунки водного дефіциту, формувати адаптивні графіки поливів та зволоження і тестувати сценарії (SSP-сценарії). Використання сучасних цифрових та автоматизованих інструментів (локальні метеостанції та датчики ґрунтової вологи та ін.) закладає основу для цифровізації управління зрошенням та водорегулюванням залежно від індикаторів впливу. Удосконалена методика дозволить підвищити ефективність водокористування на існуючих меліоративних системах, врахувати оновлені кліматичні параметри при проектуванні, зменшити вразливість агросистем до посух та інших екстремальних погодних явищ, мінімізувати втрати врожайності та забезпечити стабільність виробництва в умовах зміни клімату. Окремою перевагою є можливість ранжування інвестицій за показниками економічної ефективності.*

Ключові слова: *кліматичні ризики, зрошення, меліоративне землеробство, водний дефіцит, сценарний аналіз, сталий розвиток*

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DYNAMICS OF QUANTITATIVE AND QUALITATIVE INDICATORS OF HUMUS CONTENT IN SOIL WHEN LONG-TERM CULTIVATING WINTER RYE IN CONSTANT CROPS

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Abstract. *The main source of nutrients and energy for all living things in the soil is organic matter, thanks to which the continuous cycle of nutrients in nature is maintained. Long-term functioning of the soil in agrosystems leads to a state of equilibrium of organic matter with an appropriate level of its stability. As a result of reducing the application of fertilizers, especially organic ones, fundamental changes have occurred in the small (biotic) cycle of substances. Every year, the negative balance of humus reaches 370–400 kg/ha, and the annual decrease in its reserves exceeds 20 million tons. According to soil survey materials, in the most fertile typical black soils of the Karlivska community of the Poltava region, the humus content currently does not exceed 6.0–6.5 %, or 2.0–2.5 % less than at the time of their survey by the expedition of V.V. Dokuchaev in 1890. The problem of humus is undoubtedly one of the key ones in solving the problems of stabilizing and restoring soil fertility.*

Long-term studies with winter rye in constant crops, which are conducted at the Poltava Agricultural Research Station, make it possible to determine and generalize its influence on the dynamics of winter rye productivity. At the same time, changes in agrochemical soil indicators are also observed. As a result of the experiment on the cultivation of winter rye in constant crops, it was found that humus content in the soil is not a statistical indicator and changes in absolute values, both in the spring and summer-autumn periods, and over the years of observation. Statistical analysis of the data obtained during the studies showed a direct and inverse correlation between the humus content indicators and the hydrothermal conditions during the research. It is proposed to widely use the results of the studies in solving fundamental issues of agriculture, in deep complex studies, and for the demonstration of the role of the main factors and conditions of plant life.

Keywords: *rye, constant crops, humus content, weather conditions, correlation*

Relevance of research. The current state of the agricultural sector of Ukraine is characterized by a certain range of problems, among which the key one is the preservation and reproduction of the fertility of agricultural soils [1–5]. To determine this function, the correct choice of the main criteria is of great importance. A sufficiently informative indicator in this regard can be the content of organic carbon in the arable soil layer. Soil fertility depends on the rate of this organic matter by 85–90 %, which is essentially a form of accumulating solar energy on the Earth [6–10].

Annual decomposition, synthesis and transformation of humus, conservation and binding of nutrients in it and their continuous release and entry into the soil solution are the features of humus substances in the soil. The formation of this organic compound in the soil is a necessary basis and means for plants to obtain nutrients, as well to create an optimal ecological environment in the soil profile [11, 12].

The problem of humus is undoubtedly one of the key ones in solving the problems of stabilizing and restoring soil fertility. So these issues determined the area of the research conducted.

Analysis of the state of research and publications. The humus content influences all the properties closely related to all soil regimes, and primarily to the nutrient one. In particular, it is worth noting that 98 % of nitrogen, 60 % of phosphorus, 80 % of sulfur and a large number of other macro- and microelements accumulate in organic form, which are in organo-mineral complexes and are reliably kept from leaching [13–16]. This explains the well-known fact: the higher the humus content in the soil, the higher the productivity of plants under different weather conditions [17–20].

As a result of reducing the application of fertilizers, especially organic ones, fundamental changes have occurred in the small (biotic) cycle of substances. Each year, the negative balance of humus reaches 370–400 kg/ha, and the annual decrease in its reserves exceeds 20 million tons. According to soil survey materials in the most fertile chernozems typical of the Poltava (former Karlivsky) district of the Poltava region, the humus content currently does not exceed 6.0–6.5 %, or 2.0–2.5 % less than at the time of their survey by the expedition of V.V. Dokuchaev in 1890 [21, 22].

Research objective: to determine quantitative and qualitative changes in humus content during long-term constant cultivation of winter rye in dark gray podzolized soil.

Materials and research methods. The research was conducted in the experimental field of the Poltava State Agricultural Research Station named after M.I. Vavilov of the Institute of Pig Breeding and Agroindustrial Production of the NAAS of Ukraine in dark gray podzolized soil in the subzone of unstable moisture of the left-bank Forest-Steppe.

The experiment on growing permanent rye at the Poltava experimental field was initiated in 1884. The sowing and accounting area of the experiment is 0.4 hectares. In the entire area of the experiment, only one factor is studied – permanent cultivation of winter rye. Repetition is one-time. Agricultural technology does not change throughout the entire research period. Fertilizers, as well as chemical means of controlling weeds, diseases and pests are not used. Pre-sowing cultivation and sowing of winter rye with subsequent rolling are carried out in mid-September. The sowing rate is 6 million seeds per hectare. Over the entire historical period, 9 varieties of winter rye were sown. Varietal change was carried out after the variety was removed from zoning.

Research results and their discussion. Determining the effect of long-term constant rye cultivation on humus content in the soil shows that humus amount in the soil is not statistical and varies in absolute values, both in the spring-autumn periods and over the years of observations (Fig. 1).

Thus, if in April 2001 the humus content in the 0–20 cm soil layer was 2.58 %, then in July it decreased to 2.29 %, and in October it increased to 2.63 %. The same dynamics of the organic matter was observed by years and months and, accordingly, in percentage terms, it was equal to the following values: 2008 – 2.60; 2.30; 2.69, 2015 – 2.52; 2.22; 2.60, 2023 – 2.48; 2.29; 2.55.

These research results, in our opinion, are quite logical since the intensity of hydrolysis

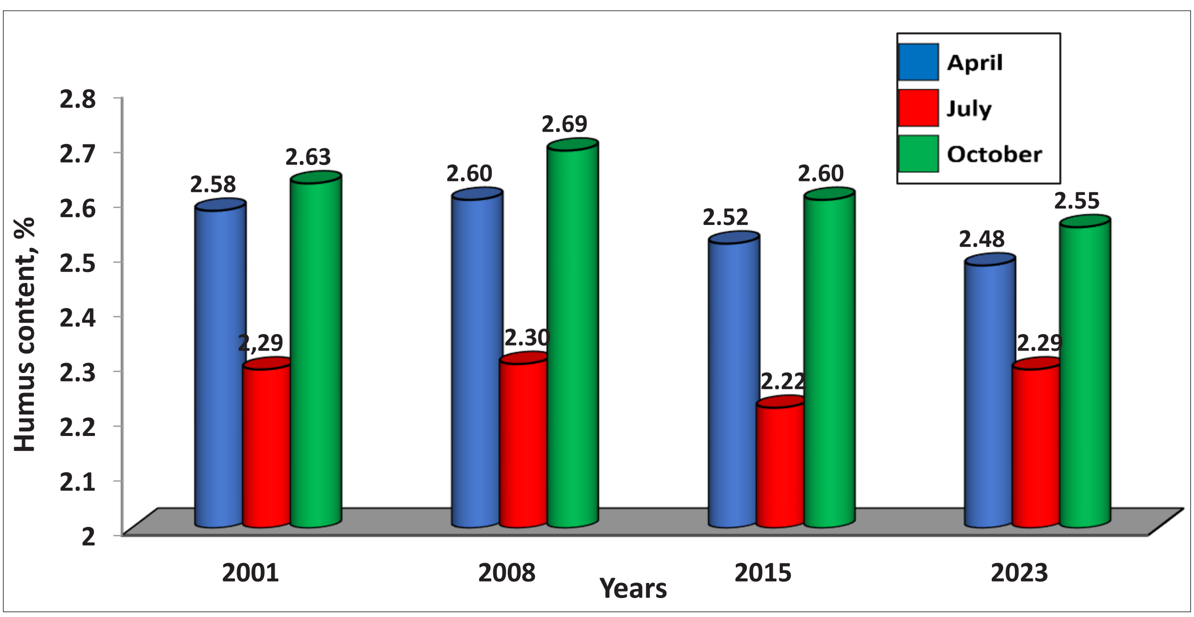

Fig. 1. Dynamics of humus content changes during the vegetation of winter rye in the years of sampling

and synthesis of organic matter is influenced by anthropogenic and natural factors. The main one is the amount of organic mass entering the soil, which directly contributes to humus accumulation in the soil. Such factors as different intensity of nutrient use from the soil by plants during their growth and development, as well as different water and temperature regimes of the soil at the time of sampling, which directly affect the intensity of hydrolysis and synthesis of organic matter, indirectly affect this process (Table 1, 2).

In addition, it is necessary to take into account that plants absorb nutrients from the soil with different intensity at different stages of their development. All this has a direct impact on the dynamics of humus content during the growing season.

When using statistical calculations and analysis of the humus content in the soil in relation to the amount of precipitation it was established the following: for the spring (March-May) and summer (June-August) periods, an average direct correlation was recorded; the correlation coefficient was r = 0.52 and r = 0.45 respectively, while for the autumn period (September-November) the correlation was average inverse, and the correlation coefficient r was −0.50.

The relationship between the humus content in soil and temperature regimes was in a somewhat different paradigm. During the spring (March-May) and summer (June-August) periods, a high negative correlation was observed and the correlation coefficient was r = −0.74 and r = −0.88 respectively. During the autumn period (September-November) the relationship was average inverse, and the correlation coefficient r was −0.62.

Long-term observations indicate that for the entire period of the experiment with the permanent rye crop, the humus content in the dark gray podzolized soil has been undergoing transformation, but this process is relatively stable.

Over the years of research, there has been a change in the qualitative indicators of humus in both 0–20 and 20–40 cm soil layers. In particular, the carbon content of humic acids during 1964, 1979, 2012, 2022 in 0–20 cm soil layer was in the following dynamics: 0.353; 0.288; 0.307; 0.294. and in 20–40 cm soil layer it was 0.258; 0.261; 0.234; 0.246 respectively. In a slightly different paradigm, this process occurred with the carbon of fulvic acids and, accordingly, by years and soil layers it had the following values: 0.306; 0.311; 0.329; 0.271 and 0.210; 0.225; 0.236; 0.220 respectively.

The ratio between the carbon of humic and fulvic acids also changed throughout the entire observation period. Thus. if in 1964 this indicator in the upper and lower layers of the soil was 1.15 and 1.26, respectively. then in 1979 it was 0.93 and 1.16, in 2012 it was 0.93 and 0.99. and in 2022 it was 1.08 and 1.12 units (Table 3). Despite the dynamics of this indicator during the research, the type of humus was static – fulvate-humate.

1. Precipitation in the years of the research, mm

Years	Months						For the year	+/– to perennials
	March-May	April	June-August	July	September-November	October		
2001	194.9	73.5	282.7	10.0	208.2	27.1	781.0	212.0
2008	152.8	58.7	129.5	27.1	125.9	31.9	491.4	-77.6
2015	172.4	38.5	168.4	8.5	54.7	2.0	539.8	-29.2
2023	132.5	77.0	221.6	67.3	226.1	82.1	732.5	163.5
Average long-term	121.0	40.0	177.0	71.0	135.0	42.0	569	x

2. Average air temperature, t °C

Years	Months						For the year	+/– to perennials
	March-May	April	March-May	July	March-May	October		
2001	9.2	11.0	20.7	18.4	7.5	6.4	8.3	0.7
2008	10.0	11.3	20.7	22.1	9.2	10.5	9.2	1.6
2015	9.9	9.4	21.1	21.6	9.8	6.7	9.8	2.2
2023	11.0	11.0	22.0	22.1	11.2	11.5	10.9	3.3
Average long-term	8.0	8.8	19.4	20.1	7.8	7.6	7.6	×

3. Composition of soil humus during cultivating winter rye in constant crops

Indicators	**Years**							
	1964		**1979**		**2012**		**2022**	
	Soil layer, cm							
	0–20	**20–40**	**0–20**	**20–40**	**0–20**	**20–40**	**0–20**	**20–40**
Humus content, %	2.35	1.76	2.26	1.84	2.33	1.81	2.29	1.70
Organic carbon in soil	1.47	1.02	1.30	1.97	1.42	1.19	1.38	1.15
Carbon in 0,1H H_2SO_4	0.066	0.056	0.095	0.072	0.088	0.069	0.084	0.059
Carbon in $N_4P_2O_3$ + NaOH	0.659	0.465	0.599	0.486	0.613	0.472	0.608	0.467
Carbon in humic acids	0.353	0.258	0.288	0.261	0.307	0.234	0.294	0.246
Carbon in fulvic acids	0.306	0.210	0.311	0.225	0.329	0.236	0.271	0.220
Ratio of humic acid carbon to fulvic acids	1.15	1.26	0.93	1.16	0.93	0.99	1.08	1.12

Conclusions. Based on the results of the research, it was established that during the long-term period of the experiment (with the permanent rye crop), the transformation of the humus content in the dark gray podzolized soil occurs in spring, summer and autumn periods, respectively, in the following paradigm: 2.55 %; 2.28 %; 2.62 %. Over the period of long-term observations, there has been a general trend towards a decrease in humus content in the soil when cultivating winter rye in constant crops.

Statistical analysis of the data obtained as a result of the research showed a direct and inverse correlation between the values of humus indicators and the hydrothermal conditions of the observations.

During long-term cultivation of winter rye in one place, the ratio between humic and fulvic acids was in the soil layers (0–20 and 20–40 cm) in the range of 0.93–1.15 and 0.99–1.26 respectively. These indicators correspond to the fulvate-humate type of humus.

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

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

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ДИНАМІКА КІЛЬКІСНИХ І ЯКІСНИХ ПОКАЗНИКІВ ВМІСТУ ГУМУСУ У ҐРУНТІ ЗА ТРИВАЛОГО ВИРОЩУВАННЯ ЖИТА ОЗИМОГО В БЕЗЗМІННОМУ ПОСІВІ

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Анотація. *Основним джерелом поживних речовин і енергетичного матеріалу для всього живого у ґрунті є органічна речовина, дякуючи чому і підтримується безперервний кругообіг поживних речовин у природі. Довготривале функціонування ґрунту в агросистемах приводить до стану рівноваги органічної речовини з належним рівнем його стабільності У результаті зменшення внесення добрив і особливо органічних, корінні зміни пройшли у малому (біотичному) кругообігу речовин. Кожний рік від'ємний баланс гумусу досяг 370–400 кг/га, а щорічне зменшення його резервів перевищує 20 млн. т. За матеріалами ґрунтового обстеження у найбільш родючих чорноземах типових Карлівської громади Полтавської області у даний час вміст гумусу не перевищує 6.0–6.5 %, або на 2.0–2.5 % менше, ніж на час їх обстеження експедицією В.В. Докучаєва в 1890 р. Проблема гумусу без сумніву є однією з ключових на шляху вирішення завдань стабілізації і відтворення ґрунтової родючості. Довгострокові дослідження з беззмінним житом, які проводяться на Полтавській сільськогосподарській дослідній станції дають можливість визначити і узагальнити його вплив на* *динаміку величини продуктивності. Разом з тим ведуться спостереження за зміною агрохімічних показників ґрунту. У результаті проведення досліду з вирощування жита беззмінного було встановлено, що величина вмісту гумусу у ґрунті показник не статистичний і змінюється, в абсолютних величинах, як за весняний та літньо-осінній періоди, так і за роками спостережень. Статистичний аналіз даних, отриманих у результаті досліджень показав прямий та зворотний кореляційний зв'язок між величинами показників гумусу та гідротермічними умовами проведення досліджень. Запропоновано результати досліджень широко використовувати при вирішенні фундаментальних питань землеробства, для глибоких комплексних досліджень, демонстрації ролі основних чинників та умов життя рослин.*

Ключові слова: *жито, беззмінний посів, вміст гумусу, погодні умови, кореляційний зв'язок*

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APPROACHES TO IMPROVE THE EFFICIENCY OF CROPS GROWING ON A SOD-PODZOLIC SOIL

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Abstract. *The article presents the results of field studies on the impact of mineral fertilizer, liming, application of sulfur-containing fertilizer and microelements on the yield and economic efficiency of growing crops on a sod-podzolic soil. The study was conducted in a stationary experiment of the Institute of Agriculture of Western Polissya in the following crop rotation: winter wheat, corn, spring barley, winter rapeseed. Limestone materials (dolomite and limestone flour) were applied in doses determined by the magnitude of hydrolytic acidity (Hh, mmol/100 g of soil) before the experiment was started, recommended doses of mineral fertilizers were applied to the crops annually, and foliar feeding with the micronutrient "Nutrivan Plus" was carried out. It has been established that the productivity of crops on this type of soil largely depends on the degree of its agrochemical conditions. The use of mineral fertilizer (NPK) alone provided limited yield increase, while the combination of fertilizers with liming with dolomite flour contributed to a significant increase in crop productivity. The highest yield (4.00 t/ha) and economic return (9.2 thousand UAH/ha) in winter wheat crop was ensured by the integrated use of NPK, dolomite flour (1.0 Hh), sulfur (S_{40}), and micronutrient fertilizers. For corn and winter rapeseed, the highest yield (9.04 and 2.94 t/ha) and profit (29.2 and 33.5 thousand UAH/ha), respectively, were obtained with the application of 1.5 Hh $CaMg(CO_3)_2$. It has been proven that growing crops without fertilizer or only with NPK is economically unprofitable. The obtained results confirm the feasibility of using an integrated system of fertilization and land reclamation on acidic soils to ensure sustainable agricultural production.*

Keywords: *chemical land reclamation, sulfur fertilizers, mineral fertilizers, yield, economic efficiency, sod-podzolic soils*

Relevance of the research. The problem of soil fertility remains relevant at present. One of the main indicators of the level of soil fertility is the reaction of soil solution, on which the formation of high yields depends.

If chemical land reclamation is ignored, 0.6–1.8 million tons of agricultural units of crop production on acidic soils are annually lost. Gross yields of winter wheat, spring barley, and winter rapeseed are reduced the most. According to the research performed by the Institute of Agriculture of Western Polissya, positive changes occurring in sod-podzolic soils under the influence of liming contribute to an increase in crop rotation's productivity by 24–42 %.

A specific feature of acidic soils is the inhibition of root system growth and microbiological activity in root-containing layer; the accumulation of mobile forms of aluminum, iron, and manganese harmful to plants; the deterioration of physical parameters; insufficient nutritional regime [1, 2].

Based on the above-mentioned, it is relevant to study the possibilities of optimizing the conditions of crop nutrition in crop rotations on sod-podzolic soils by improving the soil using crop fertilization systems and chemical land reclamation.

Analysis of recent research and publications. Violation of the laws of agriculture can lead to a stable dynamics of a decrease in the level of soil fertility, especially its humus condition – the main criterion for assessing its fertility [3, 4]. The most vulnerable to this is the territory of Polissya, where sod-podzolic soils of light texture are widespread, which is due to the predominance of the podzolic soil formation process in this zone.

They are characterized by low nutrient and organic matter content, and an acidic soil reaction. Sod-podzolic soils were formed mainly on sandy and sandy loam basis, in conditions of a rather humid climate and hilly-ridged relief. This entire complex of characteristics determines low natural fertility of sod-podzolic soils. Looking for approaches to increase the fertility of such soils is an important scientific and practical task, the solution of which determines the effectiveness of agricultural production in humid regions [5, 6]. The main direction of increasing their fertility is chemical and structural land reclamation, fertilizers, which are primarily aimed at improving the agrophysical, agrochemical, and physicochemical properties of the soil [7, 8].

The results of long-term studies have found out that for the most of the crops cultivating in the Polissya and Forest-Steppe zones of Ukraine, the optimal reaction of soil solution is within the pH_{KCl} range of 5.6–7.0 [4, 9]. It is practically impossible to achieve this level of soil reaction in natural conditions without liming. Therefore, environmentally safe and economically feasible agricultural use of these soils requires chemical reclamation and the application of fertilizers [10, 11]. Research conducted by the Institute of Agriculture of Western Polissya has established optimal doses of limestone, organic and mineral fertilizers in crop rotations on sod-podzolic soils, which ensure a productivity of 55–60 centners of feed units per hectare of crop rotation area.

The studies of a number of domestic and foreign researchers [6, 11–14] have proven that effective liming with doses within 0.5–1.5 Hh (hydrolytic acidity) provides optimal conditions for crops growth, significantly reduces the mobility of toxic forms of aluminum, the excess of which on acidic soils can suppress the root system and reduce yield by 20–50 % [12, 13].

In addition to chemical land reclamation, the effective use of sod-podzolic soils requires an integrated approach, which also includes the application of organic and mineral fertilizers, micronutrients, and sulfur-containing compounds [14, 15]. In particular, sulfur is an important element in plant protein metabolism, and micronutrients (zinc, boron, manganese, copper, etc.) increase the resistance of crops to stress factors, activate enzymatic processes, and contribute to better absorption of essential nutrients [1, 15]. The results of scientific researches show that supplementing background doses of mineral fertilizers with foliar application of micronutrients ensures increasing in crops productivity in various soil and climatic conditions [16, 17].

However, the problem of modern agriculture is the steady decrease trend in the use of organic fertilizers, the deficiency of sulfur, calcium, and magnesium as the primary causes of low fertility of sod-podzolic soils. Therefore, the combined use of dolomite flour, sulfur-containing and microfertilizers deserves special attention, which will allow not only to effectively regulate soil acidity, but also to ensure balanced nutrition for crops, improve the physicochemical properties of soil environment and increase yield in the long term.

The aim of the study was to determine the effect of different forms and doses of chemical ameliorants in combination with fertilizers on the yield and economic efficiency of growing agricultural crops on a sod-podzolic soil in the conditions of Western Polissya.

Materials and research methods. The field studies were conducted in a stationary experiment of the Institute of Agriculture of Western Polissya of NAAS in a short crop rotation on sod-podzolic soil. The crop rotation was as follows: winter wheat, corn, spring barley, winter rapeseed. The technology of growing agricultural crops is generally accepted for the Polissya zone. Protection from pests, diseases, and weeds was carried out using intensive technology.

Mineral fertilizers were applied in recommended doses: $N_{120}P_{60}K_{90}$ for winter wheat, $N_{120}P_{90}K_{120}$ for corn for grain, $N_{90}P_{90}K_{90}$ for spring barley, $N_{120}P_{90}K_{120}$ for winter rapeseed in the form of ammonium nitrate, ammophos, potassium chloride. Chemical ameliorants – dolomite ($CaMg(CO_3)_2$) and limestone ($CaCO_3$) flours – were applied before the establishment of the stationary experiment according to the experiment scheme in doses calculated by the hydrolytic acidity index of the soil (Hh, mmol/100 g of soil): 0.5–1.5 Hh.

The foliar fertilization of crops with microfertilizers "Nutrivant Plus Cereal" and "Nutrivant Oilseed" (2 kg/ha) were carried out in the phases of spring tillering and emergence into the tube of winter wheat, in the phase of 4–5 and 6–8 leaves for corn, in the phase of tillering and emergence into the tube for spring barley, and in the phase of spring rosette and the beginning of budding for winter rapeseed.

The harvest was recorded by plots, by continuous weighing of the obtained harvest with subsequent conversion to per area units. Statistical processing of the obtained research results was carried out by the ANOVA variance analysis method using the computer programs Microsoft Office Excel, and Statistica 10.0.

Weather conditions over the years of research indicate that this period was characterized by an increase in the average monthly air temperature and sharp fluctuations in the amount and intensity of precipitation. Quite often, long droughts were replaced by rains, which negatively affected the processes of plant growth, development, and the formation of an appropriate level of winter wheat productivity.

Despite the change in temperature and humidity regimes, weather conditions for crops in the Western region were close to average long-term values, which led to the formation of relatively high-yield crops production on sod-podzolic soils.

Research results and their discussion. It has been found out that the yield of agricultural crops on sod-podzolic soils largely depends on the degree of their amelioration, which includes the complex impact of several factors: mineral fertilizer (NPK), liming, application of sulfur-containing fertilizer and micronutrients. Thus, in the variant without applying any of these measures (control), the average crop yield was for winter wheat – 1.29 t/ha, for corn – 4.05 t/ha, for spring barley – 1.39 t/ha, and for winter rapeseed – 0.85 t/ha. These results indicate low productivity of sod-podzolic soils without liming and mineral nutrition, because of their high acidity, weak buffering capacity, and nutrient deficiency [2, 5, 7].

1. Productivity of crops in the rotation depending on fertilizer and doses of chemical ameliorants, average for 2016–2020, t/ha

Option	Winter wheat		Corn for grain		Spring barley		Winter rapeseed	
	yield	± before control	yield	± before control	yield	± before control	yield	± before control
Without fertilizers – control	1.29	–	4.05	–	1.39	–	0.85	–
NPK – background	2.32	1.03	5.06	1.01	2.43	1.04	1.34	0.49
Background + $CaMg(CO_3)_2$ (0,5 H_g)	3.13	1.84	6.73	2.68	3.19	1.80	1.95	1.10
Background + $CaMg(CO_3)_2$ (1,0 H_g)	3.61	2.32	7.53	3.48	3.71	2.32	2.30	1.45
Background + $CaMg(CO_3)_2$ (1,0 H_g) + S_{40}	3.80	2.51	7.92	3.87	3.87	2.48	2.56	1.71
Background + $CaMg(CO_3)_2$ (1,0 H_g) + S_{40} + micronutrient	4.00	2.71	8.40	4.35	3.98	2.59	2.66	1.81
Background + $CaMg(CO_3)_2$ (1,5 H_g)	3.90	2.61	9.04	4.99	4.08	2.69	2.94	2.09
Background + $CaCO_3$ (1,0 H_g)	3.38	2.09	7.41	3.36	3.57	2.18	2.22	1.37
HIP_{05}	0.13		0.47		0.14		0.11	

The application of mineral fertilizers (NPK) as an independent agricultural tool contributed to a statistically significant increase in the yield by 0,49–1,04 t/ha, depending on the crop. However, even with a positive impact on productivity, this effect was insufficient, and unilateral fertilizer application without land reclamation could deepen the processes of the acidification of soil solution [11, 13]. This is confirmed by the level of crop yield after liming, which is consistent with previous scientific results of the Institute [4].

Significant improvement in crop yields was achieved when combining NPK with liming with dolomite flour in doses of 0.5–1.5 Hh. The results show that for all crops, yield increases were statistically significant both relative to the background (NPK) and between each subsequent applied dose of dolomite flour (0.5; 1.0; 1.5 Hh), which was confirmed by the HIP_{05} criterion. The highest increases in comparison with the background were provided by the dose of 1.5 Hh: winter wheat – +1.68 t/ha, corn – +3.34 t/ha, spring barley – +1.55 t/ha, winter rapeseed – +1.60 t/ha.

A comparative assessment of the effect of a dose of 1,0 Hh $CaCO_3$ and $CaMg(CO_3)_2$ on the background of mineral fertilizer according to the HIP_{05} index showed the advantage of the latter for winter wheat (+0.23 t/ha) and spring barley (+0.14 t/ha). The effectiveness of dolomite flour in growing cereals is explained by the content of not only calcium, but also magnesium – a key mesoelement that participates in photosynthesis, protein synthesis, and metabolism regulation in plants. In the cases with corn and winter rapeseed, a trend towards increased yield was also observed. Improvement in mineral nutrition conditions, especially on soils with magnesium deficiency, provided an additional increase in yield by 2–7 % compared to the limestone flour option, which emphasizes the higher agrochemical efficiency of dolomite in fertilization systems on sod-podzolic soils.

The greatest synergistic effect on crop yields when applying dolomite flour in a dose of 1,0 Hh was observed with the combined impact of NPK, sulfur-containing fertilizer (S_{40}), and foliar feeding with micronutrients. In variants with their simultaneous use, the yield of winter wheat increased up to 4.00 t/ha, of corn – up to 8.40 t/ha, of spring barley – up to 3.98 t/ha, and of winter rapeseed – up to 2.66 t/ha. This represented significant increases compared to the "Background + $CaMg(CO_3)_2$ 1.0 Hh" option for all crops. However, they were insignificant or lower compared to the "Background + $CaMg(CO_3)_2$ 1,5 Hh" option.

At the same time, it is worth distinguishing between the impact of sulfur and micronutrient fertilizers. Adding only S_{40} to NPK and $CaMg(CO_3)_2$ (1.0 Hh) provided significant increases for winter wheat (+0.19 t/ha), spring barley (+0.16 t/ha), and winter rapeseed (+0.26 t/ha). While a significant additional effect of microfertilizer (compared to the option without it) was established for wheat (+0.20 t/ha) and corn (+0.48 t/ha). Therefore, the multifactorial effect of the combination of liming, NPK, sulfur, and microelements proved to be the most effective. This indicates that the agrochemical effect was not formed by the isolated influence of individual factors, but through their synergistic effect, which is consistent with the other results [4, 10, 13, 15].

In the modern conditions of a market economy, the determining factor in the feasibility of using agrotechnical methods for crops growing is their economic efficiency. The choice of optimal technological options should be based not only on yield indicators, but also on a systematic analysis of the impact of technology elements on crops productivity, the quality of the resulting products, and the level of their production costs [17].

In order to substantiate the most effective combination of agricultural measures taken for the study, the economic efficiency of fertilizer and chemical land reclamation options was calculated using 2024 prices. It was found out that the cost of the resulting products changed similarly to the yields level, demonstrating a clear relationship between agricultural measures and financial indicators (Table 2).

Conducted economic assessment of the efficiency of crops growing on the sod-podzolic soil with the application of different doses of chemical

2. Indicators of economic efficiency of agricultural crops growing depending on different doses of liming on the background of fertilization on the sod-podzolic soil, average for 2016–2020, thousand UAH/ha

Option	Winter wheat		Corn for grain		Spring barley		Winter rapeseed	
	cost of yield	cultivation costs	cost of yield	cultivation costs	cost of yield	cultivation costs	cost of yield	cultivation costs
Without fertilizers – control	10.3	15.2	30.4	30.5	11.1	14.5	17.9	19.8
NPK – background	18.6	21.2	38.0	37.9	19.4	20.6	28.1	27.2
Background + $CaMg(CO_3)_2$ (0,5 H_g)	25.0	21.5	50.5	38.2	25.5	21.0	41.0	27.5
Background + $CaMg(CO_3)_2$ (1,0 H_g)	28.9	21.9	56.5	38.6	29.7	21.3	48.3	27.9
Background + $CaMg(CO_3)_2$ (1,0 H_g) + S_{40}	30.4	22.2	59.4	38.9	31.0	21.6	53.8	28.2
Background + $CaMg(CO_3)_2$ (1,0 H_g) + S_{40} + micronutrient	32.0	22.8	63.0	39.5	31.8	22.3	55.9	28.8
Background + $CaMg(CO_3)_2$ (1,5 H_g)	31.2	22.2	67.8	38.6	32.6	21.7	61.7	28.3
Background + $CaCO_3$ (1,0 H_g)	27.0	21.6	55.6	38.3	28.6	21.0	46.6	27.6

ameliorants on the background of fertilization showed that is a profitable measure. The highest conditional net profit of 9.2 thousand UAH/ha for winter wheat was provided by the application of 1.0 dose of Hh $CaMg(CO_3)_2$ on the background of $N_{120}P_{60}K_{90} + S_{40}$ + microfertilizer (Fig. 1).

The use of 1,5 doses of Hh $CaMg(CO_3)_2$ on the background of NPK contributed to both an increase in the yield of corn for grain, spring barley, and winter rapeseed, and the economic efficiency of their cultivation with a conditional net profit of 29.2 thousand UAH, 11.0 thousand UAH, and 33.5 thousand UAH, respectively.

On average, the costs of agricultural crops growing for the crop rotation amounted to 20.0–28.4 thousand UAH/ha, and the conditional net profit for different doses of chemical ameliorants on the background of fertilization was within 8.4–20.7 thousand UAH/ha (Fig. 2).

Crops growing on the sod-podzolic soil without fertilizer and chemical melioration and against the background of fertilization in the average for the crop rotation turned out to be economically unprofitable with the loss amounted up to 2.6 thousand UAH/ha and 0.7 thousand UAH/ha, respectively.

Conclusions. On the sod-podzolic soils of Western Polissya, the application of only mineral fertilizers (NPK) without liming provides a limited increase in crops yields (0.49–1.04 t/ha), which indicates the low efficiency of such approach on acidic soils.

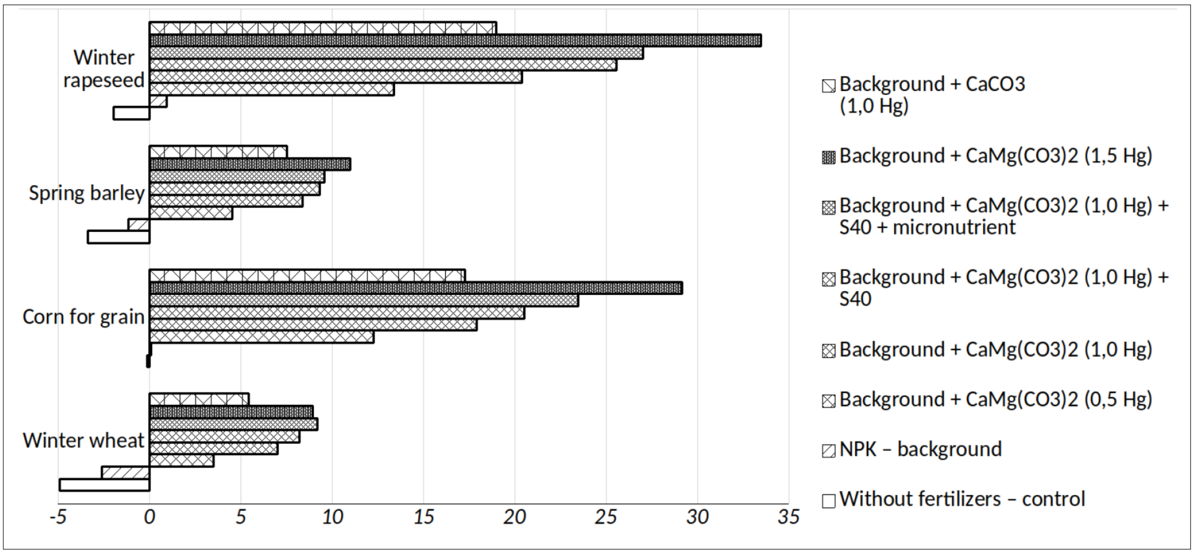

Fig. 1. Conditional net profit for agricultural crops growing depending on different doses of liming on the background of fertilization on the sod-podzolic soil, average for 2016–2020, thousand UAH/ha

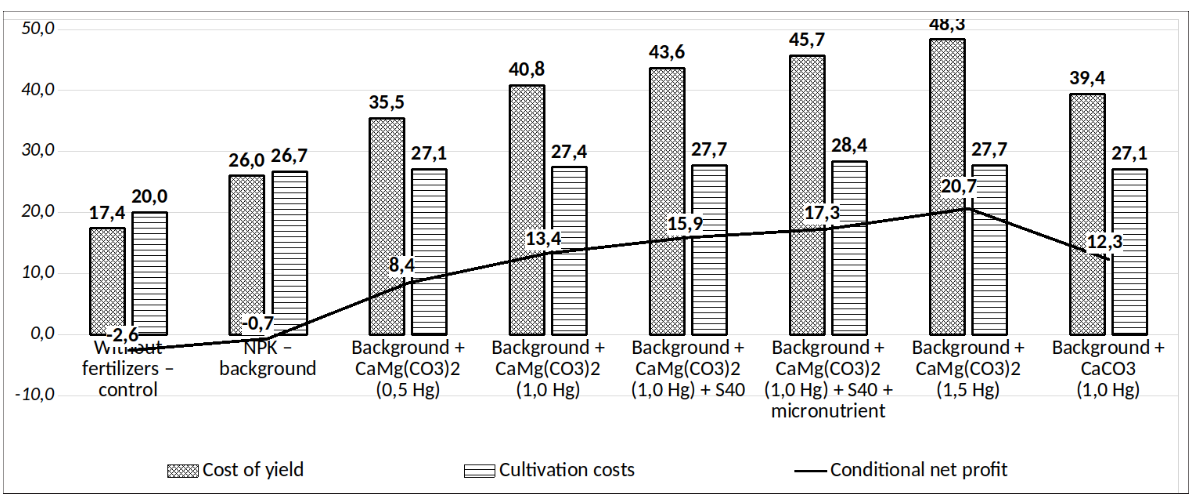

Fig. 2. Economic efficiency of crops growing depending on different doses of liming on the background of fertilization on the sod-podzolic soil, on average per the crop rotation (2016–2020), thousand UAH/ha

The liming with dolomite flour in doses of 0.5–1.5 Hh in combination with NPK contributes to a significant increase in the yields of all crops in the rotation. The additional application of sulfur (S_{40}) during liming (1.0 Hh $CaMg(CO_3)_2$) and NPK fertilization provided a significant increase in yield for winter wheat, spring barley, and winter rapeseed. The addition of the microfertilizer "Nutrivant Plus Cereal" proved to be effective for winter wheat and corn, which emphasizes the feasibility of a differentiated approach to their use depending on the crop, especially in conditions of chemical soil reclamation.

The highest agronomic efficiency for winter wheat was provided by the combination of NPK, dolomite flour (1,0 Hh), sulfur-containing fertilizer (S_{40}), and foliar feeding with microelements. This approach made it possible to increase the crop yield up to 4.00 t/ha and increase the conditional net profit up to 9.2 thousand UAH/ha.

In the case of corn for grain, winter rapeseed, and spring barley, the highest yields were achieved with the combined application of 1.5 Hh $CaMg(CO_3)_2$ and NPK. Economic analysis showed the highest profitability of this option for corn (29.2 thousand UAH/ha) and winter rapeseed (33.5 thousand UAH/ha). Therefore, complex agrochemical technology for acidic soils is not only an agronomically effective, but also economically feasible measure.

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

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

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ШЛЯХИ ПОКРАЩЕННЯ ЕФЕКТИВНОСТІ ВИРОЩУВАННЯ СІЛЬСЬКОГОСПОДАРСЬКИХ КУЛЬТУР НА ДЕРНОВО-ПІДЗОЛИСТОМУ ҐРУНТІ

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Анотація. *У статті представлено результати польових досліджень щодо впливу мінерального удобрення, вапнування, внесення сірковмісного добрива та мікроелементів на врожайність і економічну ефективність вирощування сільськогосподарських культур на дерново-підзолистому ґрунті. Дослід проведено у стаціонарному досліді Інституту сільського господарства Західного Полісся у сівозміні: пшениця озима, кукурудза, ячмінь ярий, ріпак озимий. Вапнякові матеріали (доломітове та вапнякове борошно) вносили у дозах визначених за величиною гідролітичної кислотності (Нг, ммоль/100 г ґрунту) перед закладкою досліду, щорічно під культури вносили рекомендовані дози мінеральних добрив та проводили позакореневі підживлення мікродобривом «Нутріван плюс». Установлено, що продуктивність культур на цьому типі ґрунтів значною мірою залежить від ступеня його агрохімічного окультурення. Застосування лише мінерального удобрення (NPK) забезпечило обмежене зростання врожайності, тоді як поєднання добрив із вапнуванням доломітовим борошном сприяло достовірному підвищенню продуктивності культур. Найвищу врожайність (4,00 т/га) і економічну віддачу (9,2 тис. грн/га) у посівах пшениці озимої забезпечило комплексне застосування NPK, доломітового борошна (1,0 Нг), сірки (S_{40}) та мікродобрива. Для кукурудзи та ріпаку озимого найбільшу урожайність (9,04 і 2,94 т/га) і прибуток (29,2 і 33,5 тис. грн/га) відповідно отримано за внесення 1,5 Нг $CaMg(CO_3)_2$. Доведено, що вирощування культур без удобрення або лише за фону NPK є економічно збитковим. Отримані результати підтверджують доцільність застосування інтегрованої системи удобрення й меліорації на кислих ґрунтах для забезпечення сталого агровиробництва.*

Ключові слова: *хімічна меліорація, сірковмісні добрива, мінеральне удобрення, врожайність, економічна ефективність*

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ASSESSMENT OF THE ACCURACY OF METEOROLOGICAL DATA OBTAINED FROM A VIRTUAL WEATHER STATION FOR THE PURPOSE OF ESTIMATING ETO FOR THE CONDITIONS OF THE SOUTH OF UKRAINE

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Abstract. *The article presents an assessment of the accuracy of meteorological data obtained from the Visual Crossing Weather Data (VWS VCWD) virtual meteorological station and the calculated reference evapotranspiration (ETo) based on these data for the conditions of southern Ukraine. It has been established that the data on air temperature and relative humidity are obtained with high accuracy, with MAPE and RMSE errors of 4.5 % and 0.94 °C and 9.1 % and 7.53 %, respectively. Good accuracy is characteristic of dew point temperature and solar radiation, with MAPE and RMSE errors of 20.9 % and 1.44 °C and 17.4 % and 3.41 MJ/m²·day, respectively. Dew point temperature data can also be obtained with satisfactory accuracy depending on the observation period. The MAPE and RMSE errors for water vapor pressure deficit are 46.2 % and 0.21 kPa, respectively, which corresponds to satisfactory accuracy. Depending on the observation period, water vapor pressure deficit data can also be obtained with unsatisfactory accuracy. Wind speed data at a height of 2 m, obtained with unsatisfactory accuracy, have MAPE and RMSE errors of 104.3 % and 1.20 m/s, respectively. To improve the accuracy of the meteorological data obtained, correction factors were calculated, and when applied, the accuracy of all meteorological data obtained is improved. The possibility of calculating ET using data from the Visual Crossing Weather Data virtual meteorological station for the period April-September with good accuracy has been confirmed. The MAPE error was 13.7 %, and the RMSE was 0.62 mm. To improve the accuracy of ET calculations in southern Ukraine, a correction factor of 0.95 must be used. Taking this into account, the accuracy of ET calculations for the period May-August increases to 89 %, and the RMSE is 0.63 mm. The use of refined meteorological data reduces the accuracy of ET calculations by 4.8 % and increases the RMSE by 0.15 mm. Based on the results of the research, a web application will be developed to calculate ET and ETc using the FAO56-RM methodology with data from VWS Visual Crossing Weather Data.*

Keywords: *virtual weather station, meteorological data, reference evapotranspiration, accuracy, MAPE and RMSE errors*

Relevance of the research. Currently, data from virtual weather stations (VWS) [1, 2] are increasingly used in various hydrological, environmental, and agricultural modeling programs. There is a growing demand for spatial climate data in digital form [3]. VWS is the integration of algorithms for downloading meteorological data, processing it, and using it to obtain data in nearby locations where there are no meteorological stations [1, 2]. Historically, weather data for modeling has been collected from meteorological weather stations, but they may not be close enough to the specific area being modeled. For these reasons, weather data from virtual meteorological stations can potentially replace or supplement ground-based weather measurements. [4]. To use virtual meteorological stations, it is first necessary to compare the obtained meteorological indicators with the actual ones [5]. Studies conducted around the world confirm the reliability of meteorological data obtained from virtual meteorological stations [1, 6, 7]. The reasons for the differences between data from virtual meteorological stations and measurements at weather stations may be related to spatial and temporal representativeness [8]. Another source of differences between data sets is data obtained from weather stations located at airports and in cities. Air temperature may increase and humidity may decrease at airports due to the predominance of asphalt and other non-watered surfaces. There is virtually no moisture available for evaporation on the pavement, so more solar energy is available to heat the air. This is known as the urban heat island effect. Differences may also be due to the failure to account for water use for irrigation in the land surface water balance models used in data collection systems. In arid regions where irrigation is prevalent, the microclimate near irrigated areas is affected by additional water inflow. Evaporation, which is made possible by the additional water inflow, absorbs solar energy that would otherwise heat the air in adjacent non-irrigated areas. Thus, the microclimate near irrigated areas is cooler and more humid than around non-irrigated land. This effect is called "air conditioning" [8].

To establish the accuracy of meteorological data obtained from virtual weather stations, we chose Visual Crossing Weather Data (VCWD) [4]. It provides access to all climate data necessary for calculating reference evapotranspiration (ETo) worldwide, including forecast data for the next 15 days. All data from the site is available for download via the weather data request page. A comprehensive verification of meteorological data measured by virtual meteorological stations for the conditions of southern Ukraine has not yet been carried out. Therefore, this study was conducted to verify the accuracy and quality of the meteorological data obtained and the calculated ETo from a virtual climate station for the conditions of southern Ukraine.

Analysis of recent studies and publications. Reference evapotranspiration (ETo) is important for water consumption in agriculture. Synoptic data from meteorological stations can provide reliable data for estimating ETo using the Penman-Monteith equation (FAO56-PM). However, the five main variables required by this equation suffer significant losses due to force majeure events [9]. Data loss will directly lead to errors in calculations. To achieve high data quality for calculating daily ET over a long period of time, it is necessary to first analyze the input data for omissions and errors in the records. To do this, algorithms must be selected to take into account different types of data loss and fill them in. Measurements of incoming shortwave solar radiation, air temperature, air humidity, wind speed, and precipitation at weather stations are taken at a height of 2–3 m. Accurate, continuous, and consistent measurements of these variables over years or decades are often lacking due to sensor failure, drift, age, poor calibration, debris, limited station maintenance, communication errors, lack of a sufficiently humid environment, and remote access. As a result, low-quality agricultural weather station data is common, and if not flagged for removal or correction, it will affect the accuracy of reference evapotranspiration calculations [10]. The ability to easily read, visualize, review, flag, and potentially delete, fill in, or correct historical and real-time meteorological data is essential for calculating ET at the local and global levels. Python agweather-qaqc [11] provides the ability to provide fast, thorough, and efficient meteorological data review and quality control for daily meteorological data. Many station networks use different formats for storing and recording meteorological data, and agweather-qaqc is capable of flexibly processing common input data, units of measurement, and formats so that all input data and ETo calculations can be used programmatically.

Air temperature values obtained from virtual meteorological stations are attractive due to the absence of instrumentation costs and the availability of long-term reconstructions of historical records [12]. Air temperature maps for the city of Warsaw (Poland) [13] constructed using machine learning are characterized by lower complexity and higher calculation speed in the field of urban meteorological research. The root mean square error was −1.06 °C, and the coefficient of determination was −0.94, compared to ground-based observations. The average monthly solar radiation and average daily maximum and minimum air temperatures obtained from the network of virtual climate stations of the New Zealand National Institute of Water and Atmospheric Research (NIWA) allow these data to be estimated for landscape points with reasonable accuracy and low error [6]. Studies conducted in the northeastern region of Brazil (Paraíba state) [14] on the assessment of solar radiation indicate that the calculated data from satellite images slightly exceed those observed at ground-based meteorological stations. A comparison of solar radiation data in Albania [15] provided by NASA with ground-based meteorological stations shows that ground-based data are underestimated compared to data provided by the NASA database. The conversion factor is 1.149. An assessment of the accuracy of meteorological data obtained from virtual weather stations for the conditions of Polissya, Ukraine [16], showed that data on average and maximum air temperature, as well as dew point temperature, were obtained with high accuracy. Good accuracy is characteristic of the minimum air temperature and average relative air humidity. Data on solar radiation and water vapor pressure deficit were obtained with satisfactory accuracy. Data on wind speed at a height of 2 m, total monthly and daily precipitation were obtained with unsatisfactory accuracy.

Satellite remote sensing of evapotranspiration (ET) offers a powerful approach for mapping large areas and time scales. Remote sensing ET data have significant potential for sustainable water resource management. However, experts require a reliable and thorough assessment of the accuracy of such data. Comparisons of OpenET [17] results with data from 152 eddy covariance tower stations in the United States showed that the average absolute error over agricultural land for OpenET is 15.8 mm per month, with an average bias error of –5.3 mm per month. Medium-range forecasts of daily reference evapotranspiration (ETo) are very useful for irrigation management. An analysis of artificial neural networks conducted in China [18] for ETo forecasting (FAO56-PM) showed that the correlation coefficients between observed and predicted temperatures for all stations exceeded 0.91, and the accuracy of the minimum temperature forecast ranged from 68.34 to 91.61 %, and for the maximum temperature – from 51.78 to 57.44 %. The accuracy of the ETo forecast ranged from 75.53 to 78.14 %, the average absolute error ranged from 0.99 to 1.09 mm/day, and the root mean square error ranged from 0.87 to 1.36 mm/day. The average correlation coefficient ranged from 0.70 to 0.75. For the conditions of Polissya, Ukraine [19], the accuracy of ETo calculation is 86.1 %, and the RMSE and SEE errors are 0.76 and 0.49 mm, respectively.

The purpose of the study was to evaluate the accuracy of meteorological data obtained from the Visual Crossing Weather Data virtual meteorological station in order to assess the accuracy of ET calculated based on these data and compare them with actual data obtained from the iMetos automated Internet meteorological station from Pessl Instruments.

M**aterials and methods.** The meteorological data for this study were obtained from the Visual Crossing Weather Data (VCWD) [4] for the period from April to September from 2013 to 2021 and from nine iMetos automatic weather stations (AWS) from Pessl Instruments [20], which were located in the Kherson and Zaporizhzhia regions (Table 1).

To analyze and calculate reference evapotranspiration (ET_0), average daily meteorological data were used: average air temperature (Ta) and dew point (Tdew), wind speed (u_2), and total solar radiation (Rs). Reference evapotranspiration was calculated according to the Penman-Monette FAO56-PM method [21] based on VWS VCWD meteorological data:

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

where ET_0 is reference evapotranspiration, mm/day; Rn is net radiation on the plant surface, MJ/m^2·day; G is soil heat flux density, MJ/m$_{(2)}$·day; *Ta* – 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 – vapor pressure gradient, kPa/(°C$^)$); γ – psychrometric constant, kPa/°C.

To calculate e_s and $e_{(a)}$, the values of the average air temperature and dew point were used, respectively. The average wind speed was

1. Location of AWS iMetos from Pessl Instruments

No	Station	District	Region	Latitude	E
1	Antonivka	Skladovskyi	Kherson	46.145	32.956
2	Pryvitne	Kherson		46.374	33.101
3	Novokamyanka	Kakhovka		46.601	33.382
4	Tavrichanka	Kakhovka		46.557	33.828
5	Chervona Polyana	Kakhovka		46.801	33.841
6	Bratske	Henichesk		46.784	34.077
7	Voskresenka	Henichesk		46.595	34.554
8	Velyka Bilozerka	Vasylivskyi	Zaporizhzhia	47.165	34.605
9	Vysokyi	Melitopol		46.813	34.971

converted for a height of 2 m. Other parameters included in formula (1) were calculated according to the FAO56-RM methodology [21].

Meteorological data and calculated reference evapotranspiration were compared with actual data obtained from AWS iMetos.

To assess the accuracy of the meteorological data obtained from VWS VCWD and the calculated reference evapotranspiration, the mean absolute percentage error (MAPE), Root Mean Square Error (RMSE), Standard Error of Estimate (SEE), and accuracy [22–25]:

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{x-y}{x}\right|\cdot 100\%, \quad (2)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x-y)^2}, \quad (3)$$

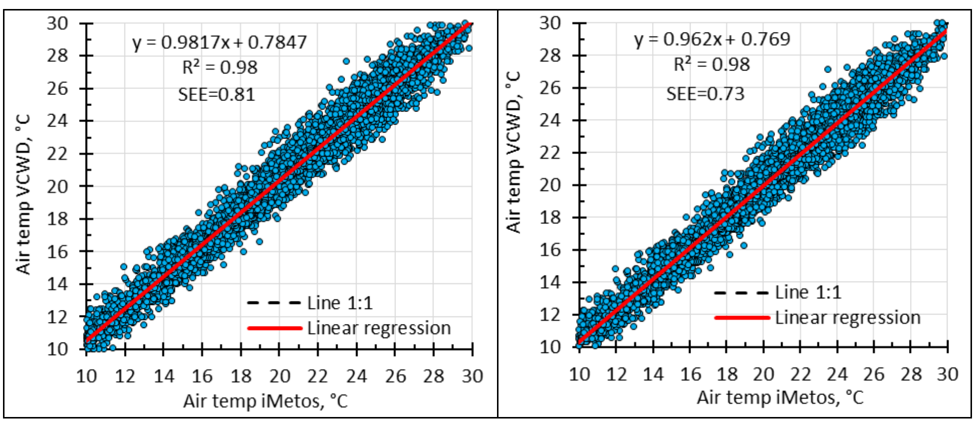
$$SEE = \sqrt{\frac{1}{(n-2)}\left[(y-\bar{y})^2 - \frac{\left[\sum(x-\bar{x})(y-\bar{y})\right]^2}{\sum(x-\bar{x})^2}\right]}, \quad (4)$$

$$Accuracy(\%) = 100\% - MAPE(\%), \quad (5)$$

where x is the meteorological indicator or ET_0according to AWS iMetos data; y is the meteorological indicator or ET_0(FAO56-PM) according to VWS VCWD data; n is the sample size.

Research results. Based on the results of air temperature assessment obtained from VWS Visual Crossing Weather Data and AWS iMetos for the period April-September, it was established that the data was obtained with high accuracy (Fig. 1). The mean absolute percentage error (MAPE) was only 4.5 % [23], and the root mean square error (RMSE) was 0.94 °C (Table 2).

To improve the accuracy of air temperature, a correction factor of 0.98 was calculated. When applied, the accuracy of the data obtained increases (Fig. 1b), and the MAPE and RMSE errors decrease by 0.7 % and 0.13 °C, respectively (Table 2). With the reduction of the observation period to May-August, the MAPE error decreased by 0.9 %, while the RMSE remained almost



a) actual b) refined

Fig. 1. Regression analysis for air temperature verification

2. MAPE and RMSE errors for air temperature, °C

Date/time	iMetos	VCWD		MAPE		RMSE	
		actual	refined	actual	revised	actual	revised
1	2	3	4	5	6	7	8
By year							
2013	19.8	20.8	20.4	6.5	5.1	1.40	1.1
2014	19.5	20.4	20.0	6.4	5.3	1.23	1.0
2015	19.4	20.0	19.6	4.0	2.8	0.81	0.58
2016	19.8	20.3	19.9	3.6	2.8	0.87	0.68
2017	19.1	19.4	19.1	4.9	4.5	0.89	0.86
2018	20.7	21.2	20.7	3.6	3.1	0.88	0.77
2019	20.2	20.4	20.0	3.4	3.3	0.79	0.79
2020	19.2	19.6	19.2	4.4	3.9	0.93	0.88
2021	18.4	18.7	18.3	3.2	3.0	0.65	0.62

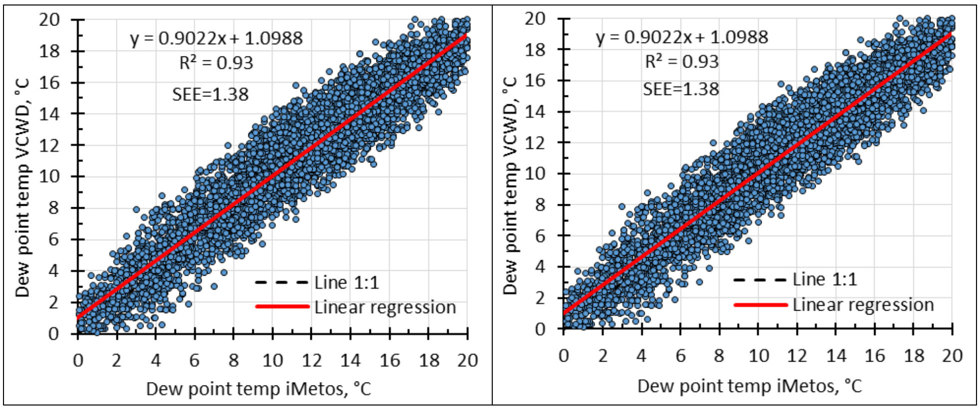
Continuation of Table 2

1	2	3	4	5	6	7	8
By month							
April	10.6	11.1	10.9	8.0	7.07	0.87	0.77
Vay	17.3	17.6	17.3	3.8	3.42	0.83	0.75
June	21.8	22.4	21.9	3.7	3.09	1.03	0.87
July	23.9	24.5	24.0	3.4	2.80	1.0	0.84
August	24.1	24.7	24.2	3.6	2.95	1.06	0.89
September	18.0	18.6	18.2	4.6	3.72	0.95	0.79
April – September	19.6	20.1	19.7	4.5	3.80	0.94	0.81
May – August	21.8	22.3	21.8	3.6	3.0	0.98	0.84
By station							
1	19.2	19.9	19.3	5.0	3.7	1.11	0.83
2	20.3	20.5	20.3	3.7	3.5	0.83	0.80
3	18.47	18.54	18.54	3.5	3.5	0.74	0.74
4	19.33	20.25	19.24	6.1	4.0	1.21	0.82
5	19.84	20.36	19.74	3.9	3.1	0.81	0.66
6	19.51	20.03	19.43	3.7	2.9	0.83	0.64
7	19.24	19.28	19.28	3.6	3.6	0.70	0.70
8	19.47	19.99	19.39	4.3	3.5	0.92	0.76
9	20.34	20.52	20.31	3.2	3.0	0.70	0.69

unchanged. Over the years of observation, the MAPE errors ranged from 3.2 % (2021) to 6.5 % (2013), and the RMSE errors ranged from 0.65 to 1.40 °C, respectively. The smallest MAPE errors were observed in the summer months, and the largest in April. The accuracy of the data obtained also depended on the iMetos station and its location. Thus, the smallest errors for air temperature are characteristic of station 9, and the largest – 4 (Table 1). However, despite all the fluctuations in MAPE errors by year, month, and station, they were all less than 10 %, which confirms the high accuracy of the data obtained.

Data for the dew point are obtained with good and satisfactory accuracy (Fig. 2). The MAPE error was 20.9 % [23], and the RMSE was 1.44 °C (Table 3). To improve the accuracy of the dew point temperature, a correction factor of 1.10 was calculated. When applied, the accuracy of the obtained data increases (Fig. 2b), and the MAPE and RMSE errors decrease by 1.4 % and 0.14 °C, respectively. With the reduction of the observation period to May-August, the MAPE error decreased by half, while the RMSE remained almost unchanged. Over the years of observation, the MAPE errors ranged from 8.3 % (2016) to 36 % (2020), and the RMSE errors ranged from 0.96 to 1.67 °C, respectively. The smallest MAPE errors were observed in June and July, and the largest in April. The accuracy of the data obtained also depended on the AWS iMetos and its location. Thus, the smallest errors for dew point temperature are characteristic of stations 2, 3, and 9, and the largest – 7. Dew point temperature data were obtained with good accuracy in 2014–2016, 2018, and 2021, from May to August, and for stations 2–4 and 8–9. For all other periods, the accuracy was satisfactory. It should be noted that the MAPE error for the period May-August, which accounts for almost all irrigation, is 10.8 % (and the refined 9.6 %), which almost corresponds to the high accuracy of the data obtained.

Data for relative air humidity are obtained with high accuracy (Fig. 3). The MAPE error was 9.1 % [23], and the RMSE was 7.53 % (Table 4). To improve the accuracy of relative air humidity, a correction factor of 1.06 was calculated. When the correction factor is applied, the accuracy of the data obtained increases (Fig. 3b), and the MAPE and RMSE errors decrease by 0.7 % and 1.11 %, respectively. With the reduction of the observation period to May-August, the MAPE and RMSE errors remained almost unchanged. Over the years of observation, the MAPE errors ranged from 7.4 % (2016) to 10.9 % (2014), and

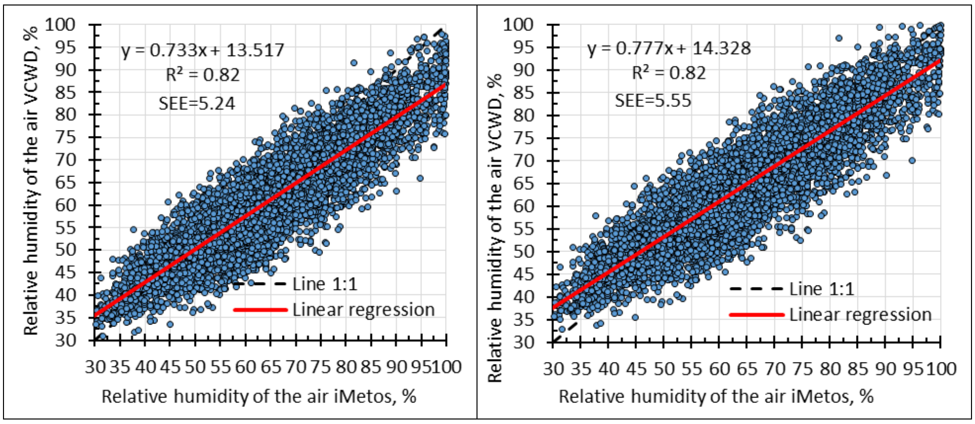


a) actual b) refined

Fig. 2. Regression analysis to verify dew point temperature

3. MAPE and RMSE errors for dew point temperature, °C

Date/time	**iMetos**	**VCWD**		**MAPE**		**RMSE**	
		actual	**revised**	**actual**	**revised**	**actual**	**revised**
By year							
2013	11.2	12.2	11.9	24.7	22.6	1.67	1.51
2014	11.1	11.7	11.3	20.8	19.7	1.67	1.57
2015	11.4	11.5	11.1	16.1	16.5	1.12	1.25
2016	12.4	12.3	11.8	8.3	9.4	0.96	1.16
2017	10.2	10.4	10.2	22.2	19.8	1.35	1.11
2018	10.9	11.2	11.1	20.7	17.8	1.61	1.35
2019	11.3	11.5	11.6	22.2	21.5	1.39	1.25
2020	10.2	9.9	9.9	36.0	33.3	1.59	1.30
2021	13.9	12.8	13.2	17.1	15.2	1.65	1.21
By month							
April	4.2	4.2	4.1	36.4	65.1	1.43	1.40
May	10.5	10.4	10.2	14	13.6	1.28	1.26
June	14.3	14.1	13.9	8.2	7.9	1.32	1.26
July	15	15	14.8	8.3	7	1.47	1.22
August	13.1	13.6	13.5	12.7	10.1	1.74	1.40
September	9.5	10.0	9.8	24.6	22.6	1.49	1.33
April – September	11.4	11.5	11.4	20.9	19.5	1.44	1.30
May – August	13.2	13.3	13.2	10.8	9.6	1.45	1.28
By station							
1	13.0	11.3	12.4	28.0	24.0	1.97	1.25
2	11.6	12	11.9	17.2	16.8	1.30	1.26
3	13.34	11.75	12.93	17.5	13	1.87	1.21
4	10.89	11.22	10.66	21.5	20.9	1.48	1.46
5	10.99	11.48	10.90	22.5	21.4	1.19	1.18
6	11.85	11.27	11.72	23.6	23	1.25	1.17
7	9.31	10.40	9.36	36.5	30.7	1.60	1.26
8	11.92	10.98	12.07	18.5	17.7	1.73	1.35
9	11.13	11.34	11.11	17.5	17	1.28	1.28



a) actual b) refined

Fig. 3. Regression analysis to verify relative air humidity, %

4. MAPE and RMSE errors for relative air humidity, %

Date/time	iMetos	VCWD		MAPE		RMSE	
		actual	refined	actual	revised	actual	revised
By year							
2013	63.0	60.9	64.6	8.8	9.1	6.96	6.71
2014	64.5	60.6	64.2	10.9	10	8.50	7.24
2015	66.9	62.4	66.1	7.6	6	7.07	5.28
2016	66.0	62.1	65.8	7.4	6	6.15	4.77
2017	62.7	60.1	63.7	8.5	8.5	6.64	6.04
2018	59	56.6	60	9.4	9.8	7.01	6.58
2019	63.1	61.0	64.6	8.2	8.8	6.54	6.30
2020	62	58.0	61.4	10.6	9.8	8.29	7.07
2021	76.4	68.7	72.8	10.4	7.2	9.87	7.17
By month							
April	70.6	66.2	70.1	9.4	8.3	8.28	6.82
May	69.7	65.8	69.8	8.2	7.5	7.39	6.18
June	68	62.5	66.3	9.5	7	8.31	6.41
July	63.2	59.2	62.7	9.2	8.3	7.58	6.43
August	56.3	53.9	57.2	9.7	10.2	7.03	6.50
September	63.1	60.8	64.5	8.5	8	6.58	6.18
April – September	65.1	61.4	65.1	9.1	8.4	7.53	6.42
May – August	64.3	60.4	64	9.2	8.4	7.58	6.38
By station							
1	70.7	61.7	71.0	13.0	6.9	10.49	5.88
2	63.1	61.6	62.8	7.8	7.7	6.04	5.76
3	75.18	68.23	75.05	10.2	6.3	8.68	5.74
4	64.55	59.50	64.10	9.8	8.3	8.02	6.30
5	62.19	60.63	61.84	6.3	6	4.87	4.59
6	67.48	61.05	67.77	10.2	6.8	8.32	5.28
7	58.23	60.28	57.87	8.6	7.6	5.57	5.34
8	68.50	60.05	68.46	12.6	7.9	10.73	6.32
9	61.72	59.35	61.14	8	7.8	6.48	5.92

the RMSE errors ranged from 6.15 to 9.87 %, respectively. The smallest MAPE errors were observed in May and September, and the largest in July (9.5 %). The accuracy of the data obtained also depended on the iMetos station and its location. Thus, the smallest errors for relative air humidity are characteristic of stations 5 and 2, and the largest – 1 and 8.

Data for water vapor pressure deficit for the period April-September are obtained with satisfactory accuracy (Fig. 4). The MAPE error was 46.2 % [23], and the RMSE was 0.21 kPa (Table 5). Depending on the observation period and station, data with unsatisfactory accuracy were also obtained. To improve the accuracy of relative air humidity, a correction factor of 0.95 was calculated. When applied, the accuracy of the data obtained increases (Fig. 4b), and the MAPE and RMSE errors decrease by 2.9 % and 0.01 kPa, respectively. With a decrease in the observation period to May-August, the MAPE error decreased by 14.2 %, while the RMSE error remained almost unchanged. Over the years of observation, the MAPE errors ranged from 23 % (2018) to 78.3 % (2015), and the RMSE errors ranged from 0.16 to 0.24 kPa, respectively. The smallest MAPE errors were observed from July to September, and the largest in April. The accuracy of the data obtained also depended on the iMetos station and its location. Thus, the smallest errors for water vapor pressure deficit are characteristic of stations 5, 7, and 9, and the largest – 2 and 6. As can be seen from Table 5, even with complete agreement between the data obtained from the automatic and virtual weather stations, the errors in the results obtained are significant. This is due to the averaging of data for this period, while all calculations were performed for daily data.

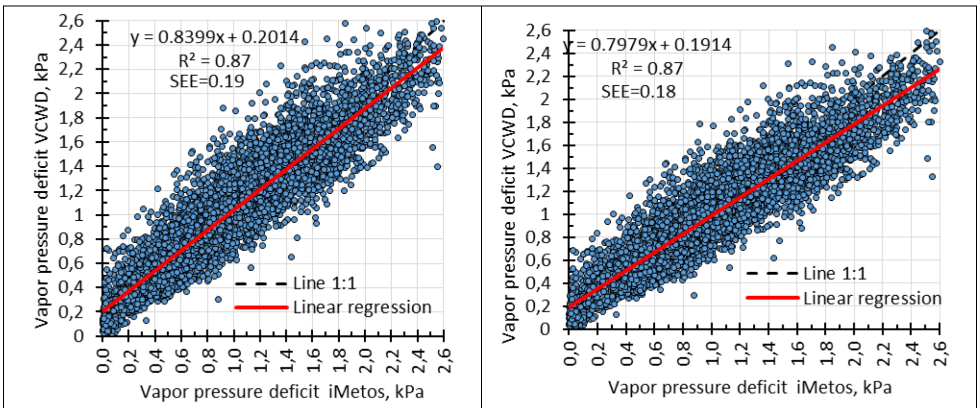


Fig. 4. Regression analysis to check the water vapor pressure deficit, kPa

5. MAPE and RMSE errors for water vapor pressure deficit, kPa

Date/time	iMetos	VCWD		MAPE		RMSE	
		actual	refined	actual	revised	actual	revised
1	2	3	4	5	6	7	8
By year							
2013	1.04	1.10	1.04	29.6	27.4	0.19	0.18
2014	1.03	1.09	1.04	60.3	56.2	0.21	0.21
2015	0.94	1.03	0.98	78.3	72.3	0.16	0.14
2016	1.01	1.10	1.05	26.8	24.1	0.18	0.16
2017	1.07	1.07	1.02	30.6	29.0	0.22	0.24
2018	1.21	1.22	1.16	23	22.3	0.24	0.25
2019	1.08	1.06	1.01	32.7	31.9	0.22	0.23
2020	1.07	1.10	1.05	30.1	28.7	0.23	0.24
2021	0.73	0.82	0.78	67.8	62.9	0.21	0.19
By month							
April	0.46	0.50	0.47	83.1	77.2	0.13	0.13
May	0.72	0.77	0.73	41.8	39.0	0.17	0.16
June	1.03	1.13	1.07	37.8	34.5	0.24	0.22

Continuation of Table 5

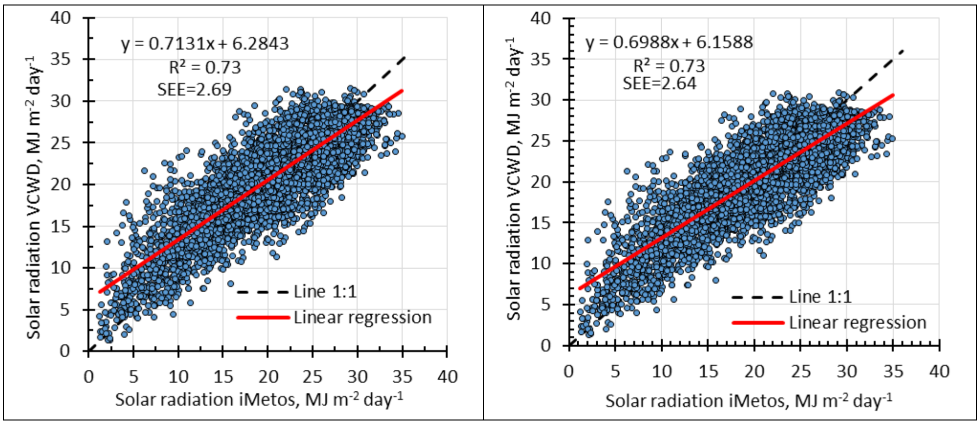
1	2	3	4	5	6	7	8
July	1.29	1.36	1.29	26.6	24.6	0.25	0.24
August	1.52	1.55	1.47	21.8	20.9	0.25	0.26
September	0.94	0.94	0.89	28.4	26.9	0.17	0.18
April – September	1.02	1.07	1.01	46.2	43	0.21	0.20
May – August	1.14	1.20	1.14	32	29.8	0.22	0.22
By station							
1	0.77	1.05	0.75	53.5	25.1	0.35	0.18
2	1.08	1.09	1.06	64.4	62.2	0.17	0.17
3	0.69	0.80	0.70	42.8	33.9	0.20	0.15
4	1.01	1.11	0.97	50.3	41.3	0.19	0.19
5	1.11	1.08	1.13	16.2	16.8	0.17	0.17
6	0.76	0.83	0.75	76.5	67.4	0.17	0.17
7	1.20	1.03	1.17	20.6	18.7	0.27	0.18
8	1.0	1.07	0.91	55.8	48.5	0.22	0.24
9	1.11	1.12	1.06	29.2	28.1	0.18	0.20

Data for solar radiation are obtained with good accuracy (Fig. 5). The MAPE error was 17.4 % [23], and the RMSE was 3.41 MJ/m²·day (Table 6). To improve the accuracy of solar radiation, a correction factor of 0.98 was calculated. When the correction factor is applied, the accuracy of the data obtained increases (Fig. 5b), and the MAPE and RMSE errors decrease by 0.6 % and 0.06 MJ/m²·day, respectively. With the reduction of the observation period to May-August, the MAPE error decreased by 2.3 %, while the RMSE error remained almost unchanged. Over the years of observation, the MAPE errors ranged from 12.2 % (2019) to 26.8 % (2014), and the RMSE errors ranged from 2.80 to 4.85 MJ/m²·day, respectively. The smallest MAPE errors were observed in July and August, and the largest in April and September. The accuracy of the data obtained also depended on the iMetos station and its location. Thus, the smallest errors for solar radiation are characteristic of stations 1 and 2, and the largest for stations 3 and 4.

Automatic weather stations measure wind speed in m/s at a height of 2 m, while virtual weather stations measure wind speed in km/h at a height of 10 m. Therefore, the obtained wind speed data must be converted to m/s for a height of 2 m [21]. The wind speed data is obtained with unsatisfactory accuracy (Fig. 6). The MAPE error was 104.3 % [23], and the RMSE was 1.2 m/s (Table 7). To improve the accuracy of wind speed, a correction factor of 0.64 was calculated. When applied, the accuracy of the data obtained increases (Fig. 5b), and the MAPE and RMSE errors decrease by 55.9 % and 0.42 m/s, respectively. With a reduction in the observation period to May-August, the MAPE error increased by 5.2 %, and the RMSE error remained almost unchanged. Over the years of observation, the MAPE errors ranged from 73.5 % (2013) to 137 % (2014), and the RMSE errors ranged from 0.9 to 1.75 m/s, respectively. The smallest MAPE errors were observed in April and July, and the largest in June and August. The accuracy of the data obtained also depended on the iMetos station and its location. Thus, the smallest error for wind speed is characteristic of station 5, and the largest – of station 2. According to data from the Askania-Nova state weather station, the average wind speed at a height of 2 m for the period April-September is 2.5 m/s [26].

Table 7 shows that the data from the virtual station is more reliable. This may be due to the incorrect installation of automatic stations, in which wind speed sensors may be located in the vicinity of buildings or trees.

Currently, the Penman-Monette FAO56-PM method [21] is widely used for irrigation management. The Visual Crossing Weather Data virtual meteorological station provides access to all the climate data needed to calculate ET. Based on the results of the assessment of the calculated reference evapotranspiration using meteorological data obtained from VWS Visual Crossing Weather Data for the period April-September, its good accuracy was established (Fig. 7). The average absolute percentage error was 13.7 % [23], and the root mean square error was 0.62 mm (Table 8).

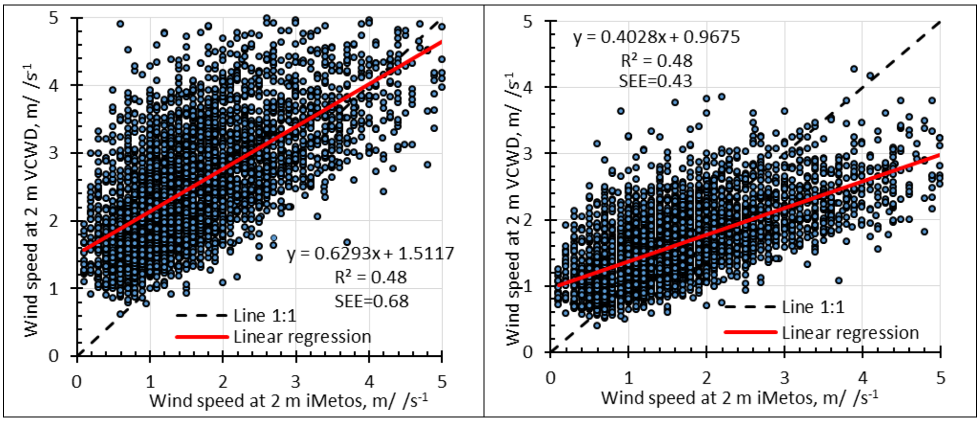


a) actual b) refined

Fig. 5. Regression analysis for checking solar radiation, MJ/m^2 ·day

6. MAPE and RMSE errors for solar radiation, MJ/m²·day

Date/time	iMetos	VCWD		MAPE		RMSE	
		actual	refined	actual	revised	actual	revised
By year							
2013	19.23	22.78	22.33	25.5	23.5	4.71	4.36
2014	18.67	22.34	21.89	26.8	24.9	4.85	4.50
2015	19.24	20.60	20.19	15.1	14.2	2.95	2.79
2016	18.78	19.84	19.44	17.3	16.4	3.10	2.98
2017	20.82	21.00	20.58	16.6	16.4	2.94	2.96
2018	21.33	21.76	21.32	14.3	14	3.0	2.98
2019	21.71	21.08	20.66	12.2	12.6	2.80	2.94
2020	21.90	21.21	20.78	12.4	12.8	2.98	3.13
2021	20.20	19.70	19.30	16.2	16.4	3.38	3.47
By month							
April	17.08	18.82	18.44	25	24.6	3.84	3.69
May	21.13	22.02	21.58	15.2	14.6	3.44	3.35
June	22.84	23.55	23.08	16.8	16	3.91	3.84
July	23.34	23.98	23.51	13.9	13.5	3.52	3.46
August	20.85	21.52	21.09	14.6	14.3	3.20	3.13
September	14.59	15.71	15.39	19.4	18.6	2.91	2.79
April – September	20.21	21.14	20.72	17.4	16.8	3.41	3.35
May – August	22.04	22.77	22.31	15.1	14.7	3.52	3.44
By station							
1	25.05	22.88	25.17	10	8.6	3.35	2.54
2	20.74	22.02	20.70	11	9.8	2.60	2.27
3	21.91	19.97	21.97	19.5	18	4.23	3.62
4	18.26	21.21	18.24	26.9	18	4.47	3.27
5	20.55	20.68	20.68	14.8	14.8	2.94	2.94
6	21.08	20.19	21.20	18.1	13.1	3.15	3
7	20.93	20.76	20.76	17.4	14.6	2.81	2.81
8	20.68	20.26	20.46	14.3	14.3	2.92	2.89
9	20.48	20.81	20.39	14.3	14.1	2.86	2.85



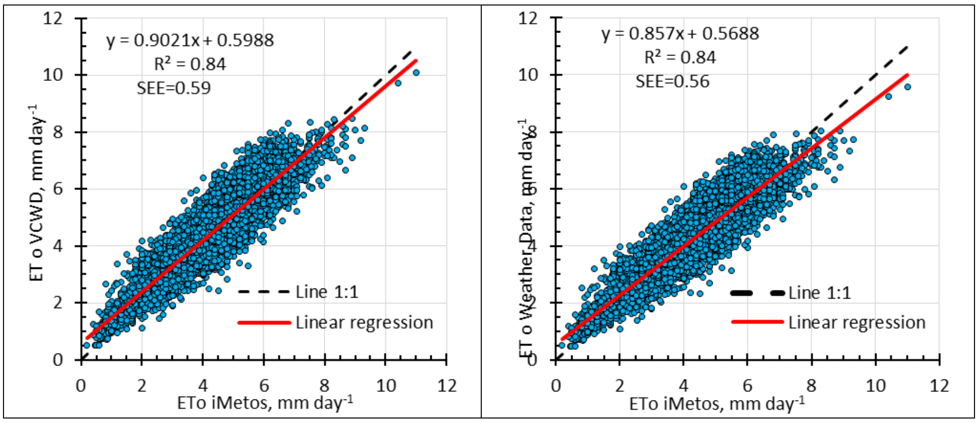
a) actual b) refined

Fig. 6. Regression analysis to verify wind speed, m/s

7. MAPE and RMSE errors for wind speed, m/s

Date/time	iMetos	VCWD		MAPE		RMSE	
		actual	refined	actual	revised	actual	revised
By year							
2013	2,05	3,12	1,99	73,5	29,1	1,31	0,70
2014	1,79	3,16	2,02	137,1	121,3	1,75	1,08
2015	1,66	2,48	1,59	128,1	62,6	1,07	0,78
2016	1,80	2,36	1,51	56,9	31,3	0,90	0,84
2017	1,83	2,60	1,67	74,0	33,6	1,09	0,83
2018	1,65	2,43	1,55	80,9	35,3	1,12	0,80
2019	1,41	2,45	1,57	94,4	30,9	1,17	0,46
2020	1,52	2,41	1,54	107,0	45,6	1,16	0,79
2021	1,53	2,35	1,51	103,6	47	1,09	0,70
By month							
April	2,24	2,86	1,83	81,5	49,5	1,09	1,11
May	1,69	2,53	1,62	106,2	51,5	1,10	0,71
June	1,43	2,46	1,58	118,8	49,2	1,23	0,59
July	1,46	2,37	1,51	96,4	39,3	1,11	0,58
August	1,65	2,59	1,66	116,5	53,7	1,26	0,80
September	1,77	2,80	1,79	106,3	47	1,38	0,86
April – September	1,71	2,60	1,67	104,3	48,4	1,20	0,78
May – August	1,56	2,49	1,59	109,5	48,4	1,18	0,67
By station							
1	-	-	-	-	-	-	-
2	1,35	2,65	1,33	169,4	58,4	1,54	0,66
3	2,10	2,54	2,06	55,5	39,7	1,0	0,92
4	2,32	2,75	2,28	56,4	42,5	0,84	0,72
5	2,06	2,38	2,02	33,5	24	0,63	0,57
6	1,77	2,37	1,73	52,6	27,3	0,81	0,57
7	1,39	2,48	1,36	101,0	27,4	1,22	0,48
8	1,43	2,38	1,43	66,6	37,2	0,60	0,51
9	1,25	2,41	1,25	133,3	41,9	1,34	0,54

Note: Wind speed was not measured at station 1.



a) actual b) refined

Fig. 7. Regression analysis for ET verification, mm/day

8. MAPE and RMSE errors for reference evapotranspiration, mm

Date/time	Metos	VCWD		MAPE		RMSE	
		actual	refined	actual	revised	actual	revised
By year							
2013	4,69	4,94	4,70	16,2	14,7	0,75	0,70
2014	4,55	4,88	4,64	15,3	13,3	0,72	0,64
2015	4,38	4,35	4,13	12,2	12,1	0,55	0,62
2016	4,22	4,34	4,13	12,5	11,9	0,61	0,59
2017	4,29	4,45	4,22	12,8	11,8	0,60	0,57
2018	4,58	4,80	4,56	13,7	12,3	0,71	0,66
2019	4,32	4,50	4,27	11,7	10,6	0,56	0,52
2020	4,25	4,47	4,24	13,9	12,3	0,63	0,58
2021	3,85	3,94	3,75	14,4	13,9	0,59	0,58
By month							
April	2,89	2,92	2,77	16,6	15,87	0,48	0,51
May	4,11	4,17	3,97	11,8	11,43	0,54	0,56
June	4,93	5,18	4,92	13,2	12,09	0,72	0,66
July	5,29	5,52	5,24	11,5	10,48	0,69	0,64
August	5,12	5,35	5,08	12	10,79	0,7	0,66
September	3,26	3,46	3,29	17,3	15,40	0,62	0,58
April – September	4,27	4,43	4,21	13,7	12,7	0,62	0,60
May – August	4,86	5,05	4,80	12,1	11,2	0,66	0,63
By station							
1	4,62	4,74	4,60	8,6	7,9	0,45	0,43
2	4,52	4,68	4,54	12,1	11,4	0,58	0,56
3	4,12	3,9	4,06	13,9	13,7	0,59	0,54
4	4,39	4,63	4,36	15,8	13,8	0,72	0,67
5	4,55	4,39	4,56	11	10,7	0,57	0,55
6	4,34	4,31	4,36	10,9	11	0,52	0,52
7	4,12	4,35	4,13	12,1	10,5	0,57	0,5
8	3,93	4,36	3,92	16,5	11,2	0,64	0,47
9	4,06	4,53	4,08	16,5	12,5	0,76	0,57

To improve the accuracy of reference evapotranspiration, a correction factor of 0.95 was calculated. When the correction factor is applied, the accuracy of the data obtained increases (Fig. 7b), and the MAPE and RMSE errors decrease by 1 % and 0.02 mm, respectively. With the reduction of the observation period to May-August (when almost all irrigation is carried out), the MAPE error decreased by 1.6 %, and the RMSE remained almost unchanged. Over the years of observation, the MAPE errors ranged from 11.7 % (2019) to 16.2 % (2013), and the RMSE errors ranged from 0.59 to 0.75 mm, respectively. The smallest MAPE errors were observed in May and July, and the largest in April and September. The accuracy of the data obtained also depended on the iMetos station and its location. Thus, the smallest errors for reference evapotranspiration are characteristic of stations 1, 5, and 6, and the largest are characteristic of stations 8 and 9.

Despite all the errors in the input data analyzed above, the accuracy of ET calculations based on data from the Visual Crossing Weather Data virtual weather station is 86 %, and the RMSE error is 0.62 mm. Applying a correction factor for the May-August period increases the accuracy of calculations to 89 %. The comparative analysis confirms the possibility of using meteorological data from VWS Visual Crossing Weather Data to calculate ETo for the purpose of further calculating the actual evapotranspiration (ETc) of agricultural crops using the FAO56-PM methodology [21].

The use of refined meteorological data should have increased the accuracy of ET calculations, but the MAPE and RMSE errors, on the contrary, increased by 4.8 % and 0.15 mm, respectively. Only for 8 stations was a decrease in MAPE and RMSE errors recorded, by 6.1 % and 0.17 mm, respectively. In our opinion, this is due to the fact that the correction coefficients were different for each station, and the use of the average coefficient did not lead to the desired result. Also, the use of a separate correction coefficient for each meteorological indicator causes technical difficulties in mass ET calculations. Therefore, the use of a single correction coefficient of 0.95 for the conditions of southern Ukraine in ET calculations is a more rational solution.

Conclusions.

1. Based on the analysis of meteorological data obtained from the Visual Crossing Weather Data virtual meteorological station, their accuracy has been established. Thus, data on air temperature and relative humidity are received with high accuracy, with MAPE and RMSE errors of 4.5 % and 0.94 °C and 9.1 % and 7.53 %, respectively.
2. Dew point temperature and solar radiation are characterized by good accuracy, with MAPE and RMSE errors of 20.9 % and 1.44 °C and 17.4 % and 3.41 MJ/m²·day, respectively. Dew point temperature data can also be obtained with satisfactory accuracy depending on the observation period.
3. The MAPE and RMSE errors for water vapor pressure deficit are 46.2 % and 0.21 kPa, respectively, which corresponds to satisfactory accuracy. Depending on the observation period, water vapor pressure deficit data can be obtained with unsatisfactory accuracy.
4. Wind speed data at a height of 2 m obtained with unsatisfactory accuracy, with MAPE and RMSE errors of 104.3 % and 1.2 m/s, respectively.
5. To improve the accuracy of the meteorological data obtained, correction factors were calculated, and when applied, the accuracy of all meteorological data obtained is improved.
6. The results of the research confirm the possibility of calculating ET using data from the Visual Crossing Weather Data virtual meteorological station for the period April-September with good accuracy. The MAPE and RMSE errors were 13.7 % and 0.62 mm, respectively.
7. To improve the accuracy of ET calculations in southern Ukraine, a correction factor of 0.95 should be used. Taking this into account, the accuracy of ET calculations for the period May-August increases to 89 %, and the RMSE is 0.63 mm.
8. The use of refined meteorological data reduces the accuracy of ET calculations by 4.8 % and increases the RMSE by 0.15 mm.
9. Based on the results of the research, a web application will be developed to calculate ETo and ETS using the FAO56-RM methodology with data from VWS Visual Crossing Weather Data.

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

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ОЦІНКА ТОЧНОСТІ МЕТЕОРОЛОГІЧНИХ ДАНИХ, ОТРИМАНИХ З ВІРТУАЛЬНОЇ МЕТЕОСТАНЦІЇ З МЕТОЮ ОЦІНКИ ET_O ДЛЯ УМОВ ПІВДНЯ УКРАЇНИ

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Анотація. *У статті наведено оцінювання точності метеорологічних даних, які отримуються з віртуальної метеорологічної станції Visual Crossing Weather Data (VWS VCWD) та розрахункової еталонної евапотранспірації (ETo) за цими даними для умов Півдня України. Встановлено, що дані температури й відносної вологості повітря, отримуються з високою точністю, похибки MAPE та RMSE яких відповідно становлять 4,5 % та 0,94 °С й 9,1 % та і 7,53 %. Для температури точки роси й сонячної радіації притаманна добра точність, похибки MAPE та RMSE яких відповідно становлять 20,9 % та 1,44 °С й 17,4 % та 3,41 МДж/м²·доб. Дані температури точки роси також можуть бути отримані із задовільною точністю залежно від періоду спостережень. Похибки MAPE та RMSE для дефіциту тиску водяної пари відповідно становлять 46,2 % та 0,21 кПа, що відповідає задовільний точності. Залежно від періоду спостережень дані дефіциту тиску водяної пари також можуть бути отримані із незадовільною точністю. Дані про швидкість вітру на висоті 2 м, отримано з незадовільної точністю, похибки MAPE та RMSE відповідно становлять 104,3 % та 1,20 м/с. Для підвищення точності отриманих метеорологічних даних були розраховані поправочні коефіцієнти, за умови їх застосування точність всіх отриманих метеорологічних даних підвищується. Підтверджено можливість розрахунку ETo за даними віртуальної метеорологічної станції Visual Crossing Weather Data за період квітень-вересень з доброю точністю. Похибка MAPE становила 13,7 %, а RMSE – 0,62 мм. Для підвищення точності розрахунку ETo в умовах Півдня України необхідно використовувати поправочний коефіцієнт, який становить 0,95. З урахуванням якого точність розрахунку ETo за період травень-серпень підвищується до 89 %, а RMSE становить 0,63 мм. Використання уточнених метеорологічних даних знижують точність розрахунку ETo на 4,8 %, а RMSE підвищують на 0,15 мм. За результатами проведених досліджень буде розроблено веб додаток для розрахунку ETo та ETc за методикою FAO56-PM з використанням даних з VWS Visual Crossing Weather Data.*

Ключові слова: *віртуальна метеостанція, метеорологічні дані, еталонна евапотранспірація, точність, похибки MAPE та RMSE*

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THE IMPACT OF CHANGING WEATHER CONDITIONS ON THE YIELD OF FIELD CROPS IN THE LEFT-BANK FOREST-STEPPE OF UKRAINE

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Abstract. *Different weather. conditions affect plant growth rates, nutrient mobility in the soil, photosynthesis intensity, and soil biota activity. Optimization of soil water-air and nutrient regimes through land reclamation makes it possible to significantly offset the negative effects of adverse weather conditions and increase the sustainability of agrophytocenosis productivity. However, in the conditions of "organic" farming in regions with a moisture deficit without sufficient water resources and mineral fertilizers, effective agricultural production is problematic. Establishing the patterns of the influence of moisture and heat conditions at certain stages of organogenesis is the theoretical basis for increasing the sustainability of agriculture, in particular when using only natural soil fertility and secondary biomass. The aim of the work was to establish the patterns of changes in the yield of field crops in different crop rotations depending on the dynamics of agrometeorological factors in conditions of insufficient moisture in the eastern Forest-Steppe of Ukraine and to assess the productivity potential of crops, taking into account the annually changing hydrothermal conditions in the system "organic" farming system without the use of mineral fertilizers. The assessment of changes in agrometeorological resources was carried out using mathematical and statistical analysis of ten-day indicators of heat supply (air temperature and precipitation) and field crop yields. Data from a 20-year stationary experiment were processed using correlation and computational-comparative analysis methods with systematic generalization. The most reliable key periods before vegetation and during organogenesis were established, when the relationship between weather conditions and crop yields manifests itself with a sufficient level of reliability. The proposed approach is based on the formation of statistical series of yield data (15–20 years) and corresponding decadal indicators of temperature and precipitation in the local area. It is recommended to first construct graphs of the dynamics of hydrothermal conditions in years with different yields to identify periods of the most obvious deviations, and then conduct a detailed search for mathematical dependencies of productivity on weather conditions.*

Keywords: *correlation, hydrothermal conditions, field crops, yield, natural soil fertility background, organic production*

Relevance of the study. Weather conditions are one of the key factors determining annual fluctuations in crop yields and, consequently, the effectiveness of management decisions in the agricultural sector [1–5]. The productivity of agricultural land is influenced by a whole range of interrelated factors: rational crop rotation, soil availability of nutrients, its agrophysical characteristics, the condition and diversity of the soil biota, the biological properties of the varieties and hybrids used, the level of organic and mineral fertilizers applied, as well as climatic and agrometeorological conditions [6–8]. The latter often play a decisive role [9–11].

Analysis of recent studies and publications. Long-term stationary agrotechnical experiments [12–17] demonstrate that due to constant annual changes in weather conditions, yield indicators can vary significantly even within the same soil and climatic region. It is known that among the most effective factors ensuring the growth of productivity and adaptability of agroecosystems, various forms of land reclamation, primarily hydrotechnical and agrochemical, occupy an important place. Improving soil moisture, aeration, and nutrition regimes usually makes it possible to partially compensate for the negative impact of unfavorable atmospheric conditions and increase the stability of agricultural technologies [18]. However, in conditions of insufficient natural moisture, lack of water resources, and the inability to use fertilizers, ensuring effective "organic" farming becomes quite a difficult task.

Under conditions of weather fluctuations, the mobility of macro- and microelements in the soil environment, the rate of plant growth processes, the intensity of photosynthesis and respiration, as well as the activity of biochemical and microbiological reactions that ensure metabolism, change. Accordingly, the development of the root system and the needs of plants for nutrients and the rate of their assimilation are transformed. Therefore, studying the patterns of bioproductivity formation in agrophytocenoses under unstable meteorological conditions is a scientific prerequisite for increasing the sustainability of agricultural systems, especially when farming relies solely on natural soil fertility and is focused on obtaining organic plant products.

In addition, plant yield is determined by how well the conditions of lighting and nutrient supply are coordinated. The temperature regime determines the accumulation of mobile nutrients in the soil. Temperature affects the rate of movement of water and soluble salts and thus influences the rate at which nutrients are supplied to plants from the soil and fertilizers.

The degree of soil moisture significantly determines the availability of nutrients and the efficiency of their assimilation by plants. In conditions of severe moisture deficiency, even sufficient reserves of macro- and microelements do not provide a positive result and can sometimes negatively affect crop formation. Excessive moisture, in turn, disrupts the optimal water-air regime of the soil, inhibits nitrification processes, reduces the supply of nutrients to plants, and contributes to the accumulation of toxic compounds. Thus, at optimal moisture content, the nitrogen assimilation coefficient from fertilizers reaches about 57 %, while at excess moisture it decreases to about 9 %.

Numerous scientific studies prove that the impact of weather and climatic conditions on agricultural results does not weaken over time, but, on the contrary, becomes more pronounced. This is manifested in a wider range of yield fluctuations relative to the average level and an increase in the difference between the most favorable and least productive years. This trend is explained primarily by the fact that modern high-yielding varieties and hybrids, characterized by intensive metabolism and high rates of energy processes, are much more sensitive to changes in the environment. They are more sensitive to any disturbances in water, heat, or nutrient regimes, which leads to increased yield variability [19–21].

In the context of rapid climate change, it is necessary to search for trends that occur over a long series of yield data in terms of the impact of variable hydrothermal indicators on crop productivity in the pre-sowing period and at different stages of the organogenesis of field crops. These data are obtained from the information base of stationary agrotechnical and variety testing experiments, as well as (or) using statistical information at the level of a separate agricultural territory and a network of regional weather stations.

From the point of view of increasing crop yields at low costs of chemical and technogenic resources and justifying measures to adjust the conditions for plant growth and development, it will be relevant to identify the decisive factors and optimal parameters of heat and moisture supply during key periods before and during their vegetation at the local territorial level. On the other hand, an important advantage of this approach is the ability to predict with a high degree of reliability not only crop productivity, but also the functioning of other components of agroecosystems under variable hydrothermal conditions.

The purpose of the study is to develop a methodology for determining critical periods of crop growth depending on hydrothermal conditions; to propose new approaches to predictive modeling of crop productivity, taking into account heat and moisture supply at the stages of organogenesis; to justify the feasibility of further research in this direction.

Materials and methods of research. For modeling, we used the information base of a stationary experiment of the Department of Agriculture and Herbology named after O.M. Mozeyko Department of Agriculture and Herbology of the State Biotechnological University, where 16 variants of field crop rotations with different predecessors of winter wheat were studied over 20 years (1996–2015): clean fallow, peas, vetch, lentils, beans, vetch-oat mixture, soybeans, and corn. The first (No. 1–8) and second (No. 9–16) groups of crop rotations differ in the third crop: sugar beets or buckwheat with the same final fourth crop of spring barley.

The soil of the stationary experiment is typical deep black soil with low humus content and heavy loam on loamy loam with a humus content of 4.94–5.21 %, easily hydrolyzed nitrogen according to Kornfield – 80–130, mobile phosphorus and exchangeable potassium according to Chirikov – 100–150 and 100–200 mg per 1 kg of soil, respectively, pH of water – 7.0, salt – 5.2–5.6.

The area of the sowing plot was 142 m² and the accounting plot was 100 m². An organic farming system was used, with only by-products of the harvest being used as fertilizer: cereal straw and sugar beet tops. The methods described in [22] were used when setting up and conducting the field stationary experiment.

Research results **and discussion.** To assess the impact of air temperature and precipitation on crop productivity, we used ten-day indicators during their cultivation, as well as before and after the growing season. In addition, a sharp reduction in water supply during the growing season is confirmed by the analysis of the Selianinov hydrothermal coefficient. Thus, in the period 1996–2005, the average HTC indicators for April–September fluctuated between 1.0 and 1.2, which, according to the generally accepted scale, corresponds to conditions of weak moisture. However, in recent years, this indicator has fallen below 0.7, indicating a noticeable drought stress. For example, for winter wheat, the period from September of the previous year to July of the following year was assessed. For early spring cereals and fodder crops, the period was from January to July, and for late crops, from January to September. First, the most contrasting yields of each of the crops studied over three or four years were compared, from the lowest to the highest. For example, we selected the following levels of winter wheat grain yield when growing the crop after peas: low yield in 2000 – 1.69 t/ha, average yield in 2015 – 3.21 t/ha, increased yield in 2014 – 4.82 t/ha, and high – yield in 2005 – 6.04 t/ha. Then, graphs of the ten-day dynamics of temperature and precipitation were constructed for the above-mentioned crop periods. This made it possible to establish the difference or deviation of hydrothermal indicators in more favorable and less favorable years in terms of yield. The most productive years in the first ten days of September were significantly cooler than in less productive years (Fig. 1). That is, the temperature regime clearly influenced crop yield before sowing (Fig. 2).

Further on in the period of crop growth and development, it is difficult to assess the difference in heat supply conditions based on ten-day indicators due to their significant fluctuations. This figure only shows that harvest years differ significantly at the end of October and November, and in certain ten-day periods of the winter months. Therefore, based on these data for contrasting years, sixth-order polynomial trend lines were constructed to identify general patterns and deviations. Figure 3 shows that years with different wheat yields differ significantly in terms of average ten-day air temperature from October to March. This means that with an increase in the average daily temperature during the specified period from 15 to 20 °C, grain yield will most likely decrease from 4–6 to 1–2 t/ha.

Based on the preliminary study, a more detailed analysis of the relationship between crop yield and thermal regime in the identified critical periods was conducted: the first ten days of September and October–March. For this purpose, the corresponding twenty-year data series were compared with the construction of first-order polynomial dependencies. It was found that when the average daily air temperature in the first ten days of September rises above 16 °C, there is a tendency for winter wheat grain yield to decrease from 4.5 t/ha. (Fig. 3) This is probably due to the deterioration of moisture supply to crops as a result of increased evaporation and transpiration.

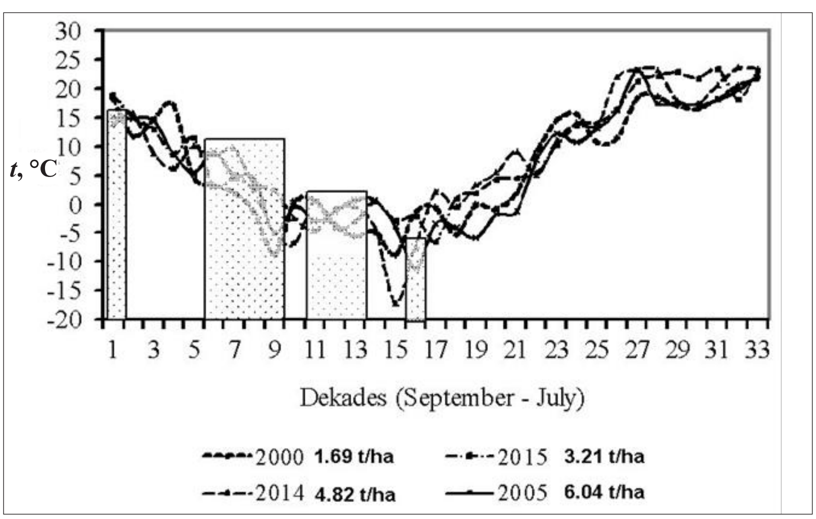

Fig. 1. Decadal dynamics of air temperature in years with different winter wheat yields

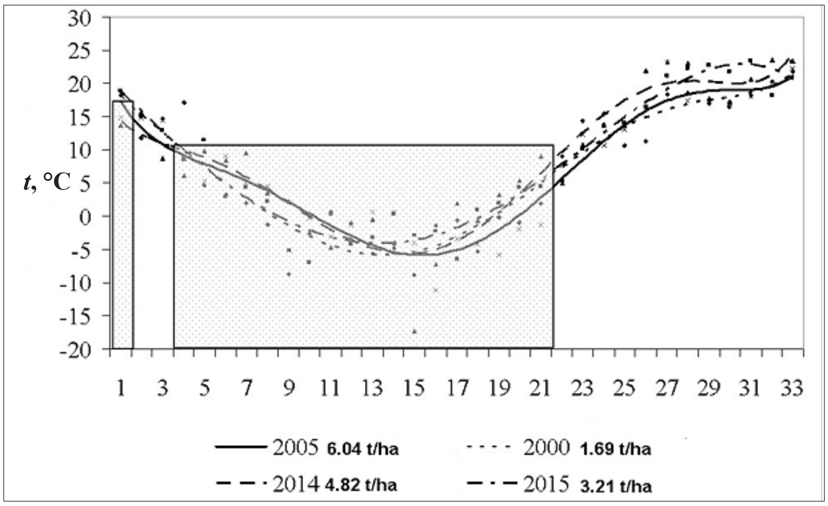

Fig. 2. Trends (6th order polynomials) in the ten-day dynamics of air temperature in different winter wheat yield years

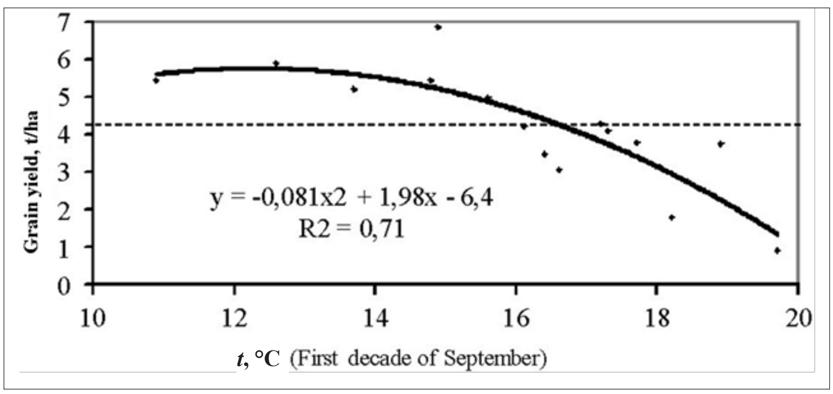

Fig. 3. Dependence of winter wheat yield on the average daily air temperature in the first ten days of September

The relationship between heat supply during the period from October to March and crop yield is shown in Figure 4. It is evident that with an increase in the average daily air temperature during this period above minus 2 degrees Celsius, there is a tendency for the productivity of winter wheat crops to increase from 3 t/ha of grain. In other words, the warmer the wintering period, the more favorable the conditions for grain yield formation.

Figure 5 shows the dynamics of precipitation from September to July in years with different crop yields. As with the temperature regime, the overall state of moisture supply can be represented in a more generalized form using sixth-order polynomial dependencies based on decadal data. Figure 5 shows that more productive years are characterized by higher precipitation in autumn, lower in winter and spring, and higher in summer.

However, a more thorough search for the relationship between moisture supply and crop yield over 20 years of data showed a tendency for crop productivity to increase when the amount of precipitation from the second ten days of September to the first ten days of June was less than 360 mm. Under such conditions, the wheat grain yield will most likely exceed 4.0 t/ha (Fig. 6). However, with a decrease in precipitation during the specified period to 200 mm, a downward trend in grain yield can be observed. There is also the possibility of achieving higher wheat yields when the crops receive 50 to 110 mm of moisture during the period from the third decade of June to the second decade of July.

A decrease or increase in this amount is likely to be accompanied by a grain yield of less than 5 t/ha (Fig. 7). In the first case, this is due to insufficient water supply at the final stage of organogenesis.

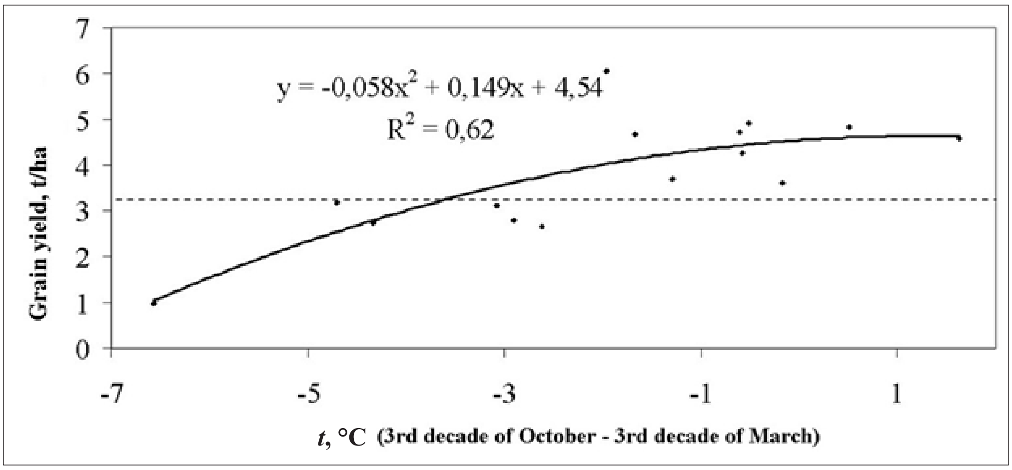

Fig. 4. Dependence of winter wheat yield on the average daily air temperature from the third decade of October to the third decade of March

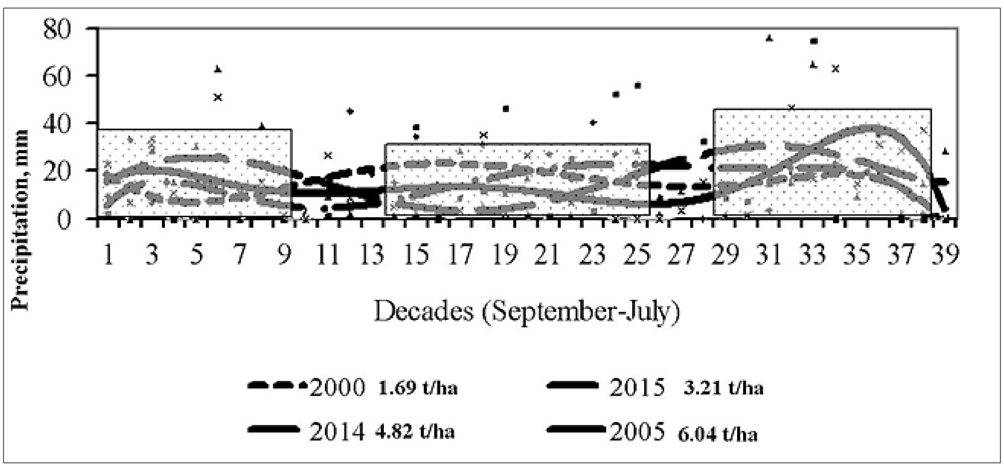

Fig. 5. Trends (6th order polynomials) in the ten-day dynamics of precipitation in different winter wheat yields

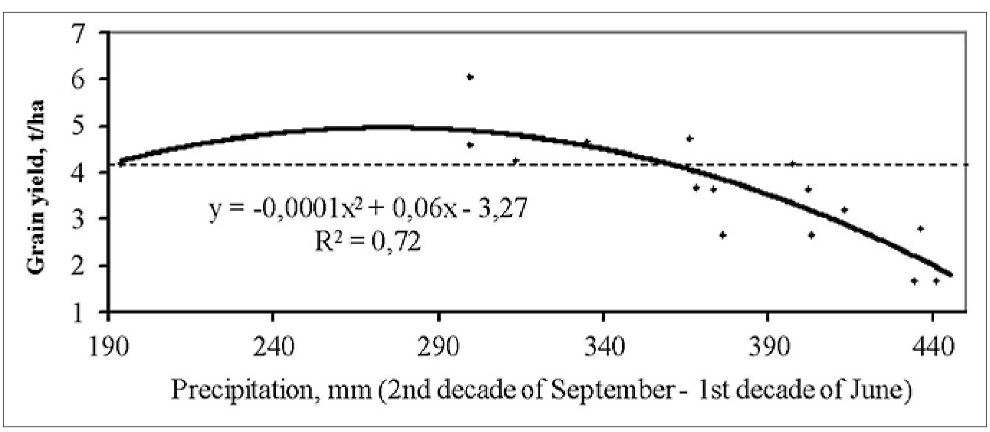

Fig. 6. The dependence of winter wheat yield on the amount of precipitation from the second ten days of September to the first ten days of June

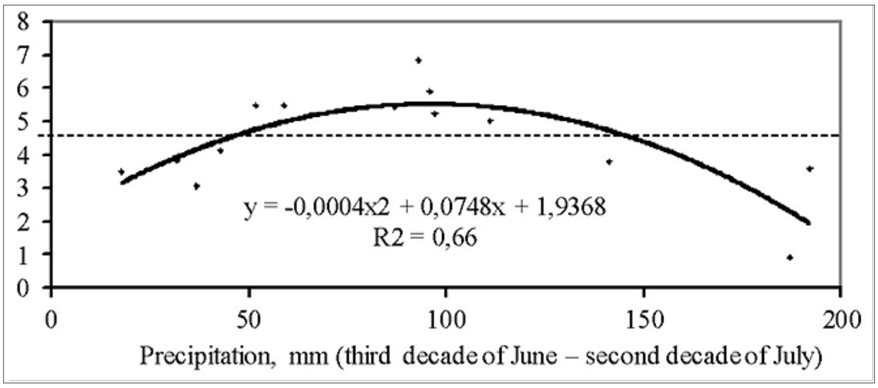

Fig. 7. Dependence of winter wheat yield on the amount of precipitation from the third decade of June to the second decade of July

In the second case, the decline in crop productivity may be associated with more intensive development of harmful organisms or increased grain losses as a result of waterlogging before harvesting. It is also necessary to pay attention to the possible influence of precipitation at the beginning of winter wheat vegetation on its yield. Figure 8 shows that in the case of atmospheric moisture supply during September within the range of 30–70 mm, in many cases the grain yield will exceed 4 t/ha. Lower moisture levels during this period can reduce crop productivity due to insufficient plant development before the winter cold. Conversely, waterlogging leads to a high risk of increased development of harmful organisms, disruption of technological processes, and the impact of other negative factors. Thus, years with different winter wheat yields differ significantly in terms of hydrothermal conditions at certain stages of its organogenesis. Higher crop productivity may be associated with cooler air temperatures in early September and natural moisture supply during this month within the range of 30–70 mm.

A higher crop yield is most likely to be achieved under conditions of higher temperatures during the cold season and moisture supply from September to April not exceeding 350 mm. At the end of the growing season (third decade of June – second decade of July), the desired amount of precipitation is within the range of 50–110 mm. Using the methodology presented in the example of winter wheat, predictive models were developed for the probable impact of hydrothermal conditions on the yield of other field crops at different stages of their organogenesis (Table 1).

When growing sugar beets, there is a tendency for their yield to increase above 30 t/ha when the average daily temperature exceeds 0°C from the third decade of February to the second decade of March (Fig. 9). That is, the warmer it is in the pre-sowing period, the more favorable the conditions for plant growth and development in the future. This is obviously due to faster soil warming in April, the possibility of earlier sowing, reducing unproductive moisture losses due to evaporation, and extending the growing season.

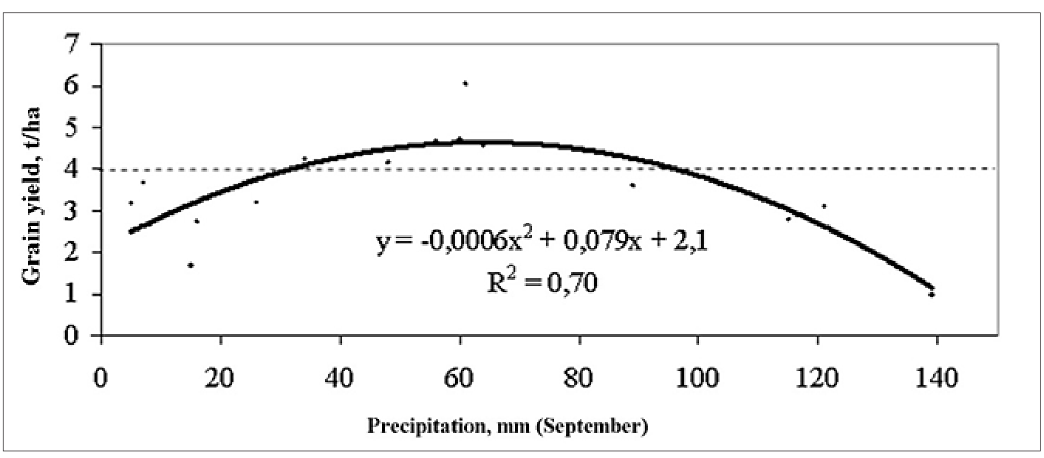

Fig. 8. Dependence of winter wheat yield on the amount of precipitation in September

1. Dependence of crop yields on precipitation and average ten-day air temperature for specific periods of time

Crop	Temperature					Precipitation				
	decade	equation	R^2	°C	t/ha	decade	equation	R^2	mm	t/ha
Winter wheat	September 1	$y = -0.081x^2 + 1.98x - 6.4$	0.71	10	> 4.5	September 1–3	$y = -0.0006x^2 + 0.08x + 2.1$	0.69	30–90	> 4.0
	October 3 – March 3	$y = -0.058x^2 + 0.149x + 4.54$	0.62	−7 – (−2)	< 3.5	September 2 – June 1	$y = -0.0001x^2 + 0.06x - 3.27$	0.72	< 370	> 4.0
Sugar beets	February 3 – March 2	$y = -0.01x^2 + 0.5x + 34$	0.62	> 0	> 32	May 3	$y = -0.0033x^2 + 0.6x + 17.5$	0.57	> 20	>28
	April 3 – May 2	$y = 0.339x^{2-}12.2x + 132$	0.56	< 14	>28	August 1 – September 3	$y = 3E - 05x^2 - 0.2x + 43.9$	0.66	< 70	>28
Buckwheat	April 2 – May 1	$y = -0.035x^2 + 0.955x - 5.06$	0.59	< 11 >14	< 1.3	July 3 – September 1	$y = -0.0001x^2 + 0.0255x + 0.35$	0.65	90–100	> 1.4
	June 2	$y = 0.035x^2 - 1.54x + 18$	0.69	< 20	> 1.3	–	–	–	–	–
	August 2-3	$y = -0.062x^2 + 2.52x - 24$	0.71	>23	< 1.0	–	–	–	–	–
Barley after beet	May 1 – June 3	$y = 0.0063x^2 - 0.51x + 9.47$	0.59	< 17	> 2.7	May 3 June 2	$y = -0.0009x^2 + 0.13x - 1.66$	0.66	50–90	> 2.5
	–	–	–	–	–	January 3 – March 2	$y = 0.0006x^2 - 0.074x + 4.0$	0.53	> 90	> 2.5
Barley after buckwheat	May 1 – June 3	$y = 0.052x^2 - 2.24x + 25.3$	0.66	< 17	> 2.5	January 3 – April 3	$y = 0.0001x^2 - 0.0115x + 1.48$	0.67	> 150	> 2.0
Peas	April 3 – May 2	$y = 0.05x^{2-}1.71x + 15.8$	0.61	< 13	> 2.5	June 2-3	$y = -0.0007x^2 + 0.08x + 0.36$	0.7	25–85	> 2.2
Vetch-oat mix	June 3 – July 1	$y = -0.27x^2 + 22.1x - 430$	0.63	38	> 18	April 1 – June 3	$y = 8E - 05x^2 + 0.033x + 6.8$	0.66	> 210	> 17
Corn MWR	March 2 – April 1	$y = 0.09x^2 - 1.124x + 18.7$	0.67	> 6	> 30	April 2 May 1	$y = 0.005x^2 - 0.2x + 20$	0.77	> 50	> 25
	July 2 – August 3	$y = 2.17x^2 - 89.4x + 936$	0.74	> 22	> 23	June 1 July 1	$y = -0.001x^2 + 0.39x - 0.63$	0.62	> 80	> 25

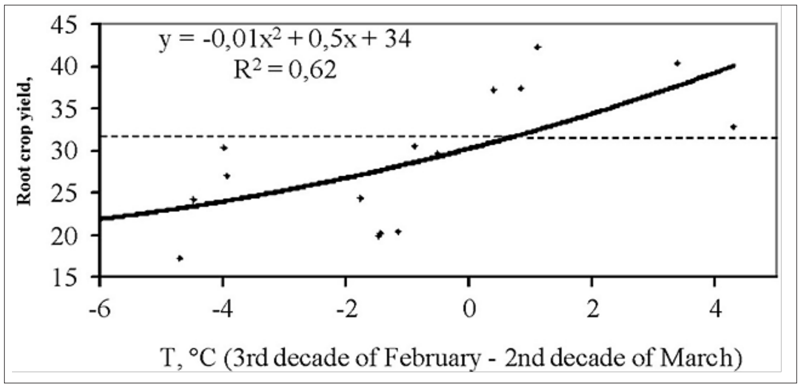

Fig. 9. Dependence of sugar beet yield on average daily air temperature from the third decade of February to the second decade of March

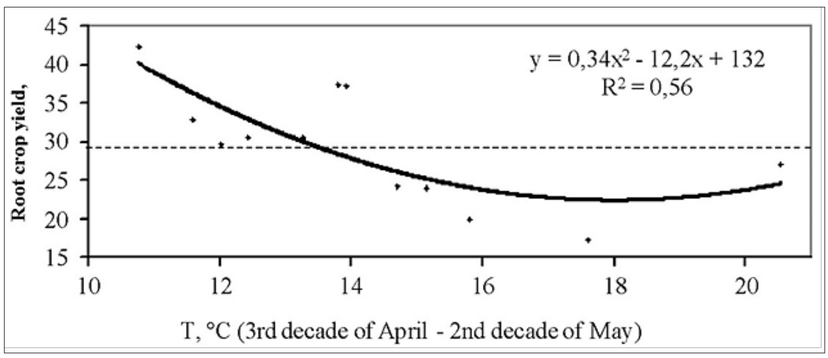

Fig. 10. Dependence of sugar beet yield on average daily air temperature from the third decade of April to the second decade of May

It should also be noted that there is a high probability of reduced crop productivity under increased heat conditions during the spring months of vegetation for this crop (Fig. 10). Thus, if the average daily air temperature from the third decade of April to the second decade of May exceeds 14 °C, the root crop yield will not exceed 30 t/ha. In terms of heat supply, mid-summer can be of great importance. Thus, Figure 11 shows the possibility of an increase in sugar beet yield from 25 t/ha if the average temperature in the first ten days of July is below 20 or above 24 °C (Fig. 11). This situation can be explained by the influence of factors other than thermal conditions, in particular the specifics of the development of harmful organisms.

During the period of active growth of sugar beet foliage, moisture conditions are particularly important. In this case, there is a tendency for root crop yields to exceed 30 t/ha when precipitation in the third ten days of May exceeds 20 mm (Fig. 12).

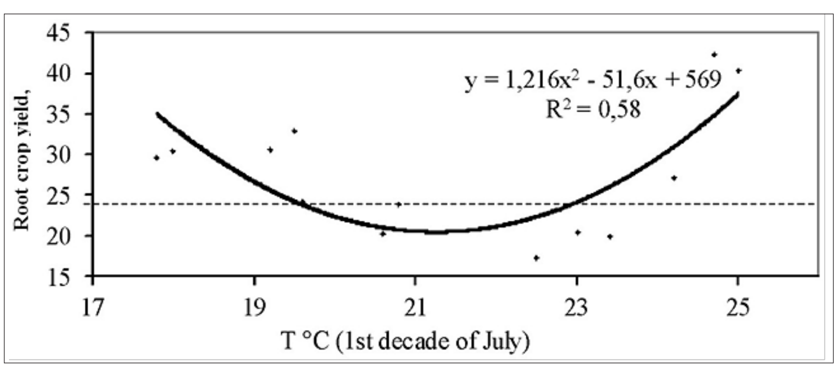

Fig. 11. Dependence of sugar beet yield on the average daily air temperature in the first ten days of July

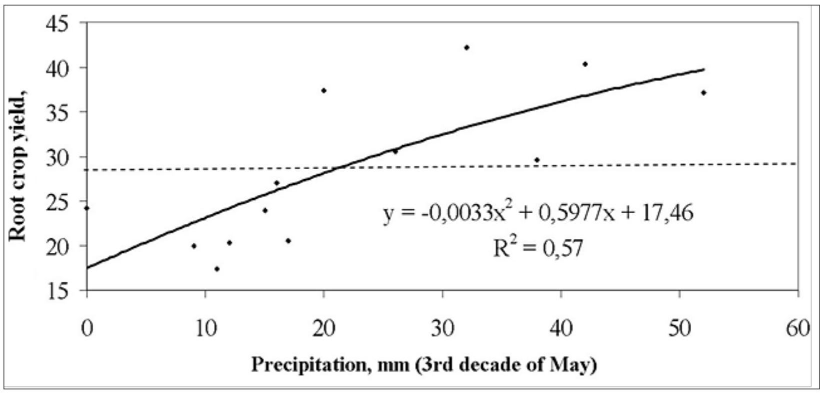

Fig. 12. Dependence of sugar beet yield on precipitation in the third ten days of May

It is highly probable that crop productivity will decrease from 30 t/ha when the amount of precipitation for the period August–September exceeds 70 mm. This can be explained by the more active development of harmful vegetation (weeds), difficulties in harvesting, and the influence of other factors (Fig. 13).

Comparison of the dynamics of ten-day air temperature in more productive buckwheat years (2001, 1.5 t/ha, and 2005, 1.85 t/ha) and in less productive years (2002, 0.8 t/ha, and 2006, 0.7 t/ha) yields (2007, 0.72 t/ha, and 2003, 1.1 t/ha) showed noticeable differences from late April to early May, in June, and in August. Indeed, with an increase in the average daily temperature in the period from the second ten days of April to the first ten days of May above 11°C, there is a tendency for the yield of this crop to increase from 1.2 t/ha to a maximum of 1.5–1.8 t/ha at 12°C (Fig. 14).

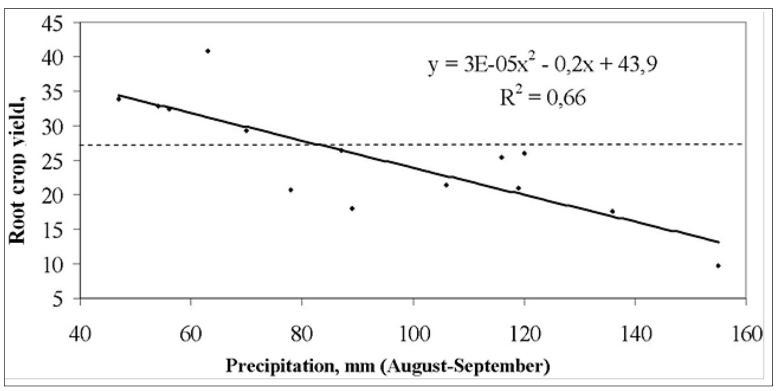

Fig. 13. Dependence of sugar beet yield on the amount of precipitation from the first ten days of August to the third ten days of September

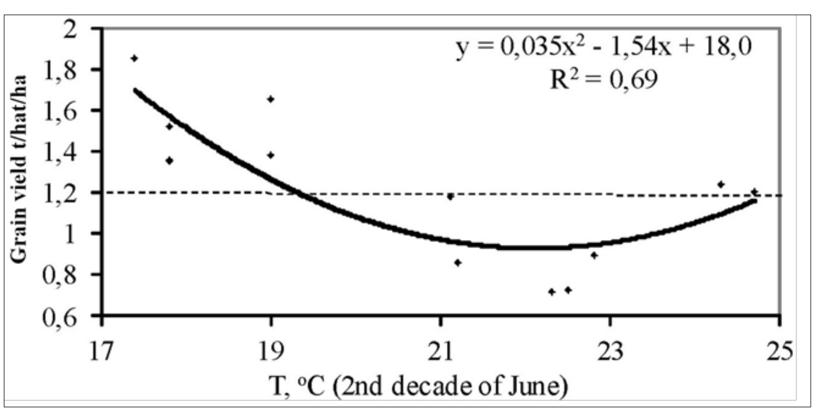

Fig. 14. Dependence of buckwheat yield on the average daily air temperature in the second ten days of June

There is also a correlation between thermal conditions in the second ten days of June and buckwheat crop productivity. Thus, if the average temperature during this period does not exceed 19 °C, a grain yield of more than 1.3 t/ha can be expected. The level of heat supply can also affect the condition of crops at the end of summer. In particular, if the average temperature for the second and third decades of August exceeds 23 °C, the risks of a decrease in buckwheat productivity from the level of 1 t/ha increase.

In terms of maximum precipitation, the most productive year, 2005 (1.85 t/ha), differs from the others in the second ten days of March, the first and second ten days of June, the first ten days of July, and the second ten days of August (Fig. 15). If we take the total amount of moisture that fell on the crops during these decades, then over a 15-year period it will correlate quite closely with grain yield (R^2=0.76). Moreover, if the total precipitation during these periods is less than 50 mm, the risk of a decrease in yield from the level of 1 t/ha increases (Fig. 16). The impact of moisture supply in the second half of summer and early autumn on buckwheat crops may also be specific. With a 65 % probability, yields above 1.5 t/ha can be achieved provided that between the third decade of July and the first decade of September, there is no less and no more than 95–105 mm of atmospheric moisture. The risk of crop failure (<1.2 t/ha) increases during harvesting (first and second decades of September) if the amount of precipitation exceeds 25 mm.

In general, spring barley reacted weakly to changes in hydrothermal conditions over the years. This is probably due to the short growing season and the rapid use of available heat and water resources before the crop matures. However, the yield of spring barley after sugar beets may depend on the average daily air temperature from May to June. If this indicator exceeds 13 °C, it is difficult to expect a crop yield higher than 2.7 t/ha. There is also a certain dependence of the yield of barley grain after sugar beets on the amount of precipitation from the third decade of May to the second decade of June. When 50 to 80 mm of precipitation falls during this period, the probability of obtaining a grain yield above 2.5 t/ha increases significantly.

The growth and development of spring barley sown after buckwheat was also influenced by the average ten-day temperature regime in May–June, with yields increasing from 2.5 t/ha when the average air temperature did not exceed 17° C. At the same time, in the absence of precipitation in the third decade of April, one should not expect crop productivity to exceed 2.0 t/ha.

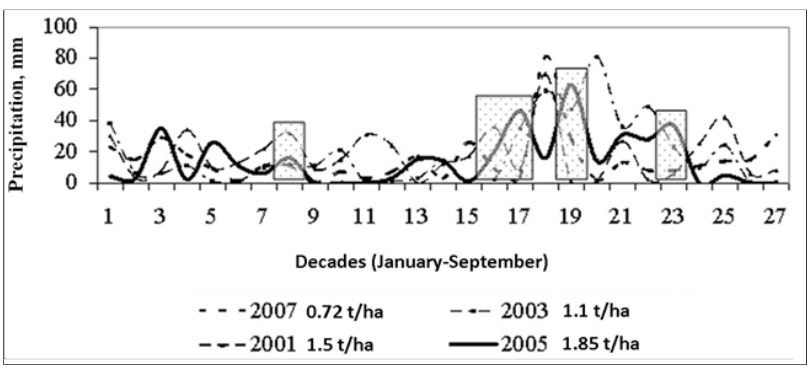

Fig. 15. Ten-day dynamics of precipitation in years with different buckwheat yields

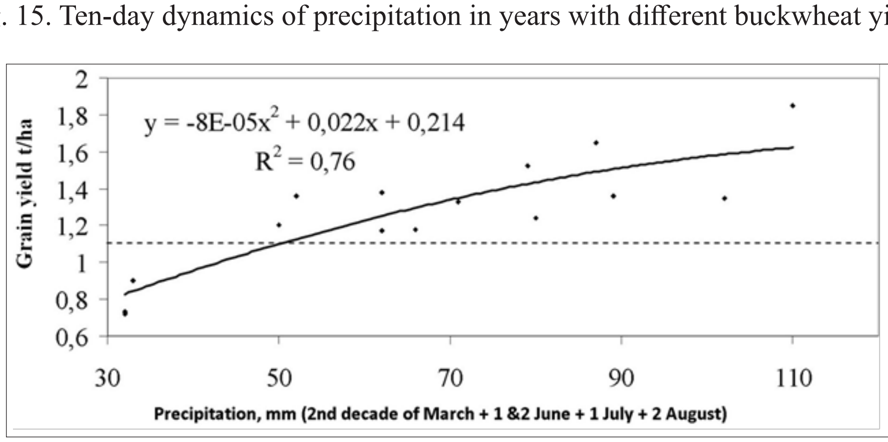

Fig. 16. Relationship between precipitation in the second ten days of March, the first and second ten days of June, the first ten days of July, and the second ten days of August and buckwheat yield

A comparison of the dynamics of different years in terms of pea yield showed that the most favorable year, 2008, differed significantly from the unfavorable year, 2014, in terms of temperature regime in almost all decades from April to July. A more thorough analysis of long-term yield and temperature series showed that at the beginning of the growing season, peas can suffer from increased heat. The figure shows that when the average daily air temperature rises above 15 °C from the third decade of April to the second decade of May, the crop's productivity potential is limited to 1.2–1.3 t/ha.

From late spring to the end of the growing season, the impact of temperature conditions can be specific. If from the third decade of May to the second decade of July this indicator is less than 18 °C or more than 22 °C, a tendency towards a significant reduction in grain yield can be observed. A lack of heat creates unfavorable conditions for plant growth and development, while hot weather causes premature ripening of the crop (Figs. 17–18). That is, a pea yield above 1.5 t/ha can be expected when the average air temperature in the first half of the growing season is above 15 °C and in the second half is in the range of 18–22 °C.

A comparison of moisture supply dynamics in favorable and unfavorable years showed that in more productive years, there was significantly less precipitation in June. A comparative analysis of long series of relevant indicators showed that atmospheric moisture affects pea productivity in the second and third decades of June. The amount of precipitation during these decades should be no less than 25 mm and no more than 85 mm (Fig. 19). In this case, a grain yield of at least 2 t/ha can be expected, with a maximum value of 3.2 t/ha for 75 mm of precipitation on crops.

The probability of obtaining a green mass yield of annual grasses (vetch-oat mix) of more than 18 t/ha will significantly decrease if the average daily air temperature is less than 19 °C and more than 21 °C during the period from the third decade of June to the first decade of July (pre-harvest period). The same effect (>18 t/ha of green mass) can be expected if the amount of precipitation in April–June exceeds 200 mm, with a maximum level of 25 t/ha at a moisture level of 300 mm.

Soybeans grown for green mass respond well to higher temperatures in the pre-sowing period, which is probably due to earlier soil "maturation" and a longer growing season. Thus, if this indicator exceeds 5 °C in the third decade of March, the possibility of obtaining more than 17 t/ha of green mass increases significantly, with a maximum level of 22 t/ha at 9 °C.

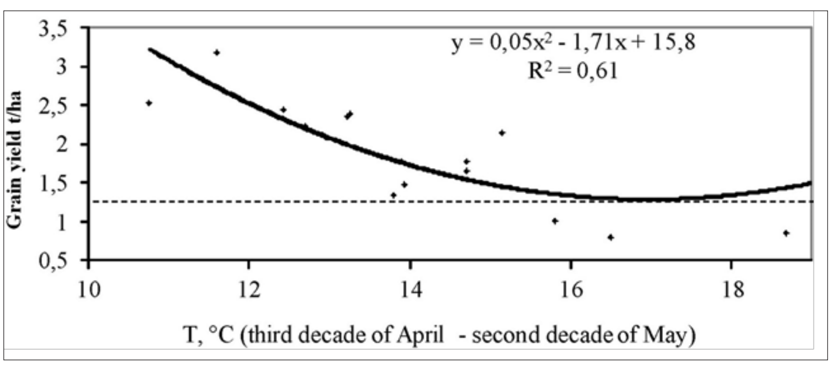

Fig. 17. Relationship between the average daily air temperature from the third decade of April to the second decade of May and pea yield

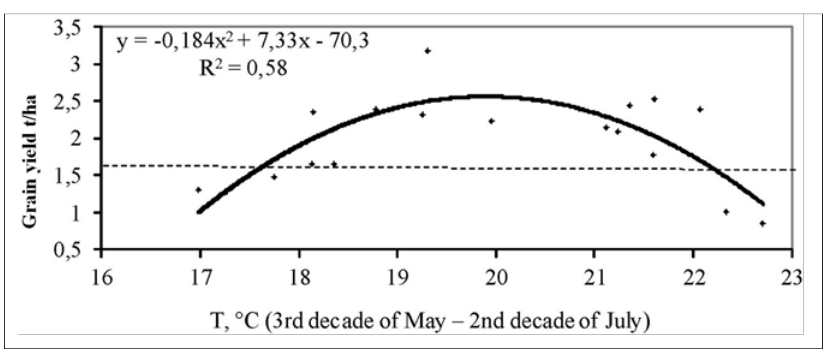

Fig. 18. Relationship between the average daily air temperature from the third decade of May to the second decade of July and the yield of peas

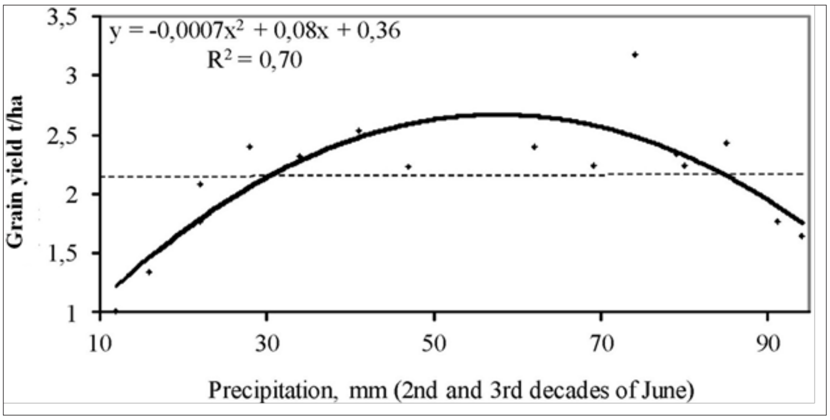

Fig. 19. Relationship between precipitation in the second and third decades of June and pea yield

For soybeans, the amount of precipitation can be important in the pre-sowing and pre-harvest stages. Thus, if more than 60 mm of moisture falls between the second ten days of February and the first ten days of April, the probability of a decrease in green mass yield from the level of 15 t/ha increases significantly. In summer (June–second ten days of July), if moisture intake does not exceed 110 mm or increases from 190 mm, a drop in green mass yield below 17 t/ha can be expected.

To preliminarily establish the impact of hydrothermal conditions in the pre-sowing period and directly during the growing season of corn for silage, the ten-day dynamics of these conditions were compared in years with different yields: 1999 – 13 t/ha, 2012 – 23 t/ha, 2007 – 32 t/ha, 2008 – 43 t/ha. It was found that the air temperature in years with different productivity differed most significantly in March and in the summer months. A comparison of long series of yield data and thermal indicators showed that corn yield can increase significantly (>30 t/ha) when the average daily temperature from the second ten days of March to the first ten days of April exceeds 6° C. Similar results were obtained from the analysis of data on heat-loving soybeans. If the heat supply to crops from the second ten days of July to the third ten days of August exceeds 22 °C, the probability of obtaining more than 25 t/ha of green mass increases significantly, with a maximum level of 36 t/ha as the temperature approaches 24 °C.

A comparative assessment of the dynamics of decadal precipitation in years with different yields showed significant variation in this indicator in the period from January to September. A significant advantage of a productive year in terms of moisture content can be noted in April and in the first half of summer. A more thorough search for dependencies showed that with an increase in precipitation from the second ten days of April to the first ten days of May from a level of 50 mm, a green mass yield of more than 25 t/ha can be expected, with a maximum level of 43 t/ha for 90 mm of precipitation. A prerequisite for obtaining more than 25 t/ha of silage mass may be precipitation of at least 80 mm from the first ten days of June to the first ten days of July.

Conclusions.

A methodological approach to establishing critical periods for the formation of field crop yields is proposed, based on the analysis of long-term (15–20 years) series of statistical data on yields and corresponding ten-day indicators of air temperature and precipitation at the local territorial level. The methodology involves a two-stage procedure: first, the construction of graphs of the dynamics of hydrothermal indicators in years with contrasting productivity to identify periods of the most pronounced deviations; at the next stage, a detailed correlation analysis of the dependence of yield on weather conditions in the identified critical periods.

Key periods of vegetation have been established when the dependence between hydrothermal conditions and field crop yields manifests itself with a sufficient level of reliability. The obtained polynomial regression models allow predicting crop productivity depending on the temperature regime and moisture supply at critical stages of organogenesis in the conditions of the Left-Bank Forest-Steppe of Ukraine.

Limitations in the reliability of the developed models have been identified, caused by the failure to take into account a complex of related factors of the bioproductivity of agrophytocenoses, namely: the duration of individual stages of organogenesis, the dynamics of the soil nutrient regime, its agrophysical properties, the phytosanitary condition of crops, the impact of extreme weather events, etc. Further improvement of predictive models requires multifactorial analysis with simultaneous monitoring of crop yields, hydrothermal conditions, and other agroecological parameters, which will increase the accuracy and practical value of crop productivity forecasting in the context of climate change.

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

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

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ВПЛИВ ЗМІННИХ ПОГОДНИХ УМОВ НА ВРОЖАЙНІСТЬ ПОЛЬОВИХ КУЛЬТУР У ЛІВОБЕРЕЖНОМУ ЛІСОСТЕПУ УКРАЇНИ

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Анотація. *За різних погодних умов змінюються темпи розвитку рослин, рухомість елементів живлення у ґрунті, інтенсивність фотосинтезу та активність ґрунтової біоти. Оптимізація водно-повітряного і поживного режимів ґрунту через меліорації дає змогу значною мірою нівелювати негативну дію несприятливих погодних умов та підвищити сталість продуктивності агрофітоценозів. Однак в умовах «органічного» землеробства у регіонах з дефіцитом зволоження без достатніх водних ресурсів і мінеральних добрив ефективне аграрне виробництво є проблематичним. Встановлення закономірностей впливу умов зволоження і теплозабезпечення на окремих етапах органогенезу є теоретичною основою підвищення сталості землеробства, зокрема за використання лише природної родючості ґрунту та побічної біомаси. Метою роботи було встановлення закономірностей змін врожайності польових культур у різних сівозмінах залежно від динаміки агрометеорологічних факторів в умовах недостатнього зволоження східного Лісостепу України та оцінка потенціалу продуктивності посівів з урахуванням щорічно змінних гідротермічних умов у системі «органічного» землеробства без застосування мінеральних добрив. Оцінку змін агрометеорологічних ресурсів здійснювали методом математико-статистичного аналізу подекадних показників теплозабезпечення (температури повітря та опадів) і врожайності польових культур. Дані 20-річного стаціонарного досліду оброблялися методами кореляційного та розрахунково-порівняльного аналізу із системним узагальненням. Встановлено найбільш вірогідні ключові періоди до вегетації та під час органогенезу, коли залежності між погодними умовами та врожайністю проявляються з достатнім рівнем достовірності. Запропонований підхід ґрунтується на формуванні статистичних рядів урожайних даних (15–20 років) та відповідних подекадних показників температури і опадів на локальному просторі. Рекомендовано спочатку побудувати графіки динаміки гідротермічних умов у різні за врожайністю роки для виявлення періодів найочевидніших відхилень, а потім провести детальний пошук математичних залежностей продуктивності від погодних умов.*

Ключові слова: *кореляція, гідротермічні умови, польові культури, урожайність, природний фон родючості ґрунту, органічна продукція*

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SOME FEATURES OF ASSESSING THE STABILITY OF HYDROTECHNICAL STRUCTURES GIVEN THE ANISOTROPY OF THE STRESS-DEFORMED STATE OF THEIR SOIL BASES

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Abstract. *The processes that cause degradation of soil properties, decrease in their strength and increase in deformability was analized. Solving the problem of determining phase velocities and vectors of elastic displacements made it possible to establish the differential coefficient of elastic anisotropy of soils that form the basis of hydraulic structures. Experimental studies of soils, which are the basis of hydraulic structures, when using ultrasonic methods made it possible to determine the factors that cause the anisotropy of elastic waves. The most informative parameter of the anisotropy of soils, which are the basis of hydraulic structures,was established. The main indicators of the manifestation of azimuthal anisotropy of bulk elastic waves were determined. The study of samples of soil bases of hydraulic structures when using the invariant-polarization method made it possible to experimentally establish the type of anisotropy and determine the value of the coefficient of elastic anisotropy of the studied samples. The angle of deviation of the elastic displacement vector from the direction of the wave normal, exceeding 90°, is a sign of possible destruction of the soil base of a hydraulic structure and enables us to localize zones of limit equilibrium.*

A study of sandstone samples was carried out when using atomic force microscopy to investigate the degree of change in the microstructure of the soil bases of hydraulic structures. The use of the acoustic emission method allowed us to obtain an image of the acoustic response during laser irradiation, which made it possible to evaluate the diffraction pattern of the studied sandstone samples. It was established that a characteristic feature of the acoustic emission spectrum of the studied samples of soil bases of hydraulic structures is the presence of numerous secondary maxima. Their occurrence indicates the complexity of the material composition and structure of soil bases, in particular, a specific combination of allotigenic and authigenic minerals, cementing substances and textural features. In the case of irreversible deformations, the influence of fluid saturation manifests itself through differential-elastic effects, caused by both the crystal structure and the nature of interphase bonds, as well as the temperature, pressure and other parameters of the soil base environment of hydraulic structures.

Keywords*: hydraulic structures, stability, soil base, acoustic emission, anisotropy*

Relevance of the research. Hydraulic structures are the structures subject to the water environment, designed for the use and protection of water resources, as well as for protection against the harmful effects of water [1]. The system “structure – soil base” can be represented as three sequentially connected elements: soil base, foundation and above-ground structure. When assessing the stability of a structure, the load transfer scheme is of direct practical importance, which depends on the structure design, the magnitude of the load on the column or on 1 m^2 of the foundation. And if the loads from the structure and equipment are more or less constant, then the structure itself changes over time: there is a gradual and irreversible change in the properties of building materials as a result of aging, corrosion, etc. [2]. The defining parameters of the foundation are its type (rigid, flexible), geometric dimensions, shape, and material strength [3]. During the operation of the structure, the foundation material changes the most as a result of fluctuations in temperature and moisture conditions under the influence of aggressive industrial effluents, etc. [4].

Analysis of recent research and publications. The most hidden and uncontrolled changes in the process of construction and operation of structures occur with the soil bases. When assessing the stability of structures, processes that lead to the deterioration of soil properties, a decrease in strength and an increase in deformability, which in turn leads to an increase in absolute and relative deformations, and sometimes to the destruction of soil bases and structures, are of great importance. Soils, depending on the type, physical state and structural strength, have different abilities for deformation developing. Numerous experimental studies show that under certain loads, when the stage of displacements begins, a compacted core is formed under the foundation in the shape of a wedge. The core is the foundation across the entire width, and the sides are formed by slip curves that pass along the edges of the foundation [5–7].

The stability of the structure depends on the type, size and depth of the foundation, as well as on the intensity of the load application. An increase in the size of the foundations and their depth leads to a decrease in the probability of bulging of the soil base and an increase in the stability of the structure. A rapid increase in additional pressure from the structure leads to a decrease in the magnitude of the destructive load, a slow increase in pressure – to the increase in destructive load. Uniform settlement of the entire structure does not cause additional stresses in the structures, but the difference in settlements of individual parts of the soil base especially affects the strength of foundations and above foundation buildings. Experience shows that the difference in settlements increases with an increase in the magnitude of absolute settlements. Deformations depend both on changes in volume (as a result of compaction, swelling, etc.) and on the deformation of individual phases that make up the soils (creep of the skeleton, compression of pore water, as well as inclusions of vapors and gases) [8–10].

Under the action of tangential stresses, local failure zones appear in the soil base, which, when the pressure from the structure increases, increase in size and form a sliding surface. The zones of limiting equilibrium of soil bases are the areas of the soil massif that are on the verge of destruction under the action of loads or other influences. Their dependence is determined by a combination of soil properties (its strength and deformability), load characteristics (magnitude, distribution) and geometric parameters of the structure resting on the soil. The determination of these zones is key to ensuring the stability of structures and preventing settlements and destractions. The limit states of the soil base manifest themselves in these zones. The information on the sizes of the zones of limiting equilibrium, where there is destruction of the soil base, allows:

– to assess the possibility of applying the theory of linearly deformed medium to calculate the stability of the structure's foundation;

– to calculate the stability of the soil base and determine real ways to increase it.

When calculating the sizes of the zones of limit equilibrium (plastic deformations), it is first necessary to determine the depth of their development by comparing the maximum angles of deviation θ_{max} with the angles of internal friction φ, which vary within the soil base.

The boundaries of the zone of limit equilibrium can be traced based on the following dependencies:

– when $\varphi > \theta_{max}$ ($\tau_\alpha > \tau_{\theta max}$) – limit equilibrium is not observed;

– when $\varphi = \theta_{max}$ ($\tau_\alpha = \tau_{\theta max}$) – limit equilibrium is observed;

– when $\varphi < \theta_{max}$ ($\tau_\alpha < \tau_{\theta max}$) – soil destruction is observed [11–13].

The angle of internal friction of soil base φ is an angle that characterizes the resistance of the soil to shear, which arises from the interaction between its particles. This parameter is key for engineering and geological calculations of foundations, as it determines the stability of the soil massif and its ability to withstand loads.

1. Types of deformations and causes of their occurrence [5]

Types of deformations	Causes of deformation
Elastic deformations: – change in volume	Change in molecular forces of elasticity of solid particles, as well as thin films of water
– distortion of shape	Change in molecular forces of elasticity, change in structural lattice
Inelastic, residual deformations: – compaction	Reduction in porosity
– swelling	Wedging effect as a result of electro-molecular forces
– creep	Mutual displacement of soil particles
– only residual	Destruction of structure, destruction of particles

An important factor, the effect of which must be taken into account, is the difference in the mechanical soil properties in different directions, or the so-called mechanical anisotropy (for example, deformation anisotropy, strength anisotropy, swelling anisotropy), and sometimes the difference in filtration properties, or filtration anisotropy. The anisotropy of the mechanical properties of soils is explained by their ordered structure with a preferential parallel orientation of particles in a certain direction [14–16].

The purpose of the study is to test the use of the invariant-polarization method, atomic force microscopy and the acoustic emission method for assessing the stability of hydraulic structures, given the anisotropy of the stress-strain state of their soil bases by conducting experimental studies and subsequent analytical calculations.

Materials and methods of the study. Field and laboratory experimental studies on the elastic properties of the studied samples of soil bases of hydraulic structures were carried out using the invariant-polarization method, atomic force microscopy and the acoustic emission method [17–19]. The Hydrustab software and algorithmic complex developed by the author was used to process the results of experimental studies of samples of soil bases of hydraulic structures and to further construct stereo projections and diagrams.

Research results and their discussion. Experimental studies of the soil base using ultrasonic methods show that the anisotropy of elastic waves is due to the crystallographic orientation of minerals, the grain shape of oriented minerals and the location of microcracks. Depending on the nature of the orientation of the structural texture elements, soils are divided into three types: unidirectional, multidirectional within one plane and spatially oriented. The key indicator of anisotropy is the differential coefficient of elastic anisotropy, the value of which reflects the degree of deviation of the soil texture from the closest isotropic medium. Thanks to this coefficient, it is possible to compare the anisotropic properties of elastic media of different symmetry. In particular, the coefficient of transversely isotropic elastic anisotropy makes it possible to assess the degree of deviation of textures of rhombic symmetry from the elastic characteristics of a transversely isotropic medium.

The characteristic surfaces of the anisotropy parameters are constructed in the form of stereographic projections of isolines, which gives a complete idea of the spatial variability of the anisotropy parameters of bulk elastic waves and reflects the influence of the symmetry of the medium. Strict restrictions are imposed on the azimuthal dependence of the differential parameters, due to the anisotropy of the soil medium. The azimuthal anisotropy of bulk elastic waves manifests itself in the following forms [20–22]:

1) difference between the phase and radial velocities of elastic waves;

2) deviation of the elastic displacement vectors and radial velocity vectors from the direction of the wave normal;

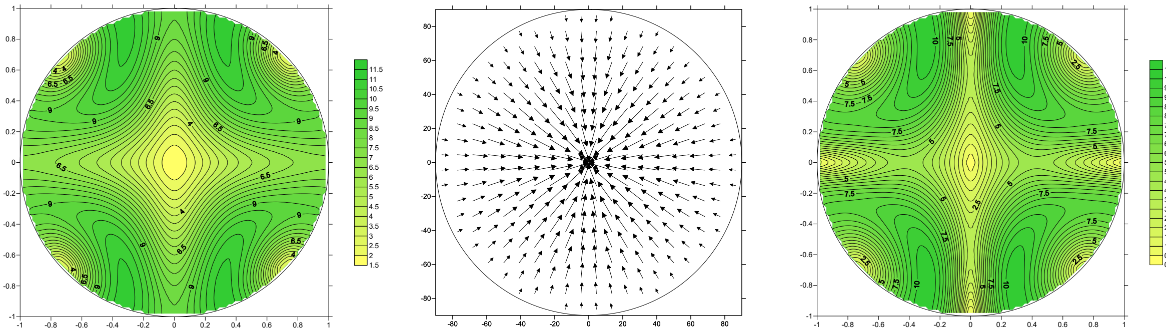
3) the presence of polarization effects, phenomena of acoustic birefringence, acoustic refraction and singular behavior of the elastic displacement vectors in the zone of the acoustic axes.

The use of stereographic projections made it possible to reflect the nature of the anisotropy of elastic waves in full, and not only in intersections selected when using coordinate planes. Fig. 1(a) shows a stereoprojection of the differential coefficient of elastic anisotropy A_d of sandstone sample № 1 of the studied soil bases, which were selected in the area of the Kyiv HPP dam. In the wave theory for transverse waves in an elastic medium the vector of elastic displacements (polarization) is always perpendicular to the wave vector (normal to the wave front), but in a "pure" homogeneous medium, this vector lies strictly in the orthogonal direction, without deviations.

But in cases of anisotropy of the medium, boundary conditions (reflection, refraction at the boundary of the media) and diffraction at obstacles a deviation angle may appear between the direction of the wave normal and the actual direction of the elastic displacement vector.

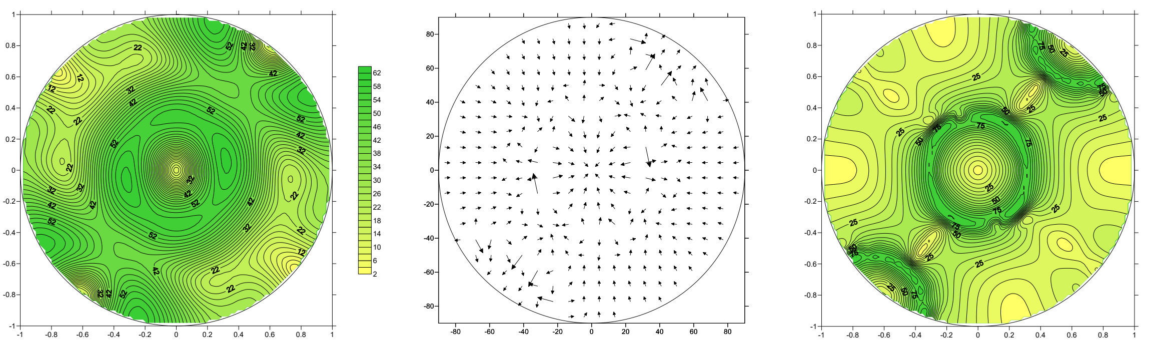
And this deviation that is an indicator of wave effects associated with diffraction and diffusion, which is a manifestation of non-orthogonal polarization or "mixed wave" (especially in anisotropic media) [23–25]. Fig. 1(b) shows a diagram of the distribution of polarization vectors of the "slow" quasi-transverse wave of sandstone sample № 1 of the studied soil bases. Based on the data obtained when constructing these stereo projections and diagrams, a stereo projection of the deviation angle of the elastic displacement vector from the direction of the wave normal $\left(\vec{U},\vec{n}\right)$ of sandstone sample № 1 of the studied soil bases was constructed, which is shown in Fig. 1(c).

The value of the elastic anisotropy coefficient varies from 0,48 % to 11,23 %. A particularly important factor determining the value of the elastic anisotropy coefficient is the spatial coincidence of the orientations of structural elements, primarily the crystallographic orientation, the orientation of sandstone grains by shape and the directions of microcrack development. The deviation of the elastic displacement vector from the direction of the wave normal varies from 0,44° to 10,63°. Fig. 2(a) shows a stereo projection of the differential elastic anisotropy coefficient A_d of sandstone sample № 2 of the studied soil bases. Fig. 2(b) shows a diagram of the distribution of polarization vectors of the "slow" quasi-transverse wave of sandstone sample № 2 of the studied soil bases.



a b c

Fig. 1. Sandstone sample № 1:
a – stereo projection of epy isolines of the differential elastic anisotropy coefficient A_d (isolines – in %);
b – diagram of the distribution of polarization vectors of a "slow" quasi-transverse wave;
c – stereo projection of the deviation angle of the elastic displacement vector from the direction of the wave normal $\left(\vec{U},\vec{n}\right)$ (isolines – in degrees)



a b c

Fig. 2. Sandstone sample № 2:
a – stereo projection of isolines of a differential elastic anisotropy coefficient A_d (isolines – in %);
b – diagram of the distribution of polarization vectors of a "slow" quasi-transverse wave;
c – stereo projection of a of deviation angle of the elastic displacement vector from the direction of the wave normal $\left(\vec{U},\vec{n}\right)$ (isolines are in degrees)

Based on the data obtained when constructing these stereo projections and diagram, a stereo projection of the deviation angle of the elastic displacement vector from the direction of the wave normal $\left(\vec{U},\vec{n}\right)$ of the sandstone sample № 2 of the studied soil bases was constructed, which is shown in Fig. 2(c). The value of the elastic anisotropy coefficient varies from 1,67 % to 62,73 %. The value of the deviation of the elastic displacement vector from the direction of the wave normal varies from 0.47° to 95,46°.

Elastic anisotropy reflects the deformation history of the soils of the foundations of hydraulic structures. In the studied samples of deformed soils, a pronounced ordering of their internal structure is observed, which causes an even more intense manifestation of the anisotropy of elastic waves. Anisotropy and structural ordering of soils constitute interrelated fundamental properties that reflect the mechanisms of deformation formation and subsequent transformations. Thus, the stereo projections and diagrams obtained for the studied sandstone samples allowed us to quantitatively assess the influence of the anisotropy of the stress-strain state of the soil bases of hydraulic structures on the stability of these structures, and also demonstrate a direct relationship between the zones of limiting equilibrium and the angle of deviation of the elastic displacement vector from the direction of the wave normal $\left(\vec{U},\vec{n}\right)$. The obtained research results for soil samples that were not under the compaction pressure of the main part of the hydraulic structure confirm the efficiency of applying the methods used for studying the soil bases of hydraulic structures of various types.

In order to study the degree of change in the microstructure of a soil base sample of hydraulic structures caused by elastic deformations (in particular, shape distortion), a study of sandstone samples was carried out when using atomic force microscopy. The elastic E and inelastic characteristics of soil bases significantly depend on the morphology of the near-surface layer. It is due to the development of flattened-lenticular layering and schistosity, the orientation of hinges and axial planes of linear folds, as well as the corresponding orientations of minerals both in their shape and internal structure. Using atomic force microscopy, 2D and 3D images of the surface of a sandstone in the (100) orientation plane obtained were obtained, which is shown in Fig. 3.

Fig. 4 (right) shows an image of the acoustic response that occurred during laser irradiation, which was accompanied by the formation of inhomogeneous thermomechanical stresses with the formation of a melt crater and the ejection of molten material onto the sample surface. The depth of the melt crater Δh, under conditions of constant power and duration of laser action, is determined by thermal conductivity (in particular, local) and a "quasi-equilibrium" spatial distribution of temperature gradients ΔT both in the direction perpendicular to the crater axis and along it. In our experiments, its value was about $h \approx 500$ µm. The complex structure of the recorded acoustic response indicates the action of several mechanisms for the transformation of localized thermal disturbance into mechanical stress waves (acoustic waves), which appear simultaneously or sequentially in time.

Comparison of the acoustic response in Fig. 4 (left) with the duration of the laser pulse and the geometric parameters of the sample indicates the probability of the second and third time maxima (pulses aligned in the time) occurring due to the acoustic emission mechanism (AE), since the time delays of their appearance and the length of the final pulse cannot be explained only within the photothermoelastic mechanism. An important task is to correctly determine the possible AE mechanisms accompanying the processes described above. The sequence of their manifestation in time can be presented as follows:

1. AE occurrence during the melting of the sandstone surface (phase transition- solid phase → liquid phase);

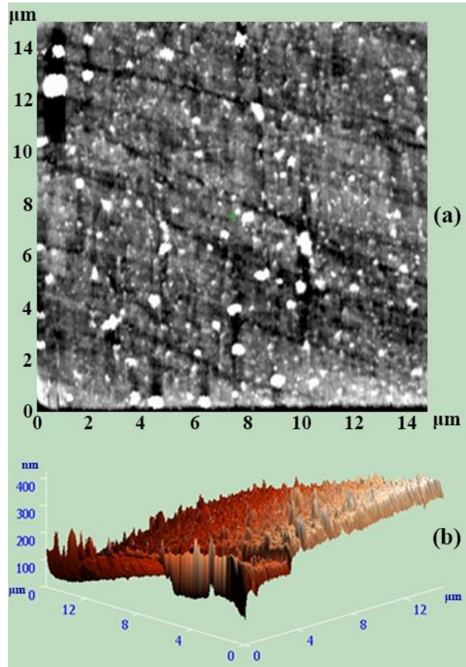


Fig. 3. Image of the microstructure of a sandstone sample in the (100) orientation plane obtained when using atomic force microscopy: (a) 2D image of the microstructure and (b) 3D image of the microstructure

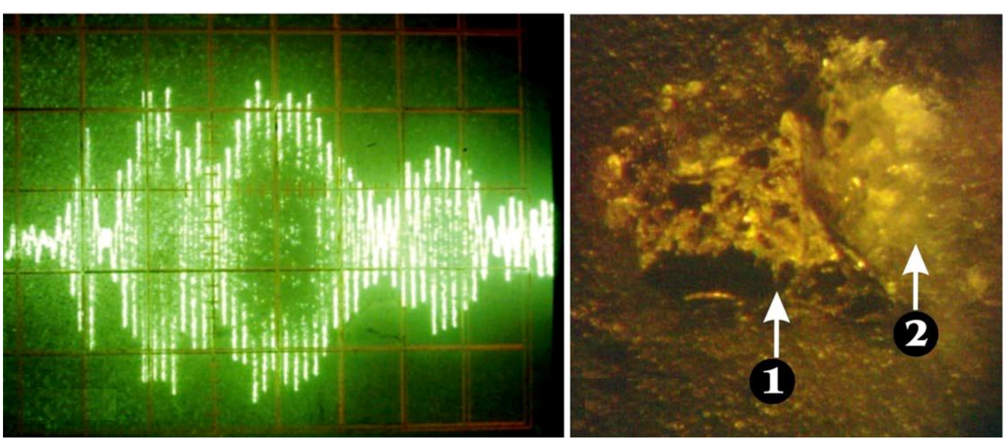


Fig. 4. Recorded AE signal response (irradiation of biotite 50 mV/div, 10 µs/div) (left); typical melting craters after irradiation of biotite grain with the appearance of microcracks (1) and quartz grain (2) with intensity $I \approx 200$ MW/cm^2 (×98) (right)

2. AE during the crystallization of the melt (phase transition – liquid phase → solid phase);

3. AE caused by crack formation.

Transition processes such as solid phase → gas and gas → solid phase can be ignored because they occur during a relatively "long" (nanosecond) laser pulse. Under the conditions of the experiments, phase transitions occur extremely quickly – for the time commensurate with the duration of the laser action ($\tau \approx 18$ нс). It is likely that it is crack formation that is the main source of the formation of the "acoustoemission component" of the acoustic response. Consideration of AE as two types of emission – discrete (high-energy) and continuous (low-energy) loses relevance in cases where the time of individual AE acts (τ) exceed the time of wave transmission through the sample t, i.e. $\tau > t$, and the lengths of wave trains λ exceed the typical dimensions of the base sample L, i.e. $\lambda > L$ [26–28].

The AE spectrum of fine-grained sandstones – cemented soils with granular porosity is characterized by the presence of numerous secondary maxima. Their appearance reflects both the diversity of the material composition and structural features of the soil base, including the combination of allotygenic and authigenic minerals, cement composition and specific texture, and to a certain extent reproduces the course of dia- and catagenetic processes. The soil bases, where the samples were taken, underwent mechanical deformations of varying intensity, which led to the formation of characteristic structural and textural features.

Under conditions of different tension or compression, massive textures arose, where high amplitudes of the main (primary) peaks were recorded in the AE spectra along with increased oscillations. In contrast, samples with directive structures generally showed lower averaged AE signal amplitudes, which is most pronounced in fine-grained varieties of sandstones. Another characteristic feature of samples with directive textures (soils formed in non-equilibrium deformation fields) is the dominance of AE spectra with inhomogeneous, stretched curves containing several signal trains.

Conclusions. The anisotropy of the studied soils is determined by their textural characteristics and the orderliness of the structural-morphological paragenesis, which is manifested in striation and linearity. An additional factor is the ordered system of microcracks formed as a result of the current state of the soil massif. The value of the deviation angles of the elastic displacement vector from the direction of the wave normal > 90° is an indicator of potential destruction in the soil base of the hydraulic structure and allows us to determine the zones of limit equilibrium.

The analysis of the acoustic emission signal allowed us to evaluate the diffraction pattern of the studied sandstone samples. In particular, the measured amplitude of the acoustic emission signal allowed us to quantitatively assess the intensity of polarization effects, phenomena of acoustic birefringence, acoustic refraction and singular behavior of elastic displacement vectors in the area of the acoustic axes of the studied soil base samples.

The conducted experimental studies and analytical calculations allowed us to test the use of the invariant and polarization method, atomic force microscopy and the acoustic emission method for assessing the stability of hydraulic structures given the anisotropy of the stress-strain state of their soil bases using the example of sandstones.

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

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

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ДЕЯКІ ОСОБЛИВОСТІ ОЦІНЮВАННЯ СТІЙКОСТІ ГІДРОТЕХНІЧНИХ СПОРУД З ВРАХУВАННЯМ АНІЗОТРОПІЇ НАПРУЖЕНО-ДЕФОРМОВАНОГО СТАНУ ЇХ ҐРУНТОВИХ ОСНОВ

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Анотація. *Проведено аналіз процесів, що спричиняють деградацію властивостей ґрунтів, зниження їх міцності та підвищення деформативності. Розв'язання задачі визначення фазових швидкостей і векторів пружних зміщень дало змогу встановити диференціальний коефіцієнт пружної анізотропії ґрунтів, які формують основу гідротехнічних споруд. Проведені експериментальні дослідження ґрунтів основи гідротехнічних споруд ультразвуковими методами дозволили визначити фактори, що обумовлюють анізотропію пружних хвиль. Встановлено найбільш інформативний параметр анізотропії ґрунтів основи гідротехнічних споруд. Визначено основні показники прояву азимутальної анізотропії об'ємних пружних хвиль. Дослідження зразків ґрунтових основ гідротехнічних споруд за допомогою інваріантно-поляризаційного методу дозволило експериментально встановити тип анізотропії та визначити величину коефіцієнта пружної анізотропії досліджуваних зразків. Кут відхилення вектора пружних зміщень від напрямку хвильової нормалі, що перевищує 90°, слугує ознакою можливого руйнування ґрунтової основи гідротехнічної споруди та дає змогу локалізувати зони граничної рівноваги. Проведено дослідження зразків пісковиків із застосуванням атомної силової мікроскопії з метою дослідження ступеня зміни мікроструктури ґрунтових основ гідротехнічних споруд. Застосування методу акустичної емісії дозволило отримати зображення акустичного відгуку при лазерному опроміненні, що надало змогу оцінити дифракційну картину досліджуваних зразків пісковиків. Встановлено, що характерною особливістю спектру акустичної емісії досліджуваних зразків ґрунтів основи гідротехнічних споруд є наявність численних вторинних максимумів. Їх виникнення свідчить про складність речовинного складу та структури ґрунтової основи, зокрема про специфічне поєднання аллотигенних і аутигенних мінералів, цементуючих речовин і текстурних особливостей. У випадку незворотних деформацій вплив флюїдонасичення проявляється через диференціально-пружні ефекти, зумовлені як кристалічною структурою і природою міжфазових зв'язків, так і температурними, тисковими та іншими параметрами середовища ґрунтової основи гідротехнічних споруд.*

Ключові слова: *гідротехнічні споруди, стійкість, ґрунтова основа, акустична емісія, анізотропія*

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INFLUENCE OF IRRIGATION ON APHID INFESTATION IN MAIZE

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Abstract. *Maize (Zea mays L.) is a crucial crop for both Ukraine and the global agricultural sector, serving as a key staple and export commodity. Ukraine ranks among the top ten maize producers worldwide, with annual production reaching 27–35 million tons and exports of 20–25 million tons. Irrigation significantly enhances maize yield, potentially increasing productivity from 6.8–7.0 tons per hectare to 12–15 tons per hectare. Given the importance of maize for food security, economic stability, and international trade, understanding factors that influence its productivity is essential. One of the major challenges in the Steppe, Forest-Steppe, and Polissia regions of Ukraine is the irregular water regime, which limits the full utilization of soil potential. Effective irrigation management not only improves water use efficiency and soil health but also promotes the proliferation of beneficial organisms, contributing to increased crop resilience.*

This study, conducted from 2020 to 2023 in the Kyiv region, investigated the development and population dynamics of aphids (Aphididae spp.) on irrigated and non-irrigated maize, alongside the role of natural predators in regulating aphid abundance. Experimental plots of 50 m² were established using a randomized design with four replications. The maize hybrid P9074 (FAO 330) was grown under controlled irrigation with water-jet sprinklers, while control plots relied on natural precipitation. Meteorological data, including air temperature, precipitation, and the Selyaninov hydrothermal coefficient (SHC), were recorded to assess their impact on aphid population density.

Results indicated that aphid infestation was higher on irrigated plots, particularly during the tassel emergence and flowering stages. Average infestation in irrigated areas reached 47.8 % during maize ripening, compared to 42.8 % in non-irrigated fields. A moderate negative correlation was found between precipitation and aphid infestation (r = -0.34), while a weak positive correlation existed with air temperature (r = 0.19). Irrigation was found to modify the microclimate significantly, reducing air temperature by 2.4–6.1 °C and increasing humidity to 78–100 %, depending on timing and water volume, with nocturnal irrigation producing the most gradual changes.

In addition, irrigation enhanced the abundance of natural aphid predators. Populations of Coccinellidae and Chrysopidae were 2.2 and 1.7 times higher, respectively, in irrigated fields compared to non-irrigated plots. Key predator species, including Chrysopa carnea Steph., played a critical role in controlling aphid populations, demonstrating that irrigation can indirectly support biocontrol mechanisms.

Overall, the study highlights that irrigation not only increases maize productivity but also influences aphid population dynamics and predator activity. These findings emphasise the importance of integrated water and pest management strategies to optimise crop yields and strengthen the ecological resilience of maize agroecosystems in Ukraine.

Keywords*: aphid, irrigation, maize, agrocenosis, predator*

Relevance of the research. Maize is a staple foodstuff which has been cultivated for thousands of years, and it is also very important crop for Ukraine. Country is one of the top 10 global producers and is a leader in exports. It produces 27–35 million tons annually and exports 20–25 million tons [1]. The estimated yield is from 6.8 to 7 tons per hectare with drip irrigation it can be from 12 to 15 tons per hectare [2]. This highlights its importance for domestic food security, the national economy, and global grain markets [3].

The impact of stress on maize production is a matter of significant concern, with the potential for deleterious consequences on food security. The predominant constraint on maize productivity in the Steppe and Forest-Steppe regions of Ukraine, and more recently in the Polissia region, is the unfavourable water regime of the soil, which hinders the realisation of the agricultural potential of these territories [4]. The implementation of irrigation enhances soil health through optimised water utilisation, mitigated erosion, and facilitated proliferation of beneficial microbes and thereby promoting increased crop yields [5].

Analysis of recent research and publications. Gebretsadik K.G. et al. [6] have stated that aphids are considered to be highly destructive agricultural pests, characterised by complex life cycles and phenotypic variability, facilitating their adaptation to diverse climates and host plants.

A study undertaken by Mahmoud H. et al. [7] established that aphids appeared at the middle of July and reached their highest number in the III decade of August – I decade of September, when the maize plants were at ripening stage. From the second week of September, the number of aphids started to go down.

For most species of aphids, the optimal temperature for development is in the range of 20–25 °C, while a temperature close to 30 °C is lethal [8]. Kuroli G. and Lantos Z. [9] recorded changes in the number of aphids and where they were located on maize crops from July to late October. Based on the results of 20 years, 52.3 % of the change in the number of maize-colonizing aphids is explained by the temperature, precipitation and relative humidity, as seen from the determination coefficient.

As demonstrated by Sana B. et al. [10], biotic factors, including but not limited to crowding, host plant quality, natural enemies (e.g., ladybirds, lacewings) have been shown to influence aphid survival and behaviour. It is noteworthy that natural predators of aphids exhibit reduced effectiveness in areas characterised by diminished biodiversity and augmented agricultural intensification [6].

It is imperative to implement meticulous irrigation management techniques to ensure a balanced equilibrium between plant health and pest control. Also, timely pest and disease control is crucial for maize, which is vulnerable to numerous insect pests affecting both aboveground and underground plant parts [11].

Corn leaf aphid (CLA; Rhopalosiphum maidis) is an economically important pest of maize and several other monocot crops [12, 13]. In addition to crop damage, CLA acts as a vector for viruses that cause devastating diseases in maize.

The present study aimed to investigate the effect of biotic and abiotic factors on the most important insect pests of maize. Consequently, constant monitoring of aphid population density in maize crops will allow us to study the impact of irrigation on the characteristics of aphid colonization of crops. The study of the formation of the species composition of aphids and their density in irrigated conditions in order to clarify the timing of protective measures on corn crops is relevant.

Material and methods. The study was carried out from 2020 to 2023 in Kyiv region, Ukraine (50.289959° N and 31.157489° E). The characteristics of aphid colonies under various management conditions of maize hybrid P9074 (FAO 330) cultivated were examined. The variant of the experiment involved studying the number of aphids present under irrigation conditions (control of the variant – natural moistening of the area). The experimental plots were of a size of 50 m², with dimensions of 10.4 m × 4.8 m. The experiment was conducted using a randomised design with four replications.

The irrigation of the plots was facilitated by a watering system comprising a water-jet rain gun. The sprinkler head, in consideration, has a water spray radius of 20–35 m and adjustable water jet pressure. The provision of water to the site was enabled by the implementation of a motor pump, which was connected to a fire hose. Water was collected from a network of water-filled canals situated in close proximity to the experimental plots. Irrigation was carried out by sprinkling in the morning, afternoon, and night hours at different watering rates from June to July.

The climatic characteristic of the research area is the presence of substantial heat and variable moisture levels [14]. The lowest average monthly temperature recorded in January was −8.7 °C, while the highest was −3.2 °C.

The lowest average monthly temperature recorded in July was 14.0 °C, while the highest was 25.4 °C. During the period of vegetation growth, the total precipitation was 429 mm, with 225 mm occurring during the summer months. The mean annual relative air humidity is 76 %, with a range of 64 to 88 % per month.

The Chernozem, which has undergone podsolisation and developed on a layer of loess rock, characterises the soil of the experimental plots. The proportion of physical clay in the layer of 0–25 cm is 27.1 %, in 25–50 cm is 26.2 %, and in 50–100 cm is 24.6 %. The soil organic matter content in the 0–50 cm is 2.35 %. The salinity degree in the plots is not saline, as the salt content does not exceed 0.064 %. The sodium content of a one-metre layer of soil is shown to be less than 0.04 % of the total absorbed cation content, thus indicating that the soil is non-saline.

The Selyaninov hydrothermal coefficient (SHC) was calculated using the formula:

$$\text{SHC} = R \times 10 / \Sigma t, \quad (1)$$

where R – the sum of precipitation in mm over the growing season (April – September) with temperatures above +10 °C;

Σt – the sum of temperatures in degrees Celsius (°C) over the same period.

The aphid colonies were monitored from mid-June, in conjunction with observations of the development of stem butterflies in maize during the phase of maize growth and development, which corresponded to the onset of tassel emergence. Observations were conducted on a daily basis for tassels, stems, leaves, cobs, and cob legs for the presence of aphids until the phase of full ripeness of maize. The onset of plant infestation and subsequent colony formation was observed at a plant infestation level of 10 %, with an aphid population of 150 individuals per 10 plants [15]. The degree of aphid infestation was determined by visual inspection of 100 plants on a 9–point scale.

The surveys were conducted by inspecting 10 crop plants in 10 random locations of the plots under irrigation, as well as non-irrigated. During the observation, two lines on each plot with the configuration of the route are analogous to the letter X were traversed.

The degree of threat to maize plants determined through the coefficient of aphid infestation by the formula:

$$K = a \times b, \quad 100 \ (2)$$

where K – the coefficient of aphid infestation;

a – the proportion of plants infested with aphids;

b – the average score of plant infestation.

Observations of beneficial entomofauna on phytophagous insects in maize fields were conducted daily, encompassing the enumeration of their adult and larval populations in conjunction with the quantification of aphid colonies on maize plants. After the enumeration process, the arithmetic mean of the number of entomophages per 100 aphid colonies was calculated.

The statistical significance of an analysis of variance (ANOVA) was conducted using SPSS 19.0 software.

Results and discussion.

Meteorological conditions during the experiment

In the study area of the Kyiv region, the following aphid species were identified as the primary cause of damage to maize plants: the common cereal aphid (*Schizaphis graminum* Rond.) and the bird cherry aphid (*Rhopalosiphum padi* L.). The number of aphids exhibited a complex and fluctuating dynamic.

A comparison of the weather conditions experienced during the research period in Kyiv region with the proportion of damaged plants indicates that the number of aphid colonies is at its maximum in years characterised by a significant increase in summer air temperatures, provided that there is sufficient moderate moisture,

1. Scale for assessing the degree of maize colonisation by aphids

The 9 score	The degree of colonisation	Occupied by colonies of the leaf surface, % and signs of the pest presence
1	initial	single individuals, <5, leaves without visible changes
2–3	weak	5–25, the presence of reddish-light yellow dots covering up to 5 % of the surface
4–5	average	26–50, pale yellow or reddish spots with purple margins covering 6–30 % of leaf surface
6–7	strong	51–75, the plant has a discoloured sheath, a corrugated and twisted plate of the upper leaf
8–9	very strong	76–100, plant withers, dries up

particularly during the period of intensive plant growth (tassel emergence). The findings of the study by Carena M. and Glogoza Ph. [16] also indicate that climatic conditions have a significant effect on the rate of colony development and the amount of grain yield reduction.

A thorough examination of the meteorological conditions during the study period reveals that the aggregate of active temperatures in 2020 and 2022 exceeded the long-term average by approximately 180 °C, while in 2023, it approached 240 °C. The 2021–2023 growing season was marked by sufficient moisture levels (SHC was 1.23–1.58), in contrast to the 2020 season where the SHC was recorded at 0.78, indicating notably arid conditions during the growing period (Table 2).

The substantial quantity of precipitation, devoid of substantial rainfall, resulted in a considerable proliferation of aphids. Conversely, arid conditions curtailed their population, concomitantly expediting the progression of plants through the phenophases of crop development. Another analysis by Csorba A.B. et al. [17] demonstrates a strong correlation between increases in the population sizes of corn leaf aphids and climate change, thereby indicating a potential link between environmental shifts and the observed increase in the prevalence and distribution of the aforementioned pests.

Features of aphid settlement in different conditions

A comparative analysis was conducted on the infestation levels of maize plants cultivated under irrigated conditions and without irrigation. The results of this analysis revealed that the former group exhibited a significantly higher incidence of aphids compared to the latter. Consequently, during the period spanning from 2020 to 2023, specifically in the phase of tassel emergence and flowering, which transpired in late June and early July, the pest infestation on irrigated crops exhibited an average prevalence of 25.0 %, accompanied by an average infestation score of 1.48. Concurrently, the infestation rate was recorded at 0.38. In the plots without irrigation, the average population of plant pests in the tassel emergence-flowering phase of maize was 18.0 %, with an average population score of 1.38. The population coefficient was 0.26 (Table 3).

Thereafter, an increase in the population density of cereal aphids in maize was observed. A study conducted during the waxy ripeness phase of maize revealed that the aphid population of crop plants in irrigated areas exhibited an average of 47.8 %, with an average population score of 2.78. Concurrently, the population coefficient 1.35 was determined. In contrast, on maize without irrigation, the pest infestation of plants averaged 42.8 %, with an average infestation score of 2.75, and an infestation rate of 1.2.

The effect of temperature and humidity on aphid reproduction

The substantial presence of pests on maize under irrigation can be attributed to the creation of optimal conditions for the reproduction of the phytophage, particularly concerning air

2. Meteorological conditions of the growing season

Indicator (average)	2020	2021	2022	2023	Long-term
Sum of active temperature (SAT) of IV–IX months, °C	3005.1	2833.1	3007.1	3063.6	2825.0
Sum of effective temperature, (>10°C) (SET) of IV–IX months, °C	1415.1	1363.1	1257.7	1463.6	1300.0
Sum of precipitation for IV–IX months, mm	235.4	371.8	476.6	375.4	343.0
SHC	0.78	1.31	1.58	1.23	1.21

3. Colonisation of maize plants by aphids

Year	Populated plants, %	score	Irrigation coefficient of colonisation	Populated plants, %	Score	Non-irrigation coefficient of colonisation
tassel emergence-flowering phase						
2020	27.0	1.4	0.38	18.0	1.4	0.25
2021	20.0	1.4	0.28	12.0	1.2	0.14
2022	31.0	1.8	0.56	25.0	1.7	0.43
2023	22.0	1.3	0.29	17.0	1.2	0.20
waxy grain ripeness						
2020	60,	3.0	1.80	51.0	3.0	1.53
2021	38.0	2.6	0.99	32.0	2.5	0.80
2022	54.0	3.0	1.62	52.0	3.0	1.56
2023	39.0	2.5	0.98	36.0	2.5	0.90

temperature and humidity, as well as the plant's condition. As Tali M.K. et al. [18] noted, the mean aphid population exhibited a significant positive correlation with mean atmospheric temperature. Also, the pivotal role of relative air humidity in the proliferation and reproduction of aphids on maize. Favourable conditions for the intensive reproduction of these phytophages on plants are created when a percentage exceeding 60 % [19].

Concurrently, it is imperative to acknowledge that the irrigation of maize engenders pronounced fluctuations in air temperature and relative humidity. These fluctuations exert a deleterious effect on the reproduction and development of numerous species of aphids. The study in Kyiv region of the watering rate on changes in the microclimate of the experimental plot indicates that the minimum rate of 2 m^3 per hectare does not affect changes in air temperature. However, the rate of two times has been shown to lead to a short-term decrease in air temperature (1 hour) by 0.9 °C and an increase in air humidity by 17.0 %. Based on irrigation data, including time of day and irrigation water discharge rate, as well as weather data, an analysis of the impact of irrigation on changes in microclimate in maize was conducted.

Irrigation in the morning hours

The irrigation at a rate of 50 m^3/ha in the morning (8–12 a.m.), the air temperature decreased by 2.4 °C from 16.7 °C to 14.3 °C, and the air humidity increased by 51.9 % from 48.0 % to 99.9 %. Over the next 3 hours, the air temperature increased by 5.7 °C from 14.3 °C to 20.0 °C, and the air humidity increased by 48 % from 99.9 % to 51.9 %.

The norm of irrigation of 110 m^3/ha in period 10–11 a.m. the average air temperature increased from 17.2 °C to 21.6 °C, and the air humidity decreased from 52.0 % to 36.5 %.

Consequently, the implementation of irrigation during the morning hours, contingent on the output rate, results in a short-term decline in temperature and an augmentation in air humidity. After the cessation of irrigation, an augmentation in temperature and a diminution in air humidity to reference values for days without irrigation were observed over the ensuing hours.

Irrigation during the day.

At a rate of 100 m^3/ha from 1–3 p.m. the average air temperature decreased from 27.8 °C to 25.1 °C, the air humidity increased from 63.4 % to 67.4 %, and over the next 2 hours it dropped to 58.4 %.

An 8-hour irrigation cycle with an irrigation rate of 252 m^3/ha conducted in the morning and afternoon resulted in a decline in air temperature from 17.2 °C to 16.1 °C, accompanied by an augmentation in air humidity from 84.4 % to 99.9 %. Over the subsequent five-hour period, the air temperature increased from 16.1 °C to 20.8 °C, while the air humidity gradually decreased from 99.9 % to 73.2 %.

The irrigation at a rate of 450 m^3/ha from 11 a.m. to 1 p.m. resulted in a decline in air temperature of 6.1 °C and an increase in air humidity of 35.5 %. Subsequent to the cessation of watering, a rise in air temperature from 23.3 °C to 33.6 °C was observed, accompanied by a precipitous decline in air humidity from 80.8 % to 30.1 %.

The watering with rate of 150 m^3/ha in the afternoon (3–6 p.m.) the air temperature decreased by 4.5 °C in the first hour from 31.8 °C to 27.3 °C, and by 16.3 °C in the next three hours. At the same time, air humidity increased by 64.3 % from 33.8 % to 98.1 %. Two hours after the end of irrigation cycle, the air temperature increased by 2.0 °C from 16.3 °C to 18.3 °C, and the air humidity decreased by 24.6 % from 98.1 % to 73.5 %.

Therefore, during periods of high air temperatures (29.3 C – 33.6 C), the short-term irrigation with high rate of irrigation results in immediate, though transient, alterations to the microclimate of the agrocenosis. This option has a detrimental effect on the number of maize phytophages, especially aphids. The population of these insects can be significantly reduced through the process of defoliation, whereby the maize leaves are removed.

Irrigation at night hours.

During 4 hours of sprinkling with 30 m^3/ha at night (11 p.m – 1 a.m.) the air temperature decreased by 6.5 °C from 23.7 °C to 17.2 °C, the air humidity increased by 53.3 % to 99.9 % and remained at this level for 10 hours after the start of irrigation.

The irrigation with rate of 300 m^3/ha in period of 6–9 p.m. the average air temperature decreased by 5.4 °C from 22.8 °C to 17.4 °C, the air humidity increased from 89.9 % to 99.9 %, remaining at the same level for the next 9 hours.

The irrigation of 150 m^3/ha over 8 hours at night (8 p.m. – 3 a.m.) resulted in a decrease in air temperature by 3.9 °C and an increase in air humidity by 24.7 % from 75.2 % to 99.9 %. After 7 hours, the air temperature increased by 4.4 °C, and the air humidity decreased by 25.8 % from 99.9 % to 74.2 %. The rate of irrigation of 150m^3/ha was poured from 11–12 p.m. based on this the average air temperature decreased by 0.9 °C from 17.3 °C to 16.4 °C, and the air humidity increased from 88.3 % to 99.8 %, remaining at the same level for the next 9 hours.

At an irrigation rate of 300 m^3/ha with irrigating from 1 to 4 a.m. the average air temperature decreased by 4.5 °C from 22.8 °C to 18.3 °C, the air humidity increased from 87.1 % to 99.9 %, remaining at the same level for the next 9 hours.

It was determined that the irrigation during the evening and night-time, even under lower rate of irrigation, can result in a substantial increase in air humidity, reaching a level of 99.9 % over an extended period. The air temperature in maize agrocenoses after irrigation decreased by an average of 4.3 °C (0.9 °C –6.5 °C).

Furthermore, an investigation into the impact of weather conditions, specifically air temperature and precipitation, during the period of June to September, revealed an inverse proportional relationship between precipitation and the coefficient of aphid infestation of maize plants (r = -0.34) and a weak direct relationship between air temperature and the coefficient of aphid infestation of maize plants (r = 0.19) (Table 4).

Irrigation effects on aphids and predators in maize.

It was observed that the incidence of aphids on maize occurred at approximately the same time during the research period. The winged settlers were first observed on the plants in early June. The presence of phytophage colonies was identified in the initial and subsequent decades of July, with a marked increase in the number of pests during the late July to mid-August period.

During the last decade of August and the first decade of September, elevated air temperatures induced accelerated maturation of the cobs and consequent release of moisture to the maize, thereby resulting in the occurrence of black layer on the maize kernel. As previously stated, the appearance of a black spot on the base of the kernel is indicative of the plant's inability to receive nutrients from the plant, thus leading to the death of the plant itself. Concurrently, the leaves of the crop rapidly desiccated from the base to the apex. Aphid colonies were relocated to the upper green leaves of maize in order to continue feeding on them. The presence of a black layer on the maize kernel in late August suggests that the crop yield is no longer affected by aphids.

The irrigation in maize cultivation has been demonstrated to result in a substantial augmentation in the abundance and ecological significance of entomophages, concurrently enhancing the resistance and compensatory capacity of the plants themselves. It was determined that this action serves to mitigate the adverse effects of aphid infestation. The study revealed that representatives of the order Coleoptera, specifically the seven-point ladybird (*Coccinella septempunctata* L.), the variable ladybird (*Hippodamia (Adonia*) *variegata* Gz.) and the five-point ladybird (*Coccinella quinquepunctata* L.), exhibited remarkable efficacy in the regulation of aphids at all stages of their development. During the period of tassel emergence, a greater number of entomophagous insects was found under irrigation conditions. The mean number of representatives of Coccinellidae averaged 40.8–89.6 individuals per 100 aphid colonies, which was 2.2 times higher than in conditions without irrigation (Figure 1).

The presence of the fourteen-spotted ladybird (*Calvia quatuordecimguttata* L.), the fourteen-spotted propylea (*Propylea quatuordecimpunctata* L.), the Asian harmony (*Harmonia axyridis* Pall.) and the two-spotted ladybird (*Adalia bipunctata* L.) was also confirmed in Kyiv region. In some research, as Carena & Glogoza (2004) have previously indicated, the utilisation of natural predators to control the corn leaf aphid has been demonstrated to be an effective strategy, in addition to the employment of biochemical and physical barriers [16].

In July, the highest density of predators from the family Chrysopidae (larvae and adults) was observed, and these predators were found to be actively destroying aphids. Observations revealed a greater number of these predators at the stage of tassel formation on maize under irrigation.

4. Influence of weather conditions on aphid infestation in maize

Indicator	2020	2021	2022	2023	Average
the relationship between precipitation and					
% of plants infested with aphids	−0.18	−0.08	−0.26	−0.55	−0.27
score	−0.38	−0.06	−0.28	−0.23	−0.24
coefficient of colonisation	−0.42	−0.12	−0.30	−0.51	−0.34
the relationship between air temperature and					
% of plants infested with aphids	0.04	−0.02	0.23	0.40	0.16
score	0.06	0.23	0.28	0.29	0.22
coefficient of colonisation	−0.03	0.12	0.28	0.37	0.19

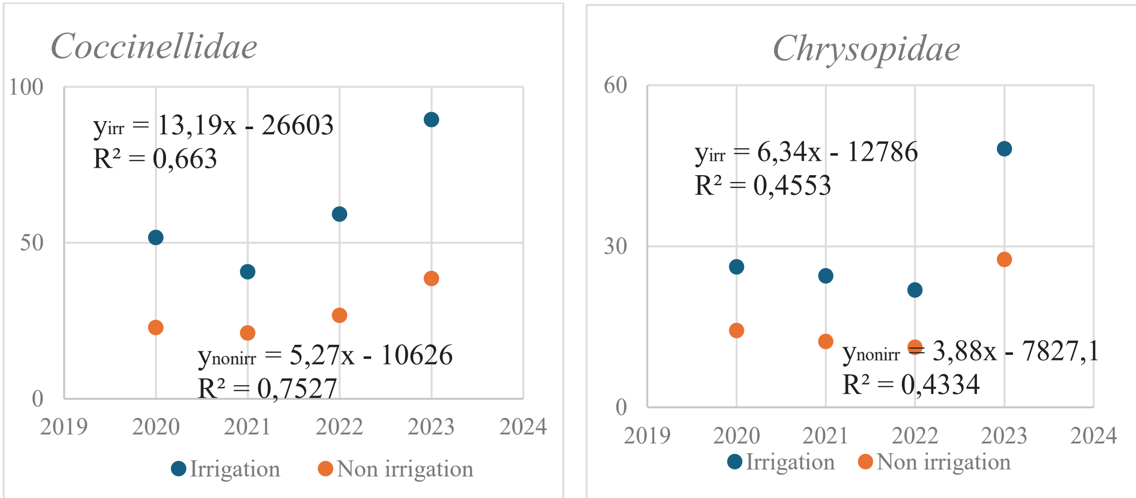

Fig. 1. The number of entomophages on maize under different conditions

The mean number of Chrysopidae representatives was found between 15.9 and 48.2 specimens per 100 aphid colonies, which was 1.7 times higher than the mean number observed in conditions without irrigation. This phenomenon can be attributed to the increased density of the aphid population in irrigated maize fields. The most prevalent species among the entomophages was the common goldeneye (*Chrysopa carnea* Steph.).

Furthermore, the presence of flies belonging to the family Syrphidae (*Diptera: Syrphidae*) was detected, including the bandaged syrphus (*Syrphus ribesii* L.), the marmalade fly (*Episyrphus balteatus* De Geer) and the decorated syrphus (*Sphaerophoria scripta* L.). The impact of predatory gall midges (*Diptera: Cecidomyiidae*), specifically *Aphidoletes aphidimyza* Rond., on the population dynamics of aphids was examined. The results indicated that these insects had minimal impact on aphid abundance due to their low population density. The presence of certain species of predatory insects was found to be random, presumably due to the proximity of other agrocenoses to maize. The presence of a sufficient food source in irrigated conditions attracted entomophages and contributed to their survival and propagation.

Conclusions. In the research area of Kyiv region, the following aphid species were observed to be predominantly responsible for the colonisation and damage to maize plants: the common corn aphid (*Schizaphis graminum* Rond.) and the cherry aphid (*Rhopalosiphum padi* L.).

The implementation of irrigation has been demonstrated to effect alterations in the microclimate of maize, with a decline in air temperature ranging from 2.4 °C to 6.1 °C, contingent on the prevailing conditions and the quantity of water employed. Concurrently, the humidity level has been shown to increase to 78–100 %. It has been demonstrated that nocturnal irrigation is the most gradual method of altering temperature and humidity. During the process of maize ripening in irrigated areas, the average aphid infestation was recorded to be 47.8 %, with an infestation score of 2.78 and a coefficient of 1.35. In non-irrigated maize, the infestation rate averaged 42.8 %, with an average score of 2.75 and a coefficient of 1.2.

The study established a moderate negative correlation between precipitation and the aphid infestation coefficient ($r = -0.34$) and a weak positive correlation between air temperature and infestation ($r = 0.19$).

The increased aphid density in irrigated maize fields resulted in a 2.2-fold higher mean number of Coccinellidae and a 1.7-fold higher mean number of Chrysopidae compared to non-irrigated conditions. The findings demonstrate that irrigation supports greater predator abundance, particularly of key species like *Chrysopa carnea* Steph., thereby enhancing natural aphid control in maize agroecosystems.

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

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

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ВПЛИВ ЗРОШЕННЯ НА ЗАСЕЛЕННЯ КУКУРУДЗИ ПОПЕЛИЦЕЮ

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Анотація. *Кукурудза (Zea mays L.) є важливою культурою для аграрного сектора як України, так і для світу, оскільки є основним товаром для експорту. Україна входить до десятки найбільших виробників кукурудзи в світі з річним виробництвом 27–35 мільйонів тон та експортом 20–25 мільйонів тон. Зрошення значно підвищує врожайність кукурудзи, потенційно збільшуючи врожайність з 6,8–7,0 т/га до 12–15 т/га. Враховуючи важливість кукурудзи для продовольчої безпеки, економічної стабільності та міжнародної торгівлі, розуміння факторів, які впливають на її продуктивність, має важливе значення. Однією з основних проблем Степу, Лісостепу та Полісся України є нерівномірний водний режим, що обмежує повне використання потенціалу родючості ґрунту. Ефективне управління зрошенням не тільки покращує ефективність використання води, але й сприяє розмноженню корисних організмів, поліпшуючи здоров'я екосистеми ґрунту та сприяючи підвищенню стійкості врожаю сільськогосподарських культур.*

У цьому дослідженні, яке проводилося з 2020 по 2023 рік у Київській області, вивчався розвиток та динаміка популяцій попелиць (Aphididae spp.) на зрошуваних та незрошуваних посівах кукурудзи, а також роль природних хижаків у регулюванні чисельності попелиць. Експериментальні ділянки площею 50 м² були створені за допомогою рандомізованого дизайну за чотирьох кратного повторення. Гібрид кукурудзи P9074 (ФАО 330) вирощували в умовах контрольованого зрошення, тоді як контрольні ділянки закладалися за природного – у вигляді опадів. Для оцінки впливу на щільність популяції попелиці реєстрували метеорологічні дані, включаючи температуру повітря, опади та гідротермічний коефіцієнт.

Результати показали, що заселення попелицею рослин кукурудзи було вищим на зрошуваних ділянках, особливо у фенофазу викидання волоті та цвітіння. Середня заселеність на зрошуваних площах досягла 47,8 % під час дозрівання кукурудзи порівняно з 42,8 % на незрошуваних полях. Помірну негативну кореляцію виявлено між сумою опадів і заселенням попелицями ($r = -0{,}34$), а слабку позитивну між температурою повітря і заселенням попелицями ($r = 0{,}19$). Було відмічено, що зрошення суттєво змінює мікроклімат, знижуючи температуру повітря на 2,4–6,1 °C і підвищуючи вологість до 78–100 %, залежно від часу проведення цього агроприйому та об'єму використаної води. При цьому полив у вечірні та нічні години найбільш плавно впливав на зміну температури і відносної вологості повітря.

Крім того, зрошення збільшувало чисельність природних хижаків попелиці. Щільність популяції представників родин Coccinellidae та Chrysopidae була в 2,2 та 1,7 рази відповідно вищою на зрошуваних полях, порівняно з незрошуваними ділянками. Ключові види хижаків, у тому числі Chrysopa carnea Steph., відіграли вирішальну роль у контролі популяцій попелиці. Це вказує на те, що зрошення може опосередковано підтримувати механізми біоконтролю.

Загалом дослідження підкреслює, що зрошення не тільки підвищує продуктивність кукурудзи, але також впливає на динаміку популяції попелиці та активність хижаків. Ці результати висвітлюють важливість інтеграції зрошення посівів культури із стратегією боротьби зі шкідниками для посилення екологічної стійкості агроекосистем кукурудзи та оптимізації її врожайності в Україні.

Ключові слова: *попелиця, зрошення, кукурудза, агроценоз, ентомофаг*

ЗМІСТ

ЗРОШЕННЯ – ДРЕНАЖ

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Меліорація

і водне господарство

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