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THE PROBLEM OF IRRIGATION WATER SHORTAGE AS A SYSTEMIC FACTOR LIMITING THE SUSTAINABLE DEVELOPMENT OF IRRIGATED AGRICULTURE IN THE CONTEXT OF CLIMATE CHANGE

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

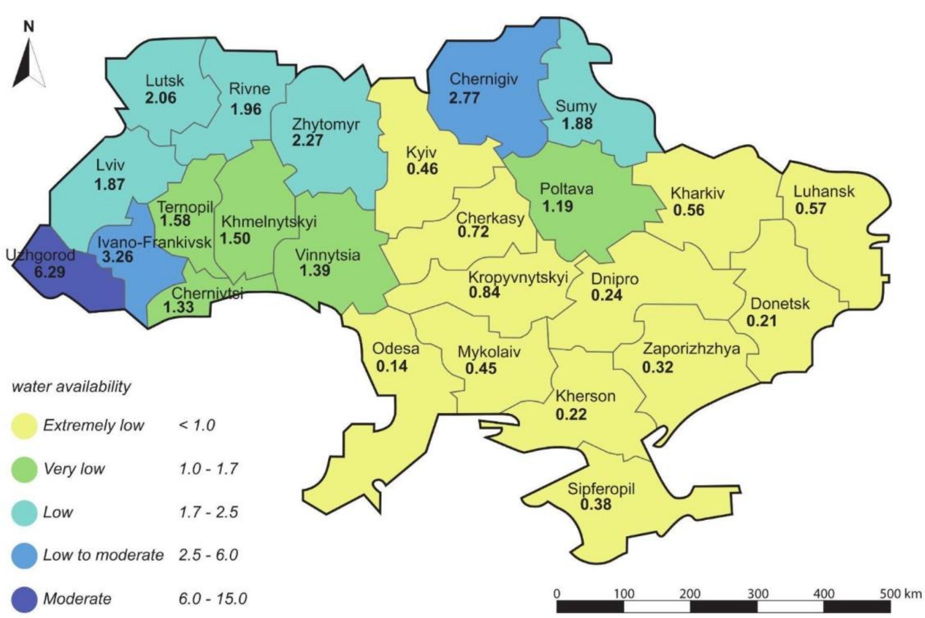

Fig. 1. Availability of local water resources in regions of Ukraine, thousand m³/year per person [10]

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

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

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

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

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

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

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

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

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

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

The study utilized the following information sources:

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

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

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

$$ET_c = ET_0 \times K_c,$$

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

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

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

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

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

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

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

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

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

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

Y_i – actual yield under water-deficient conditions;

P_i – product sales price;

A_i – planted area [9, 26].

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

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

where B_i – revenue from crop sales;

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

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

r – discount rate.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

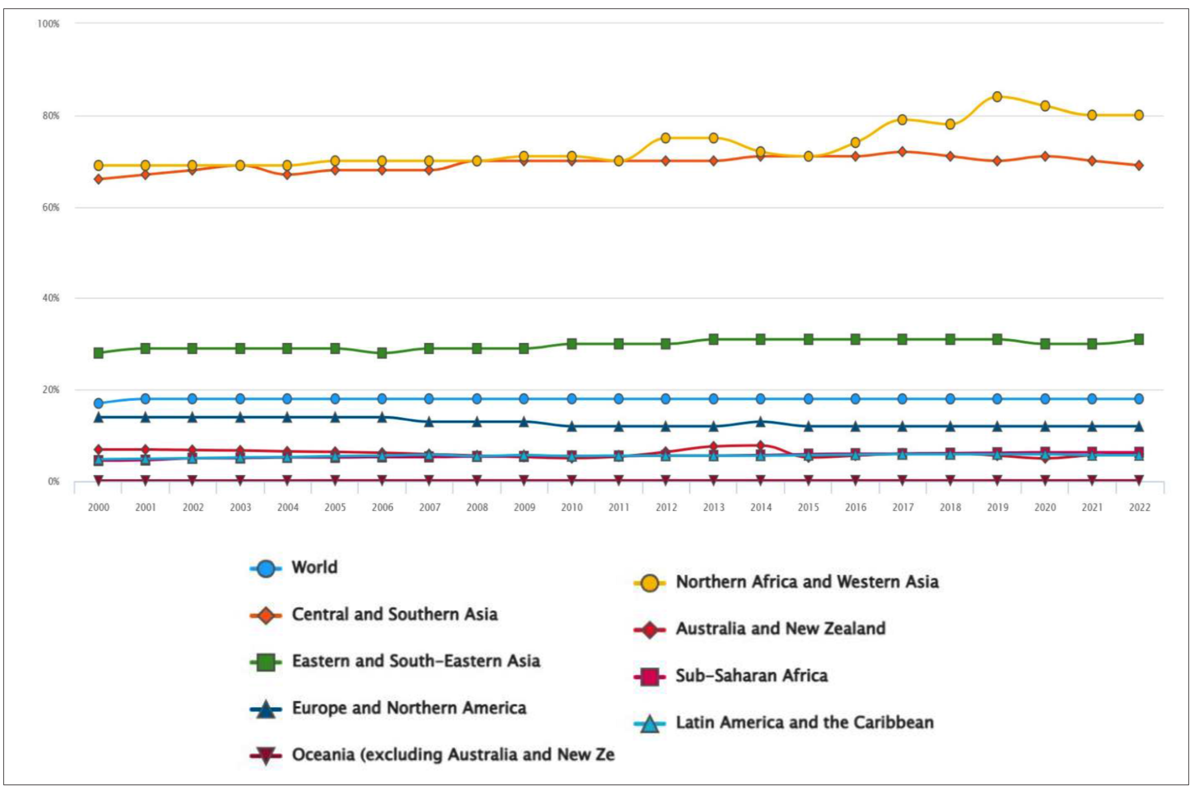

Fig. 2. Dynamics of the Water Stress Index (WSI) worldwide, 2000–2022

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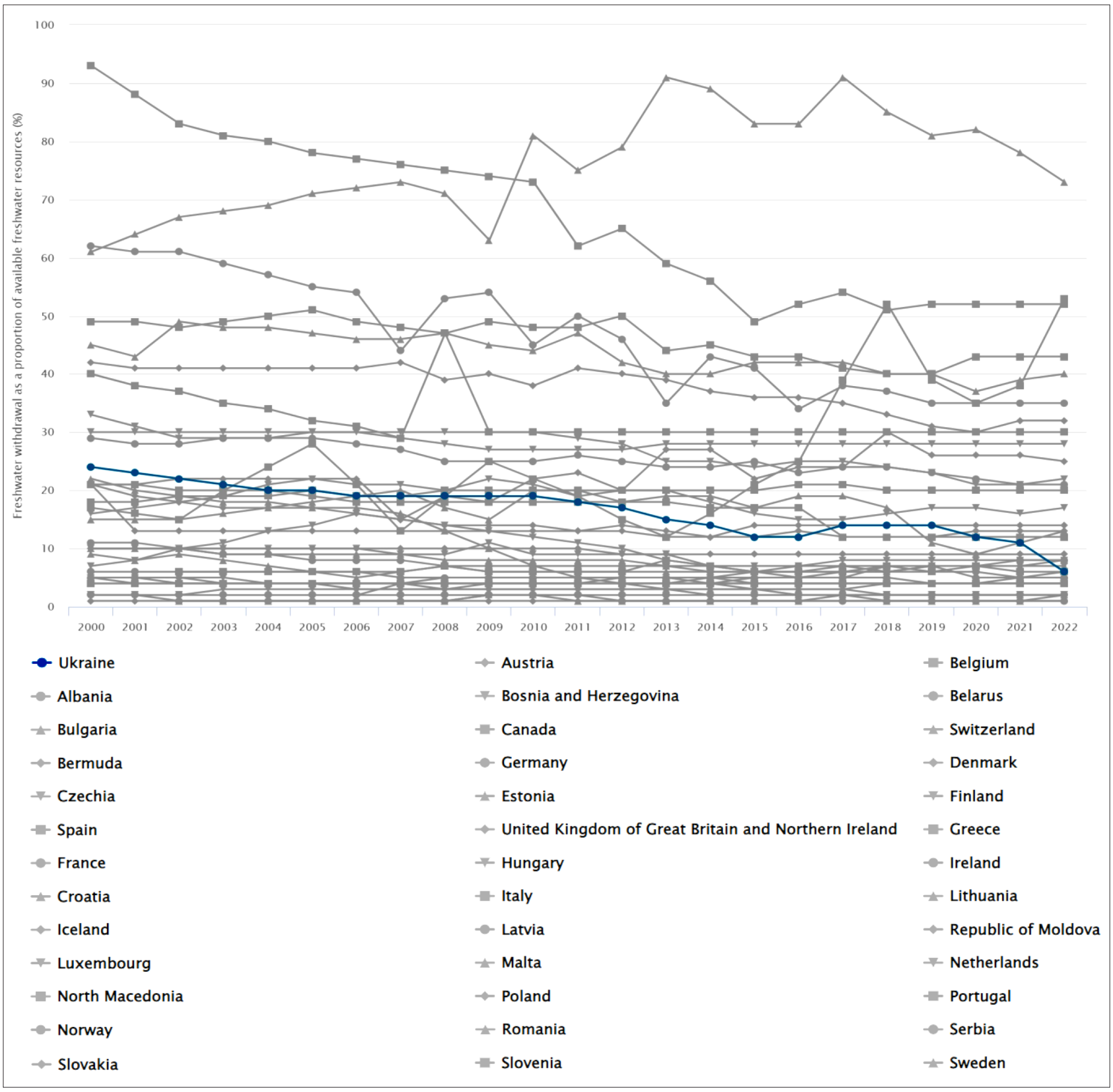

Fig. 3. Dynamics of the Water Stress Index (WSI) in European countries, 2000–2022

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

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

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

where Y – crop yield;

ET_c – crop evapotranspiration during the growing season.

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

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

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

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

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

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

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

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

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

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

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

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

where Y is the actual yield;

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

ET_c – actual crop evapotranspiration;

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

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

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

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

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

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

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

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

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

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

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

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

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

Conclusions:

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

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

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.

References

1. United Nations. (n.d.). *World Population Prospects*. un.org. https://population.un.org/wpp/.

2. Food and Agriculture Organization of the United Nations. (n.d.). *Aquastat – Global Information System on Water and Agriculture*. fao.org. https://www.fao.org/aquastat/.

3. Food and Agriculture Organization of the United Nations. (n.d.). *Water for sustainable food and agriculture*. fao.org. https://openknowledge.fao.org/server/api/core/bitstreams/b48cb758-48bc-4dc5-a508-e5a0d61fb365/content.

4. Rockström, J., Falkenmark, M., Folke, C., Lannerstad, M., Barron, J., Enfors, E., Gordon, L., Heinke, J., Hoff, H., & Pahl-Wostl, C. (2014). *Water resilience for human prosperity* (pp. 189–243). Cambridge University Press. https://doi.org/10.1017/CBO9781139162463.

5. Molden, D. (2013). *Water for food, water for life: A comprehensive assessment of water management in agriculture* (pp. 412–516). Routledge. https://doi.org/10.4324/9781849773799.

6. Mekonnen, M., & Hoekstra, A. (2016). Four billion people facing severe water scarcity. *Science Advances*, *2* (2), Article e1500323. https://doi.org/10.1126/sciadv.1500323.

7. Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). *Crop evapotranspiration: Guidelines for computing crop water requirements* (FAO Irrigation and Drainage Paper No. 56). FAO. fao.org. http://www.fao.org/3/x0490e/x0490e00.htm.

8. IPCC. (2022). *Climate Change 2022: Impacts, Adaptation and Vulnerability. Working Group II Contribution to the Sixth Assessment Report*. ipcc.ch. https://www.ipcc.ch/report/ar6/wg2/.

9. Fischer, G., Tubiello, F. N., van Velthuizen, H., & Wiberg, D. A. (2007). Climate change impacts on irrigation water requirements: Effects of mitigation, 1990–2080. *Technological Forecasting and Social Change*, *74* (7), 1083–1107. https://doi.org/10.1016/j.techfore.2006.05.02

10. Romashchenko, M. I., Husyev, Y. V., Shatkovskyi, A. P., Saidak, R. V., Yatsiuk, M. V., Shevchenko, A. M., & Matiash, T. V. (2020). Vplyv suchasnykh klimatychnykh zmin na vodni resursy ta silskohospodarske vyrobnytstvo [Impact of climate change on irrigation water demand]. *Land Reclamation and Water Management*, (1), 5–16. https://doi.org/10.31073/mivg202001-235 [in Ukrainian].

11. Sinha, R., Poolad, K., Lorenzo, R., et al. (2023). *The future of irrigation in Ukraine*. World Bank Group. worldbank.org. http://documents.worldbank.org/curated/en/099062524074575405.

12. Organisation for Economic Co-operation and Development. (2021). *Toolkit for water policies and governance: Converging towards the OECD council recommendation on water*. oecd.org.
https://www.oecd.org/content/dam/oecd/en/publications/reports/2021/03/toolkit-for-water-policies-and-governance_783de7b0/ed1a7936-en.pdf.

13. IPCC. (2021). *Climate Change 2021: The Physical Science Basis. Working Group I Contribution to the Sixth Assessment Report*. https://www.ipcc.ch/report/ar6/wg1/.

14. Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S. E., Sullivan, C. A., Liermann, C. R., & Davies, P. M. (2010). Global threats to human water security and river biodiversity. *Nature*, *467* (7315), 555–561. https://doi.org/10.1038/nature09440

15. Claudia, H., & Petra, D. (2019). Global assessment of current and future groundwater stress with a focus on transboundary aquifers. *Water Resources Research*, *55* (6), 4760–4784. https://doi.org/10.1029/2018WR023321.

16. Fereres, E., & Soriano, M. A. (2006). Deficit irrigation for reducing agricultural water use. *Journal of Experimental Botany*, *57* (2), 147–159. https://doi.org/10.1093/jxb/erl165.

17. Pereira, L. S., Oweis, T., & Zairi, A. (2002). Irrigation management under water scarcity. *Agricultural Water Management*, *57* (3), 175–206. http://dx.doi.org/10.1016/S0378-3774 (02)00075-6.

18. Kulbida, M. I., Yelistratova, L. O., & Barabash, M. B. (2013). Suchasnyi stan klimatu Ukrainy [Current state of Ukraine's climate]. *Problems of Environmental Protection and Ecological Safety*, *35*, 118–130.

19. Shevchenko, O. (2017). Chynnyky aktualizatsii hlobalnoi zminy klimatu [Causes of Global Climate Change]. *Modern Historical and Political Issues*, (35-36), 269–282.

20. Shatkovskyi, A. P., Zhuravlov, O. V., & Vasiuta, V. V. (2022). The use of phytomonitoring to control irrigation. *Journal of Water and Land Development*, *54*, 21–25. https://doi.org/10.24425/jwld.2022.141551.

ISSN 2616-5562 (Online)
ISSN 2616-5643 (Print)

21. Kovalenko, I. O., & Shatkovskyi, A. P. (2023). Vodnyi rezhym i vrozhainist tomativ za pidgruntovoho kraplynnoho zroshennia [Water regime and yield of tomato under drip irrigation]. *Agrarian Innovations*, *19*, 62–66. https://doi.org/10.32848/agrar.innov.2023.19.10 [in Ukrainian].

22. Kaliley, V. V., Shatkovskyi, A. P., & Retman, M. S. (2023). Rezhymy kraplynnoho zroshennia ta efektyvnist vykorystannia vody hibrydamy soniashnyku [Efficiency of drip irrigation of sunflower hybrids]. *Land Reclamation and Water Management*, *1*, 60–65. https://doi.org/10.31073/mivg202301-357 [in Ukrainian].

23. World Resources Institute. (n.d.). *Aqueduct Water Risk Atlas*. wri.org. https://www.wri.org/aqueduct.

24. Food and Agriculture Organization of the United Nations. (2023). *Ukraine: Impact of the war on agriculture*. fao.org. https://openknowledge.fao.org/server/api/core/bitstreams/8c2a59a8-50b3-4e6b-9605-e005a4f28c1c/content.

25. Zhuravlov, O.V., Shatkovskyi, A.P., Vasiuta, V.V., Cherevychnyi, Y.O., Marinkov, O.A., Kovalenko, I. O., & Gulenko, O. I. (2022). Porivniannia rozrakhunkovykh metodiv vyznachennia evapotranspiratsii za kraplynnoho zroshennia [Comparison of calculation methods for determining evapotranspiration under drip irrigation]. *Land Reclamation and Water Management*, *1*, 40–49. https://doi.org/10.31073/mivg202201-324

26. Porter, J., & Semenov, M. (2005). Crop responses to climatic variation. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *360* (1463), 2021–2035. https://doi.org/10.1098/rstb.2005.1752.

27. United Nations Water. (n.d.). *Sustainable Development Goal 6 (SDG 6) on water and sanitation Data Portal*. https://sdg6data.org/index.php/.

28. World Bank Group. (2023). *Ukraine rapid damage and needs assessment*. worldbank.org. https://documents1.worldbank.org/curated/en/099184503212328877/pdf/P1801740d1177f03c0ab180057556615497.pdf.

29. Lykhovyd, P. (2021). Irrigation needs in Ukraine according to current aridity level. *Journal of Ecological Engineering*, *22* (8), 11–18. https://doi.org/10.12911/22998993/140478

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

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

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

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

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

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