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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$\text{CWB} = R\text{-}PET, \; mm. \quad (2)$$

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

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

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

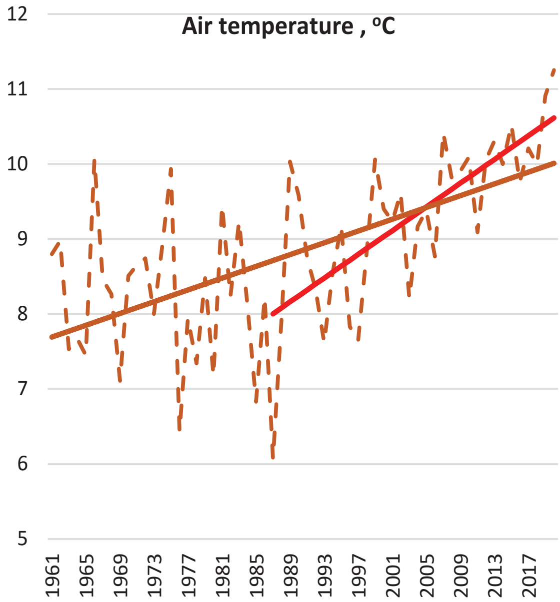

Fig. 1. Dynamics of the average annual air temperature for 1961–2020,°C

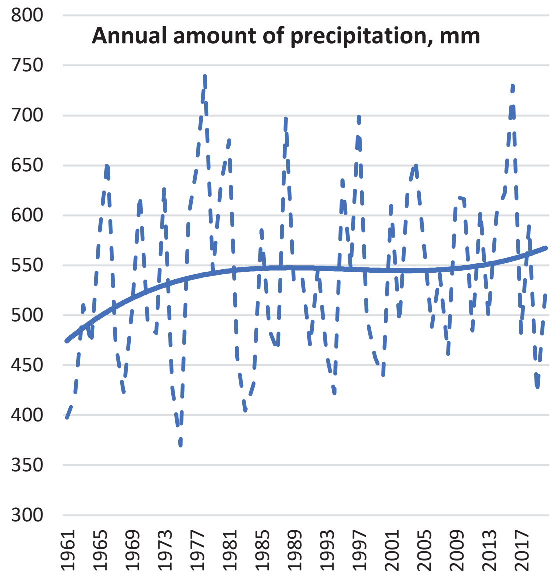

Fig. 2. Dynamics of annual precipitation for 1961–2020, mm

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

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

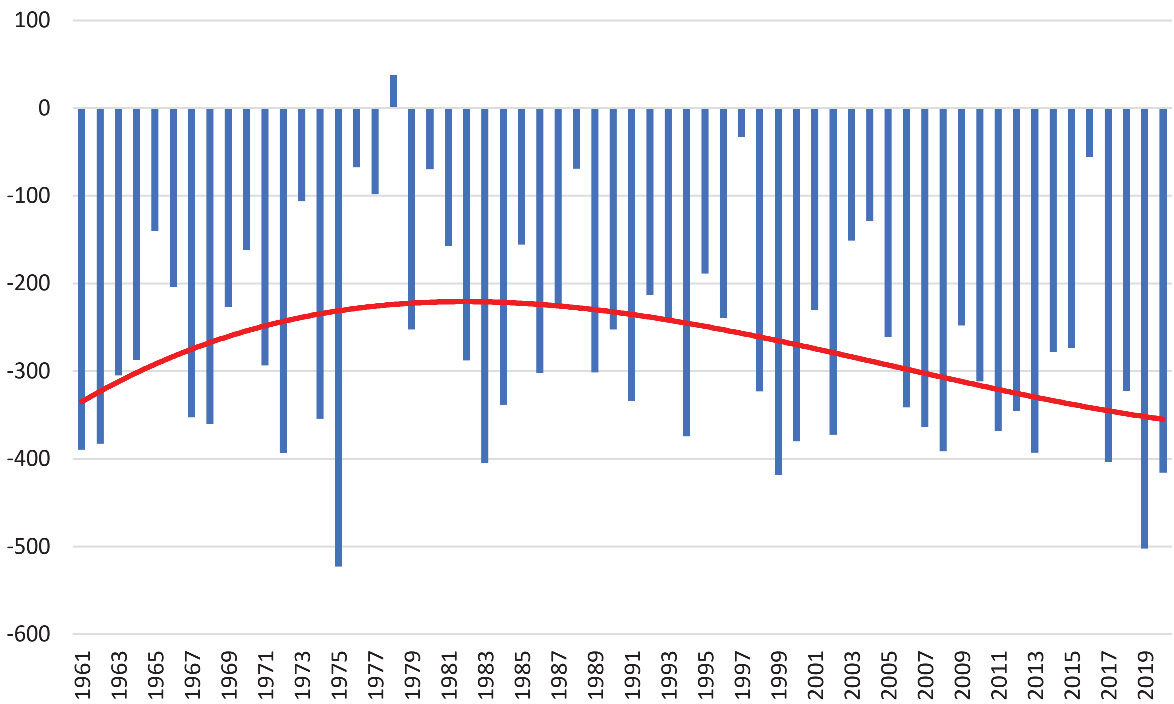

Fig. 3. Dynamics of the annual climatic water balance for 1961–2020, mm

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

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

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

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

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

The analysis of the given data indicates an increase in production costs when using artificial irrigation by 1.7–2.1 times with a significant increase in the cost of gross profit – up to

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

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

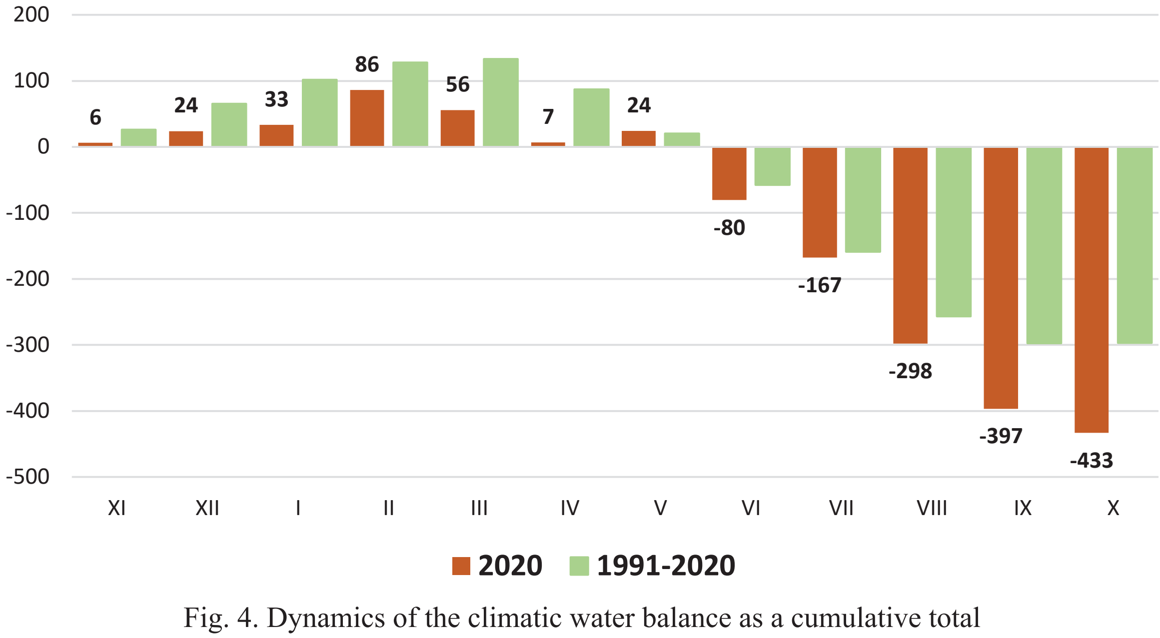

Fig. 4. Dynamics of the climatic water balance as a cumulative total for the 2019–2020 hydrological year (Krasnograd, Kharkiv region)

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

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

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

Crops	Design yield, ton/ha	Irrigation rate, m³/ha	*Costs for water transportation (2 UAH/m³), UAH/ha	**Total irrigation costs, UAH/ha	Total cultivation costs, UAH/ha	Cost of gross production, UAH/ha	Gross profit, UAH/ha	Profitability, %
Winter wheat	8	600	1200	1440	17550	40136	22586	129
Corn for grain	12	2600	5200	6240	23445	56028	32583	139
Sun-flower	4	1300	2600	3120	18675	43440	24765	133

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

8000 UAH when growing winter wheat, up to 18 000 UAH when growing corn for grain, and up to 10 000 UAH when growing sunflowers.

Therefore, the main negative manifestation of modern climate change is a significant decrease in the moisture availability of the territory and, accordingly, an increase in the need for additional water resources for irrigation. Such changes, in view of the entire area of available irrigated land in the Kharkiv region, require additional 28 million m³ of water. Even having the actual irrigated area of about 9000 hectares, the water demand to ensure high crop productivity increases by almost 4 million m³. Thus, applying irrigation, despite the almost the same production profitability, the estimated gross profit of 9–18 000 UAH exceeds the option without irrigation. In addition, it should be borne in mind that irrigation practically eliminates the risks associated with droughts.

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

The assessment of the climatic water balance by the months of the hydrological year as a cumulative total for the studied period shows that the positive balance in the region is kept on average until the end of May. Recalculating the deficit of the climatic water balance to the irrigation rate, the water demand for early crops is about 600 m³/ha, and for late crops it is 2500 m³/ha. The results of simulation modeling of the economic efficiency of irrigation when cultivating the main crops in the Kharkiv region indicate the efficiency of its application, and especially of its restoration on the areas with existing reclamation infrastructure.

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

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

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