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Adaptive model of precision irrigation for cereal crops based on yield prediction modeling and water resource optimization

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Abstract. The relevance *of the study is driven by increasing climate instability, growing water scarcity, and the need to improve the efficiency of water use in cereal crop production. Traditional irrigation approaches fail to adequately adapt to the variability of agroclimatic and soil conditions, resulting in yield losses and inefficient water consumption. In this context, the need for implementing adaptive models based on predictive assessment of agricultural performance becomes particularly актуальною.* ***The purpose*** *of the study is to improve the efficiency of water resource use and ensure stable yields of cereal crops through the development of an adaptive precision irrigation model based on yield prediction modeling.* ***Methods.*** *The study applies methods of generalization and systematization of scientific approaches, structural-functional analysis, modeling, and comparative analysis to substantiate the conceptual framework of irrigation management.* ***Results.*** *The influence of agroclimatic, soil, and technological factors on yield formation under irrigation conditions has been investigated. Modern approaches to irrigation management within precision agriculture have been* *systematized, and methodological approaches to the use of yield prediction modeling in water management have been generalized. Key scientific and practical problems of implementing adaptive models have been identified, including data instability, limited model transferability, and infrastructure constraints. It has been proven that the integration of predictive yield parameters into irrigation management ensures more rational water allocation and improves agricultural efficiency.* ***Conclusions.*** *As a result, an adaptive precision irrigation model has been substantiated, combining yield prediction with water resource optimization and functioning as a cyclic decision-making system. The findings confirm the feasibility of transitioning to prediction-oriented irrigation management as a basis for enhancing the resilience of agricultural production. Future research should focus on the development of hybrid models, improvement of data processing algorithms, and expansion of the integration of adaptive systems into digital agricultural management environments.*

Keywords: *agroclimatic variability, water conservation, water use management, agricultural efficiency, digital farming, agricultural data, decision-making.*

Адаптивна модель прецизійного зрошення зернових культур на основі прогнозного моделювання врожайності та оптимізації водних ресурсів

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Анотація. Актуальність дослідження *зумовлена загостренням проблеми інтеграції вразливих груп населення України до ринку праці в умовах* *воєнних викликів, трансформації економічного середовища та структурних змін зайнятості. Зростання кількості ветеранів і осіб з інвалідністю, а також наявність бар'єрів економічного, фізичного, інституційного та психологічного характеру потребують формування нових підходів до забезпечення їхньої ефективної участі у трудових процесах. Особливого значення набуває застосування інструментів соціально орієнтованої економіки, які поєднують економічну доцільність із соціальною відповідальністю та сприяють сталому включенню зазначених категорій населення до економічної діяльності.* ***Метою дослідження*** *є обґрунтування інструментів соціальної економіки для інтеграції ветеранів і осіб з інвалідністю до ринку праці.* ***Методи.*** *У процесі дослідження використано методи узагальнення та систематизації, порівняльного аналізу та структурно-функціонального підходу для формування комплексної моделі механізмів інтеграції. Інформаційною базою стали офіційні статистичні дані, результати соціологічних опитувань, а також матеріали державних інституцій.* ***Результати.*** *У результаті дослідження проаналізовано динаміку залучення вразливих груп до програм зайнятості та встановлено наявність розриву між потенційною готовністю роботодавців до найму та фактичним рівнем працевлаштування. Визначено ключові обмеження інтеграції, серед яких домінують економічні та фізичні чинники поряд з інституційними бар'єрами. Узагальнення потреб ветеранів засвідчило високий попит на перекваліфікацію, додаткову освіту та інституційний супровід. Проаналізовано інструменти державної політики зайнятості та виявлено позитивну динаміку кількісних показників їх реалізації, зокрема у частині розвитку грантових програм і стимулювання роботодавців, водночас встановлено фрагментарність чинних проєктів.* ***Висновки.*** *Отримані результати підтверджують необхідність формування гнучких і комплексних механізмів підтримки вразливих груп населення. Практичне значення роботи*

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полягає у можливості використання запропонованої моделі для вдосконалення державної політики зайнятості та підвищення ефективності інтеграційних процесів.

Ключові слова: *агрокліматична варіативність, водозбереження, управління водокористуванням, ефективність агровиробництва, цифрове землеробство, аграрні дані, прийняття рішень.*

Problem statement. Under conditions of increasing climate instability, intensification of drought phenomena, and growing scarcity of freshwater resources, improving the efficiency of irrigation for cereal crops becomes a critical factor in ensuring food security and the economic sustainability of agricultural production. Traditional irrigation management approaches, based on fixed norms and calendar schedules, fail to account for the spatial and temporal variability of agroclimatic conditions, soil moisture status, and crop growth stages, which leads to either excessive water use or under-irrigation, yield losses, and soil degradation. At the same time, advances in precision agriculture, remote sensing, sensor networks, and predictive modeling create new opportunities for developing adaptive solutions capable of integrating heterogeneous data and dynamically adjusting irrigation regimes. The problem lies in the absence of a coherent methodological framework for constructing adaptive models that simultaneously ensure accurate yield prediction, efficient water resource optimization, and resilience to environmental uncertainty. Existing models are often focused either on agronomic aspects without incorporating economic efficiency or on resource optimization without sufficient accuracy of biophysical predictions, which limits their practical applicability across farms of different scales and complicates their integration into digital agricultural management systems. Thus, the scientific problem is inherently interdisciplinary and is associated with the need to synthesize methods from agronomy, hydrology, economics, and data-driven modeling in order to develop an adaptive precision

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irrigation model that balances yield performance and water conservation. Its solution has significant practical implications, as it enables increased productivity of cereal crops, reduced water and energy consumption, minimized environmental risks, and the establishment of a foundation for intelligent agricultural management systems.

Analysis of recent research and publications. A review of contemporary studies on adaptive precision irrigation of cereal crops based on yield forecasting and water resource optimization demonstrates the multidimensional nature of scientific approaches and their gradual integration within a unified research framework. Yu. Perehuda substantiates the essence of competition in animal husbandry as an economic category, emphasizing the importance of resource efficiency and adaptive management in agricultural production systems [1]. Further developing this perspective, Yu. Perehuda highlights the role of digital marketing tools in regulating the competitiveness of agricultural sectors, indirectly confirming the growing importance of digital technologies in decision-making processes, including water resource management [2]. V. H. Skliar investigates ecological niches and the dynamics of natural regeneration of forest-forming species, providing a methodological basis for understanding the dependence of biological productivity on environmental conditions, which is essential for adaptive irrigation modeling [3]. I. Skliar et al. demonstrate the variability of plant growth responses under different ecological and cenotic conditions, confirming the necessity of incorporating environmental heterogeneity into adaptive agricultural models [4].

A separate group of studies reflects the transformation of agricultural systems under modern socio-economic and environmental challenges. K. V. Demianenko et al. analyze the introduction of new aquatic biological resources, emphasizing the importance of adapting production systems to changing natural conditions, which aligns with the broader concept of adaptive resource management [5]. V. Olkhovsky proves that precision agriculture systems act as a compensatory mechanism under labor shortages, highlighting the increasing role of automation and digitalization in

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agricultural management [6]. H. Zavolodko and S. Mytrofanov underline the significance of artificial intelligence in restoring agricultural production under war and climate challenges, emphasizing its role in enhancing system resilience [7]. O. I. Symonenko et al. substantiate the importance of predictive modeling of cereal and legume production as a tool for improving planning accuracy, directly supporting the integration of yield forecasting into irrigation management systems [8]. A. M. Rokochynskyi et al. analyze climate change impacts on land reclamation regimes, demonstrating that shifting climatic conditions require a transition toward adaptive water management approaches [9].

The most directly relevant contributions to precision irrigation, yield prediction, and water optimization are presented in international studies. Y. Peng et al. justify precision irrigation as a key tool for sustainable water-saving in crop production, integrating water demand prediction with irrigation optimization strategies [10]. Y. Wang et al. propose a spatially distributed optimization model for irrigation water management under uncertainty and climate change, expanding traditional approaches toward integrated spatio-temporal decision-making [11]. J. Bellvert et al. demonstrate that decision-oriented models of crop water consumption significantly improve both water-use efficiency and farm profitability, highlighting the economic dimension of adaptive irrigation systems [12]. Y. Shan et al. show that combining climate scenarios with yield prediction models enhances the effectiveness of irrigation strategies, particularly for cereal crops such as maize [13]. I. A. Lakhiar et al. provide a comprehensive review of precision irrigation technologies, emphasizing their integration with data analytics, environmental assessment, and yield optimization under changing climatic conditions [14]. E. Bwambale et al. develop a data-driven model predictive control approach, proving that real-time data integration significantly increases the adaptability and efficiency of irrigation systems [15].

Identifying previously unresolved parts of the overall problem and

setting a task. Despite advances in irrigation and precision agriculture research, a coherent integration of agroclimatic, soil, and technological factors with yield prediction modeling remains insufficiently developed. Existing approaches are fragmented and focus on isolated components, which limits their adaptability and practical applicability due to data constraints and lack of unified methodologies.

At the same time, the linkage between predictive yield parameters and water optimization under uncertainty is inadequately addressed, restricting the transition to result-oriented irrigation management. Addressing these gaps is essential for improving water use efficiency and yield stability, which determines the focus of this study on developing an integrated adaptive model.

Formulation of the article's goals (task statement). The aim of the article is to improve the efficiency of water resource use and ensure stable yields of cereal crops through the development of an adaptive precision irrigation model based on yield prediction modeling.

Objectives of the article:

1. To analyze the influence of agroclimatic, soil, and technological factors on yield formation and to generalize approaches to yield prediction in water management.

2. To systematize modern precision irrigation approaches and identify their limitations.

3. To identify key implementation problems and develop an adaptive precision irrigation model based on yield prediction and water optimization.

Main material. The formation of cereal crop yields under irrigation conditions is determined by a complex interaction of agroclimatic, soil, and technological factors, which operate not in isolation but within a dynamically changing environment. Agroclimatic parameters – temperature, precipitation, evapotranspiration, and solar radiation – shape the water balance and determine the intensity of plant physiological processes. Soil characteristics – texture, water-

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holding capacity, structure, and fertility – define the ability to accumulate and supply moisture to the root system. Technological factors – irrigation regimes and methods, agronomic practices, crop varieties, and fertilization – act as instruments for targeted influence on productivity. The coordination of these groups of factors ensures efficient water use and yield stability under increasing climatic variability (table 1)

Tablle 1

Influence of key factors on cereal crop yield formation under irrigation

Group of factors	**Specific parameters**	**Mechanism of influence on yield**	**Practical effect**
Agroclimatic	Air temperature, amount and distribution of precipitation, evapotranspiration rate, solar radiation	Determine photosynthesis intensity, transpiration, and duration of the growing period	Yield variability, need for irrigation adjustment
Soil	Texture, water-holding capacity, structure, humus content	Affect moisture accumulation and nutrient availability	Uniform crop development, efficiency of water use
Technological	Irrigation rates and regimes, irrigation method, agronomic practices, crop varieties	Regulate water supply and optimize growth conditions	Yield increase, reduction of water and resource losses

Source: complied by the author based on [3, p. 10; 9, p. 52; 10, p. 368; 12, p. 325; 14].

In contemporary irrigated agriculture, the interaction of these factors is operationalized through the integration of field monitoring tools and analytical decision-support models, enabling a transition from normative to situational water management. Agroclimatic indicators are no longer treated merely as background conditions but function as dynamic signals for adjusting irrigation strategies – under elevated temperatures and precipitation deficits, farmers increasingly modify irrigation frequency rather than total volumes, thereby reducing plant stress during critical growth stages. Field-level observations demonstrate that, even with unchanged seasonal irrigation norms, redistributing water supply toward key phenological phases such as tillering and grain filling can significantly improve yield outcomes without increasing overall water consumption [14].

The role of soil conditions is equally critical, as they determine the actual efficiency of technological interventions. For instance, in light-textured sandy soils with low water-holding capacity, large single irrigation applications often result in substantial percolation losses, whereas split irrigation enhances moisture retention within the root zone [10, p. 368]. Conversely, in heavy clay soils, excessive irrigation frequency may lead to waterlogging and reduced soil aeration, necessitating a careful balance between irrigation intervals and wetting depth. In this context, technological parameters function as adaptive tools aligned with soil-specific properties rather than universal solutions.

The application of modern technologies – soil moisture sensors, weather stations, and satellite-based vegetation indices – allows these interactions to be quantified and incorporated into operational decision-making. Real-time soil moisture data, for example, enables precise timing of irrigation events, preventing both water deficit and excess, which directly affects crop water productivity. Practical implementations indicate that even partial adoption of such technologies can reduce water use while maintaining or increasing yields, as irrigation becomes responsive to actual crop conditions rather than generalized standards. Importantly, the effectiveness of this system is determined not by individual factors but by their coordination – agroclimatic conditions define the dynamics of water demand, soil properties constrain its retention and availability, and technological solutions regulate its supply [12, p. 325]. In modern conditions, such integration forms the practical foundation of adaptive irrigation management, enabling not only higher and more stable cereal yields but also more rational use of water resources and reduced environmental pressure on agricultural systems.

Modern irrigation management within precision agriculture has evolved from uniform water application toward data-driven, site-specific control of water delivery, integrating real-time monitoring, modeling tools, and automated systems. These approaches are designed to increase water use efficiency and crop productivity by aligning irrigation inputs with the spatial and temporal variability of field conditions. At the same time, the diversity of technological solutions – ranging from sensor-based systems to satellite-driven analytics and machine learning models – reflects both the progress in this domain and the fragmentation of methodological frameworks. As a result, the systematization of these approaches requires not only classification by technological features but also an assessment of their operational constraints and scalability in real agricultural environments (table 2).

Table 2

Systematization of modern approaches to irrigation management in precision agriculture and their limitations

Approach	Core principle	Data basis	Key limitations
Sensor-based irrigation control	Irrigation scheduling based on in situ soil moisture measurements	Soil moisture sensors, temperature probes	Limited spatial coverage, sensitivity to sensor placement errors
Remote sensing-based management	UAV data to assess crop water status	NDVI, Normalized Difference Water Index (NDWI), thermal imagery	Temporal resolution constraints, cloud interference, indirect measurement nature
Model-based irrigation scheduling	Simulation of crop water requirements using biophysical models	Weather data, soil parameters, crop coefficients	Dependence on calibration accuracy, complexity of parameterization
Automated irrigation systems	Real-time adjustment of	Integrated sensor and	High initial investment,

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	irrigation through control algorithms	weather data streams	technical maintenance requirements
Machine learning-based optimization	Prediction and optimization of irrigation regimes using data-driven models	Historical yield data, weather patterns, soil indicators	Data dependency, risk of overfitting, limited interpretability

Source: complied by the author based on [6; 10, p. 370; 11; 12, p. 330; 15].

In current agricultural practice, these approaches are increasingly implemented in combined configurations rather than as standalone solutions, which allows compensating for their individual limitations. Sensor-based irrigation control ensures high accuracy at specific points, yet in large fields it is typically supplemented with satellite data to avoid spatial bias – for example, combining soil moisture sensors with Normalized Difference Vegetation Index (NDVI) maps enables differentiation of irrigation zones within a single field. Remote sensing, including satellite imagery and Unmanned Aerial Vehicles (UAV), provides full-field coverage but requires ground validation, as vegetation indices may indicate stress without distinguishing its exact cause – water deficit or nutrient imbalance [15].

Model-based scheduling is widely applied in farms using weather-driven platforms, where irrigation timing is calculated based on evapotranspiration forecasts; however, in practice these models must be regularly adjusted to local soil and crop conditions to maintain accuracy. Automated irrigation systems demonstrate the highest operational efficiency in controlled environments, such as center pivot systems with variable rate technology, where water application is dynamically adjusted across management zones [6]. At the same time, machine learning models are increasingly used in large агробізнес structures to optimize irrigation strategies based on historical datasets, though their effectiveness declines when transferred to new fields without sufficient training data.

Thus, practical implementation is characterized by selective integration – farms combine sensor measurements, remote observations, and predictive models to achieve a balance between precision and reliability, while technological choice is determined not only by potential accuracy but also by economic feasibility and data availability.

Yield prediction modeling has become a central methodological component in water resource management for irrigated agriculture, enabling the transition from reactive irrigation scheduling to anticipatory decision-making based on expected crop responses. Unlike conventional approaches that rely on current field conditions, predictive models integrate historical, environmental, and crop-specific data to estimate yield outcomes under different water supply scenarios. This allows irrigation strategies to be aligned not only with immediate plant needs but also with targeted productivity levels, thereby improving the efficiency of water allocation under resource constraints. The methodological diversity of yield prediction modeling reflects differences in data structure, analytical logic, and application scale, which necessitates their systematization from the perspective of practical usability in irrigation management (table 3).

Table 3

Methodological approaches to yield prediction modeling in water resource management

Modeling approach	Analytical basis	Input variables	Application focus	Operational constraints
Statistical regression models	Empirical relationships between yield and influencing factors	Historical yield data, weather indicators, irrigation volumes	Quantification of yield response to water input	Limited adaptability to non-linear and extreme conditions
Process-based crop models	Simulation of physiological	Soil characteristics, climate data,	Scenario analysis of yield under	High data requirements,

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	crop growth processes	crop parameters, irrigation regimes	varying water availability	need for calibration
Remote sensing-driven models	Derivation of yield indicators from vegetation indices	Satellite imagery, vegetation indices, thermal data	Spatial estimation of crop performance	Sensitivity to data quality and indirect measurement limitations
Machine learning models	Pattern recognition in multi-dimensional datasets	Historical yield, weather, soil, and management data	Predictive optimization of irrigation strategies	Dependence on large datasets, interpretability challenges
Hybrid modeling frameworks	Integration of biophysical and data-driven methods	Combined datasets from sensors, models, and remote sources	Improved prediction accuracy and adaptability	Complexity of integration and computational demands

Source: complied by the author based on [8; 10, p. 372; 11; 13; 15].

In practical applications, the effectiveness of these approaches is determined by their ability to operate under incomplete and heterogeneous data conditions while maintaining predictive reliability. Statistical models are commonly used at farm level due to their simplicity – for example, yield–water response functions allow estimation of marginal productivity of irrigation, supporting decisions on whether additional water input is economically justified. However, their linear structure limits their responsiveness to abrupt climatic deviations, such as heat stress during critical growth stages [8]. Process-based crop models are widely applied in research-oriented and technologically advanced farming systems, where they are used to simulate irrigation scenarios under projected weather conditions. In practice, such models enable pre-season planning of water allocation, for instance by estimating expected yield under different irrigation quotas in water-limited regions. Nevertheless, their operational use requires continuous calibration, particularly in fields with heterogeneous soil properties, which constrains their scalability. Remote sensing-based approaches are increasingly used for spatial yield estimation, especially in large-scale agricultural enterprises [11]. By linking vegetation indices such as NDVI to biomass accumulation, these models allow identification of zones with differential productivity, which in turn informs variable irrigation strategies. However, their indirect nature requires integration with ground data to avoid misinterpretation of stress signals. Machine learning models demonstrate high predictive performance in data-rich environments, where they capture complex interactions between water availability and crop response. In practice, they are used to generate irrigation recommendations based on multi-year datasets, yet their transferability across regions remains limited without retraining. Hybrid approaches, combining process-based logic with data-driven calibration, are emerging as the most effective solution – for example, integrating crop growth models with real-time sensor inputs allows continuous adjustment of yield forecasts and corresponding irrigation decisions [9, p. 52]. Thus, in modern water resource management, yield prediction modeling functions as a decision-support layer that connects environmental variability with irrigation control. Its practical value lies not in a single methodological approach but in the adaptive integration of multiple modeling paradigms, enabling more precise alignment between water use and expected agricultural output.

The implementation of adaptive precision irrigation models is constrained by a set of interrelated scientific and practical limitations that reduce their robustness in real conditions. A core issue is the variability and incompleteness of input data, as agroclimatic and soil parameters are spatially heterogeneous and often insufficiently monitored, leading to unstable model outputs, particularly under extreme weather conditions. In addition, many models rely on simplified or quasi-stationary relationships between environmental factors and crop response, which are increasingly unreliable under climate variability.

A further constraint is limited transferability – models calibrated for specific conditions frequently lose accuracy in other environments, requiring repeated adjustment [13]. This is compounded by the absence of unified methodological standards and difficulties in integrating heterogeneous data sources, including sensor measurements, satellite observations, and farm records.

From a practical perspective, adoption is restricted by high implementation costs, infrastructure gaps, and operational risks related to sensor reliability and data transmission. The use of machine learning approaches introduces additional challenges linked to data dependency and limited interpretability. Organizational factors also remain significant – insufficient technical capacity and reliance on conventional practices slow adoption, while weak economic justification and regulatory constraints on water use further limit practical deployment.

The adaptive precision irrigation model for cereal crops is designed as an integrated decision-support framework that links yield prediction with dynamic water allocation in order to maximize productivity under constrained water availability. The model is based on the principle of anticipatory management – irrigation decisions are determined not only by current field conditions but by expected crop response expressed through predictive yield parameters. Its relevance is обусловлена the need to balance yield stability with water-saving requirements under increasing climate variability and resource limitations. Unlike conventional irrigation scheduling approaches, which rely on fixed thresholds or isolated indicators, the proposed model integrates predictive analytics with operational control, ensuring that water application is directly aligned with target yield outcomes. Methodologically, the model combines elements of yield forecasting, resource optimization, and feedback adjustment, forming a closed-loop system that continuously updates irrigation strategies based on incoming data and predicted performance (fig. 1).

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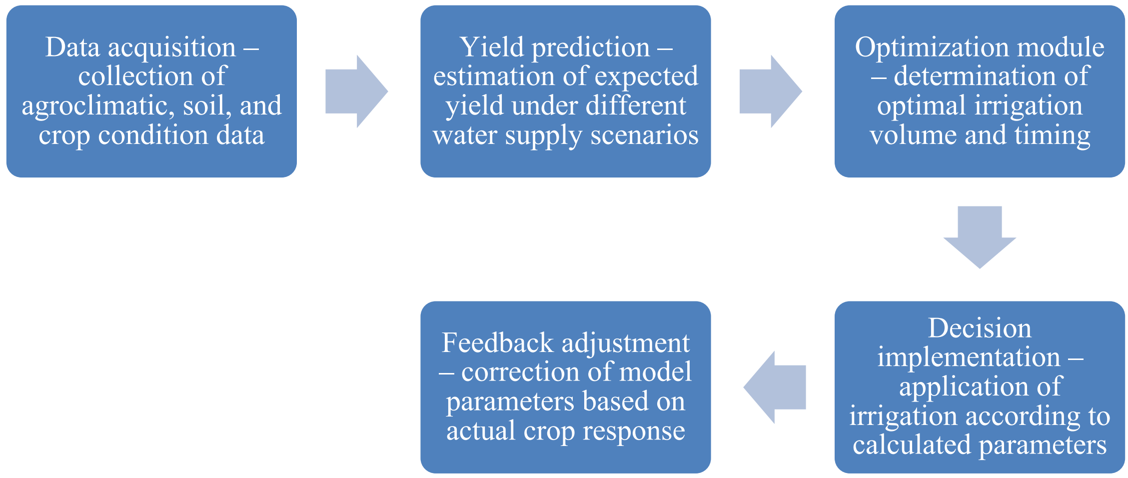

Fig. 1. Stepwise structure of the adaptive precision irrigation model

Source: author's own development

In practical conditions, the model operates as a cyclic management system where each stage directly influences the next, ensuring continuous adaptation to changing environmental and production conditions. At the beginning of the season, predictive modules generate yield scenarios based on available water resources and expected weather patterns, allowing farms to predefine irrigation strategies under different risk levels. During the growing period, real-time data – such as soil moisture or weather updates – are incorporated into the system, refining predictions and triggering adjustments in irrigation schedules. For example, if mid-season forecasts indicate a reduction in expected precipitation, the model reallocates available water to critical growth stages rather than maintaining uniform distribution, thereby preserving yield potential. Conversely, in periods of lower stress, irrigation intensity is reduced to prevent unnecessary water use. The feedback component ensures that discrepancies between predicted and actual crop responses are incorporated into subsequent cycles, improving model accuracy over time. In modern agricultural systems, such a model enables a transition from reactive irrigation to predictive and resource-efficient management, where water use is justified by its contribution to yield formation. Its implementation provides measurable effects – stabilization of yield under variable conditions, reduction of

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water losses, and improved economic efficiency through targeted resource allocation – while maintaining flexibility for adaptation across different farming scales and technological capacities.

Conclusions. The study establishes that the effectiveness of irrigation management for cereal crops is determined by the integration of yield prediction modeling with adaptive water allocation rather than by isolated technological solutions. It is substantiated that the transition from normative to prediction-oriented management enables alignment of water use with expected yield outcomes, thereby improving both resource efficiency and production stability. The proposed adaptive model demonstrates practical relevance by combining predictive analytics with dynamic adjustment mechanisms, which allows maintaining yield levels while reducing non-productive water losses. At the same time, key constraints are identified, including data inconsistency and spatial heterogeneity, limited transferability of models across different agroecological conditions, and the absence of unified methodological frameworks for integrating digital tools into farm management. Additional barriers include high implementation costs, infrastructure limitations, and operational risks related to data quality and system reliability, which collectively reduce the practical applicability of advanced models. The results confirm that adaptive irrigation based on predictive modeling improves water allocation by prioritizing critical growth stages and expected productivity, leading to more efficient and economically justified resource use. However, the achieved effects depend on the level of digitalization, data availability, and managerial capacity, which necessitates context-specific model adaptation. Further research should focus on the development of hybrid modeling approaches that integrate biophysical crop processes with data-driven methods, as well as on improving model robustness under data uncertainty. перспективним є також удосконалення економічних механізмів оцінювання ефективності з урахуванням довгострокових екологічних ефектів та розширення інтеграції адаптивних моделей у цифрові agricultural management systems.

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