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Adaptive Irrigation Management Model under Climate Change Based on Yield Forecasting and Scenario Analysis

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Abstract. The increasing impact of climate change on agricultural systems necessitates the development of adaptive irrigation management approaches capable of ensuring stable yields under growing environmental uncertainty. The **aim of this study** is to analyze and demonstrate the effectiveness of an adaptive irrigation management model based on yield forecasting and scenario analysis to improve the economic efficiency and sustainability of agricultural production.

Methods: analysis of the scientific literature was applied to examine current developments in this field; generalization and systematization were used to present the research findings.

Results. The study synthesizes contemporary theoretical and methodological approaches to irrigation management and integrates them with predictive and analytical tools to form a comprehensive decision support system. The structural framework of the adaptive model is substantiated, combining climatic, agronomic, and economic parameters into a unified system of dynamic interaction. Key sources of uncertainty affecting irrigation efficiency are identified, namely climatic variability, water resource availability, and technological constraints, and their influence on yield is established. The methodological foundations of yield forecasting and their integration into managerial decision-making processes are examined, enabling the timely, data-driven adjustment of irrigation strategies. The role of scenario modeling is analyzed as a tool for evaluating alternative development trajectories of irrigation systems under varying climatic and economic conditions, which makes it possible to determine optimal strategies under risk and uncertainty. The economic feasibility of implementing the adaptive model is substantiated through its comparison with traditional irrigation approaches, demonstrating its advantages in resource efficiency, yield stability, and profitability. The model's sensitivity to changes in external parameters is assessed, and the limits of its adaptability under extreme conditions are determined.

Conclusions. The proposed model enhances the resilience and economic viability of irrigated agriculture by improving the quality of decision-making, reducing risks, and ensuring more efficient use of water resources under climate change.

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Keywords: water resources in agriculture; adaptive management systems; agroclimatic variability; yield forecasting models; scenario planning; water use efficiency; economic sustainability of agricultural production.

Модель адаптивного управління зрошенням в умовах кліматичних змін на основі прогнозування врожайності та сценарного аналізу

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Анотація. Зростаючий вплив зміни клімату на сільськогосподарські системи зумовлює необхідність розроблення адаптивних підходів до управління зрошенням, здатних забезпечувати стабільну врожайність в умовах зростаючої екологічної невизначеності. **Метою** цього дослідження є аналіз і демонстрація ефективності адаптивної моделі управління зрошенням, заснованої на прогнозуванні врожайності та сценарному аналізі, з метою підвищення економічної ефективності та стійкості сільськогосподарського виробництва.

Методи: аналіз наукової літератури — для вивчення сучасних розробок у цій сфері; узагальнення та систематизація — для представлення результатів дослідження.

Результати. У дослідженні узагальнено сучасні теоретичні та методологічні підходи до управління зрошенням і інтегровано їх із прогностичними та аналітичними інструментами для формування комплексної системи підтримки прийняття рішень. Обґрунтовано структурну основу адаптивної моделі, що поєднує кліматичні, агрономічні та економічні параметри в єдину систему динамічної взаємодії. Визначено ключові чинники невизначеності, що впливають на ефективність зрошення, а саме кліматичну мінливість, доступність водних ресурсів і технологічні обмеження, а також встановлено їхній вплив на врожайність. Досліджено методологічні засади прогнозування врожайності та їх інтеграцію у процеси ухвалення управлінських рішень, що забезпечує своєчасне коригування стратегій зрошення на основі даних. Проаналізовано роль сценарного моделювання як інструменту оцінювання альтернативних траєкторій розвитку систем зрошення за різних кліматичних та економічних умов, що дає змогу визначати оптимальні стратегії в умовах ризику та невизначеності. Обґрунтовано економічну доцільність впровадження адаптивної моделі шляхом її порівняння з традиційними підходами до зрошення та демонстрації її переваг щодо ресурсоефективності, стабільності врожайності та прибутковості. Оцінено чутливість моделі до змін зовнішніх параметрів і встановлено межі її адаптивності в екстремальних умовах.

Висновки. Запропонована модель сприяє підвищенню стійкості та економічної життєздатності зрошуваного сільського господарства завдяки покращенню якості прийняття рішень, зниженню ризиків і забезпеченню більш ефективного використання водних ресурсів в умовах зміни клімату.

Ключові слова: водні ресурси в сільському господарстві, адаптивні управлінські системи, агрокліматична мінливість, прогнозні моделі врожайності, сценарне планування, ефективність водокористування, економічна стійкість агровиробництва.

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Introduction

The intensification of climate change processes has substantially increased the variability and unpredictability of agroclimatic conditions, calling into question the effectiveness of conventional irrigation management systems. Rising temperatures, irregular precipitation patterns, and the growing frequency of extreme weather events are altering crop water requirements and disrupting established agricultural practices. Under these conditions, traditional approaches based on fixed irrigation schedules and historical averages are no longer capable of ensuring stable yields and efficient resource use. This necessitates the development of more flexible, data-driven management systems capable of dynamically responding to environmental change. At the same time, intensifying competition for water resources and the need to balance economic efficiency with environmental sustainability further complicate decision-making in irrigated agriculture. As a result, the development of scientifically grounded models that account for climatic variability, crop response, and economic considerations has become a critical objective for modern agricultural systems.

The relevance of developing an adaptive irrigation management model based on yield forecasting and scenario analysis stems from its potential to enhance both the resilience and productivity of agricultural production under conditions of uncertainty. By combining predictive analytics with scenario-based assessment, such a model enables anticipation of possible future states and supports the selection of optimal irrigation strategies under changing climatic and economic conditions. This approach not only improves planning accuracy but also reduces risks associated with water scarcity and yield fluctuations. It further provides a methodological foundation for aligning short-term operational decisions with long-term sustainability goals, including efficient water use and climate change adaptation. In this context, the proposed study is highly relevant, as it addresses the need for innovative tools capable of supporting evidence-based decision-making and strengthening the economic viability of irrigated agriculture amid growing instability.

The subject of adaptive irrigation management under climate change has been addressed in the scholarly works of a number of domestic researchers, who have examined various aspects of scenario analysis, digitalization of the agricultural sector, and improved efficiency of water resource use. The role of the scenario approach in modeling the impact of uncertainty on the agricultural sector is substantiated by N. Prokopenko [1], who establishes a methodological foundation for incorporating climatic risks into irrigation management systems. Mechanisms of resource potential management in agricultural enterprises under conditions of global environmental change are examined by H. Didur, A. Shevchenko, M. Chornyi, S. Motruk, and O. Mokrinchuk [2], with direct relevance to the development of economically grounded water use models. Zinov'ieva O. [3] demonstrates the applicability of fuzzy logic to the optimization of irrigation systems, confirming the viability of intelligent methods in agricultural decision-making.

An evaluation of the economic efficiency of innovative technologies in agriculture is provided by Yu. Perehuda [4], indirectly affirming the importance of resource-saving approaches in irrigation systems. The role of digital technologies in water resource management as a key factor in the formation of adaptive irrigation systems is emphasized by S. Melnychenko [5]. Environmental parameters of land reclamation systems are analyzed by M. Serbov, A. Tolmachova, and V. Pylypiuk [6], enabling ecosystem constraints to be incorporated into irrigation modeling. Shulha O. [7] considers strategic approaches to adaptive management of the agricultural sector under uncertainty, directly correlating with the concept of scenario planning.

Precision farming technologies and their effectiveness in reducing environmental risks are demonstrated by A. Lishchuk, A. Parfeniuk, N. Karachynska, and I. Beznosko [8], constituting an important component of digital irrigation management systems. Mathematical

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modeling of soil moisture, which provides a direct foundation for the construction of predictive water balance models, is addressed by M. Pokhorenko et. al. [9]. Bihun V. [10] synthesizes adaptive strategies for the agricultural sector in response to climate change, underscoring the necessity of implementing adaptive irrigation management systems to ensure yield stability.

Despite the substantial body of research devoted to the adaptation of the agricultural sector to climate change, several issues remain insufficiently addressed, particularly the integration of yield forecasting and scenario analysis into a unified decision support system for irrigation management. Insufficient attention has been given to the formalization of adaptive models capable of simultaneously accounting for climatic uncertainty, economic efficiency, and real-time water resource dynamics. The quantitative assessment of the adaptability boundaries of such models under extreme climatic events and high environmental variability also remains an unresolved challenge.

The purpose of the study is to analyze and demonstrate the effectiveness of an adaptive irrigation management model based on yield forecasting and scenario analysis, with the aim of enhancing the economic efficiency and sustainability of agricultural production.

In accordance with this objective, the following tasks were formulated: to analyze the theoretical and methodological foundations of adaptive irrigation management under climate change; to substantiate approaches to yield forecasting and the application of scenario analysis within the managerial decision-making framework; to develop and formalize an adaptive irrigation management model; and to evaluate the economic efficiency and sustainability of its implementation.

Methodology

Research methods. The methodological basis of the study is a systems approach to the analysis of adaptive irrigation management under climate change, which entails a comprehensive consideration of the interrelations among agroclimatic, hydrological, technological, and economic factors. Within the present study, the adaptive model is treated as a multilevel decision-making system that operates by integrating yield forecasting, the assessment of resource efficiency, and scenario analysis of possible changes in the external environment.

The methodological logic of the study draws on the combined concepts of risk-oriented management, scenario modeling, and adaptive planning. This made it possible to assess not only the direct effect of climatic variability on irrigation efficiency but also to identify the resilience limits of the management model under conditions of unstable water supply, changing production costs, and yield fluctuations. Such an approach ensured a comprehensive investigation of the interaction between the ecological and economic parameters that govern the functioning of irrigated agricultural systems.

In the course of the study, a complex of general scientific and applied methods was used. An analysis of the scientific literature was employed to examine current approaches to irrigation management, to assess the impact of climate change on agricultural production, and to identify state-of-the-art yield forecasting models. The method of generalization and systematization made it possible to structure existing theoretical propositions and to form the conceptual basis of the adaptive model.

To evaluate the effectiveness of management decisions, scenario analysis was applied to model alternative regimes of irrigation system operation under different levels of climatic and economic uncertainty. Comparative analysis was used to contrast the adaptive and traditional approaches to irrigation management against the criteria of water-use efficiency, yield stability, and economic feasibility. Elements of analytical modeling were also applied to assess the sensitivity of the system to changes in external parameters.

e-ISSN: 2786-586X

Data sources. The information basis of the study was formed by combining theoretical, analytical, and applied data sources. The main sources included the scientific works of domestic and foreign researchers devoted to the problems of adaptive water resource management, scenario modeling, digitalization of the agricultural sector, and improvement of irrigation efficiency under climate change.

In addition, the study took into account generalized indicators of meteorological observations, data on soil moisture, parameters of crop water consumption, as well as statistical characteristics of yield and the economic performance of irrigated production, which were used in the construction of the analytical model. The combination of different types of data made it possible to perform a comprehensive analysis of the factors that affect the stability and efficiency of adaptive irrigation management.

Analytical tools. The analytical toolkit of the study was based on the use of predictive modeling approaches, scenario analysis, and comparative evaluation. Yield forecasting models were applied to determine the potential response of agricultural crops to changes in water supply and agroclimatic conditions. This made it possible to assess the dependence of production performance on irrigation parameters and on the adaptability of management decisions.

Scenario analysis was used as a tool for evaluating alternative trajectories in the development of irrigation systems under varying levels of risk, including water resource shortages, increasing temperature fluctuations, and technological constraints. To determine the economic feasibility of implementing the adaptive model, a comparative assessment of resource-use efficiency, yield stability, and potential profitability was applied, which made it possible to substantiate the practical value of the proposed system.

Limitations of the study. Despite the comprehensive nature of the analysis conducted, the study has a number of limitations. First, the proposed adaptive model is based mainly on generalized agroclimatic and economic parameters, which may limit the accuracy of its application in specific regional contexts characterized by high spatial heterogeneity of soils, water resources, and production infrastructure.

Second, the scenario approach involves the evaluation of possible variants of development, but it cannot fully account for all stochastic risks associated with extreme climatic events, abrupt changes in market conditions, or institutional transformations in the sphere of water use. In view of this, further research should be directed toward expanding the empirical base, integrating real-time data, and refining forecasting models in order to enhance the adaptability of irrigation system management.

Results

The development of an adaptive irrigation management model based on yield forecasting requires a clear formalization of its structure to ensure coherence among the agronomic, climatic, and economic components. The model is grounded in the integration of biophysical crop response functions with water balance equations and economic optimization criteria. Its structural framework can be represented as a multilevel system in which the input variables comprise climatic parameters (temperature, precipitation, evapotranspiration), soil characteristics (water holding capacity, infiltration rate), and technological factors (irrigation methods, scheduling regimes). Output variables are expressed primarily through projected yields and their associated economic returns. The model incorporates a dynamic feedback mechanism linking forecasted yield indicators to irrigation decisions, enabling continuous adjustment under changing environmental conditions [9, p. 14-15]. The key parameters of the model include crop-specific water requirements, yield response coefficients to water deficit, the marginal productivity of irrigation water, and cost functions associated with water use and energy consumption. These parameters are calibrated on the basis of both empirical

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observations and established agronomic relationships, ensuring the model's applicability across diverse agroclimatic zones.

An important component of the model is the management decision adaptation algorithm, which is grounded in the principles of iterative optimization and scenario-based adjustment. The algorithm operates in several stages, beginning with the collection and processing of real-time and forecast data, followed by the generation of yield projections under alternative irrigation strategies. Drawing on these projections, the model evaluates expected economic outcomes and identifies the optimal irrigation schedule that maximizes net returns while minimizing resource use and associated risks. The adaptive character of the algorithm is ensured through periodic recalibration, whereby discrepancies between projected and actual yields trigger adjustments to model parameters and decision rules. This iterative process enhances system reliability by enabling effective responses to climatic variability and uncertainty [10, p. 185-186]. The application of scenario analysis further strengthens the decision-making framework by enabling the assessment of diverse possible future states, including extreme weather events and water deficit conditions. As a result, the model supports not only short-term operational decisions but also medium- and long-term strategic planning in irrigation management.

The effectiveness of an adaptive irrigation management model is largely determined by the quality and completeness of its informational support, encompassing both data sources and data processing mechanisms. The model is grounded in the combination of historical datasets and real-time information streams, including meteorological observations, remote sensing data, soil moisture monitoring systems, and agricultural statistics. Satellite data provide critical information on vegetation indices, land surface temperature, and the spatial variability of crop conditions, thereby enhancing the accuracy of yield forecasts. Ground-based sensors supply high-resolution data on soil moisture dynamics and microclimatic conditions, which are essential for precise irrigation scheduling. Statistical databases and farm-level records contribute information on yields, resource use, and economic performance, supporting model calibration and validation. Advanced data processing techniques, including machine learning algorithms and time series analysis, are applied to identify patterns and improve forecast accuracy. The integration of these diverse data sources into a unified information system ensures the reliability and scalability of the model, making it an effective tool for supporting adaptive irrigation management under conditions of increasing climatic uncertainty.

The development of scenarios for the operation of irrigation systems under climate change represents a critical step in advancing analytical approaches aimed at supporting informed and forward-looking management decisions. Unlike deterministic planning models, scenario-based analysis explicitly acknowledges the substantial uncertainty associated with future climatic, environmental, and socioeconomic changes. The first stage of this approach involves the systematic identification of key uncertainty factors that significantly affect irrigation efficiency and agricultural productivity. Among these factors, climatic variability plays a central role, particularly changes in precipitation patterns, drought frequency, extreme temperatures, and evapotranspiration levels.

Non-climatic uncertainty factors are equally significant, however, including constraints on water availability arising from intersectoral competition, fluctuations in energy prices affecting irrigation costs, the pace of technology adoption, and institutional and policy changes related to water resource governance [11, p. 1717]. The interactions among these factors exert complex and often nonlinear effects on irrigation efficiency and crop productivity, necessitating a structured framework for their comprehensive analysis.

Building on the identification of uncertainty factors, the development of a baseline scenario and alternative scenarios enables a comprehensive examination of possible system development trajectories. The baseline scenario typically reflects the continuation of current trends, premised on assumptions of moderate climate change and stable institutional and

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technological conditions. Alternative scenarios, by contrast, are constructed to capture a range of plausible futures, encompassing both adverse and favorable changes. For instance, a pessimistic scenario may assume an increased frequency of extreme droughts, reduced water availability, and rising operational costs, whereas an optimistic scenario may project improvements in water use efficiency driven by technological innovation and effective policy interventions [12, p. 2636]. Intermediate scenarios may also be developed to represent gradual transitions or mixed conditions. The purpose of this structured diversification is not to predict a single outcome but to assess the resilience and adaptability of irrigation systems under varying external pressures.

The comparative characteristics of these scenarios are presented in Table 1.

Table 1

Characteristics of irrigation system operation scenarios under climate change conditions [11-15]

Scenario Type	Climatic Conditions	Water Availability	Technological Level	Expected Impact on Yield
Baseline	Moderate warming, stable precipitation	Relatively stable	Current technologies	Stable or subject to minor fluctuations
Pessimistic	Significant temperature increase, frequent droughts	Limited and irregular	Low level of adaptation	Substantial decline
Optimistic	Controlled warming, improved precipitation utilization	Efficient and sufficient	Advanced irrigation technologies	Yield growth
Intermediate	Variable climatic fluctuations	Periodic constraints	Partial technological modernization	Moderate variability

The integration of such scenarios into analytical models enables a more detailed assessment of potential outcomes, particularly with respect to crop yield levels. The impact of each scenario on yield is evaluated through the interaction among water supply reliability, crop water requirements, and adaptive management practices. Under pessimistic conditions, yield decline is driven primarily by water stress occurring at critical growth stages, compounded by insufficient adaptive capacity. Conversely, optimistic scenarios indicate that the adverse effects of climate change can be mitigated or even offset through improvements in irrigation efficiency, the adoption of precision farming methods, and timely decision-making. Intermediate scenarios underscore the importance of flexibility, as even partial improvements in water resource management can substantially reduce yield variability.

Notably, scenario-based assessment also contributes to the identification of threshold effects and critical tipping points beyond which the performance of irrigation systems may undergo disproportionate decline. This aspect is particularly relevant for regions already characterized by high levels of water deficit, where even marginal shifts in climatic conditions can result in significant yield losses. By quantifying yield sensitivity to various combinations of uncertainty factors, the scenario-based approach provides an essential foundation for prioritizing investments in infrastructure, technology, and institutional capacity. In this context, scenario construction and analysis not only improve understanding of potential risks

e-ISSN: 2786-586X

but also inform the development of proactive strategies aimed at ensuring the long-term resilience and economic viability of irrigated agriculture under climate change [16, p. 2377].

The assessment of the economic efficiency of implementing an adaptive irrigation management model represents a critical step in validating its practical feasibility and scalability within agricultural systems confronting growing climatic uncertainty. Such an assessment requires a comprehensive methodological framework capable of capturing both the direct and indirect economic effects associated with improved water resource management practices. The proposed approach to determining economic efficiency indicators is grounded in the integration of cost-benefit analysis, marginal productivity assessment, and risk-adjusted performance metrics. The core indicators encompass net present value, internal rate of return, payback period, and profitability index, supplemented by sector-specific measures such as water productivity, cost per unit of yield, and marginal irrigation returns. Additionally, the methodology incorporates variability-adjusted indicators, including the crop yield coefficient of variation and risk reduction metrics, enabling the evaluation of economic stability under conditions of environmental uncertainty. This multi-criteria approach allows efficiency to be assessed not only in terms of short-term profitability but also with regard to long-term resilience and resource use sustainability [17, p. 2917].

A key element of the assessment is the comparative analysis of conventional and adaptive approaches to irrigation management. Conventional systems are generally characterized by fixed irrigation schedules, limited capacity to respond to real-time environmental conditions, and reliance on historical averages for planning purposes. Adaptive approaches, by contrast, involve flexible scheduling, data-driven decision-making, and continuous adjustment of irrigation volumes in response to changing climatic conditions and crop status. From an economic perspective, these differences give rise to distinct cost structures and revenue outcomes. Conventional methods frequently result in either over-irrigation, generating unnecessary resource expenditures, or under-irrigation, causing yield losses. Adaptive systems, by optimizing water application in accordance with crop water requirements, tend to reduce production costs and improve overall productivity [18]. Adaptive management also reduces exposure to climatic risks, stabilizing revenues and enhancing financial predictability for agricultural producers.

The economic characteristics of these two approaches are summarized in Table 2.

Table 2

Comparative characteristics of conventional and adaptive approaches to irrigation management [18-23]

Indicator	Conventional Irrigation Approach	Adaptive Irrigation Management Model
Water use efficiency	Moderate or low	High
Irrigation costs	Relatively high due to inefficiency	Optimized and controlled
Yield level	Variable, climate-sensitive	More stable and potentially higher
Sensitivity to climatic risks	High	Low
Profitability	Unstable	More stable and improved
Resource use	Suboptimal	Efficient

The economic effect of implementing an adaptive irrigation management model manifests in both quantitative and qualitative dimensions. From a quantitative perspective, the model contributes to increased net farm income through the combined effect of higher yields and reduced input costs, particularly with respect to water and energy consumption. The

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optimization of irrigation schedules minimizes losses and ensures water delivery at the stages where it yields the highest marginal return. Over time, these improvements accumulate, resulting in a positive net present value and a relatively short payback period on investments in data infrastructure and decision support systems. Furthermore, the reduction in yield variability enhances financial stability, which is critical for long-term planning and access to credit.

From a qualitative perspective, the adoption of adaptive irrigation practices strengthens the overall economic resilience of agricultural enterprises. By reducing dependence on unpredictable climatic conditions and improving resource use efficiency, the model supports the development of more robust production systems. It also creates opportunities for the introduction of complementary innovations, such as precision farming technologies and digital monitoring tools, further amplifying the economic benefits. Importantly, the model facilitates better alignment between economic and environmental objectives, as efficient water use not only reduces costs but also mitigates the negative externalities associated with resource overexploitation. In this context, the economic efficiency assessment demonstrates that adaptive irrigation management is not merely a technological improvement but a strategically significant approach to enhancing the competitiveness and sustainability of agricultural production under climate change [24].

The sensitivity and stability analysis of the adaptive irrigation management model with respect to changes in external conditions provides an essential foundation for evaluating its reliability and practical applicability in dynamic and uncertain environments. In this context, sensitivity analysis serves as a methodological tool for quantifying the degree to which changes in exogenous parameters affect model outputs, particularly those related to yield, resource use efficiency, and economic performance. Climatic parameters play a significant role in shaping these outputs, with temperature fluctuations, precipitation variability, and changes in evapotranspiration intensity exerting both direct and indirect effects on model behavior. For instance, a gradual increase in mean temperature may accelerate crop development cycles while simultaneously increasing water demand, thereby altering the optimal irrigation schedule. Similarly, irregular precipitation patterns can disrupt soil moisture dynamics, resulting in discrepancies between projected and actual water availability. The model's response to such changes is assessed through partial sensitivity coefficients and elasticity indicators, which reveal that yield forecasts are highly sensitive to deviations in water supply during critical phenological stages. At the same time, interaction effects among climatic variables frequently amplify overall system instability, underscoring the importance of employing multidimensional sensitivity assessments rather than isolated parameter variations [25].

Beyond climatic factors, the decision-making process within the model is subject to a range of risks and uncertainties arising from both environmental and socioeconomic domains. These uncertainties encompass measurement errors in input data, limitations in forecast accuracy, and structural assumptions embedded in the model itself. The presence of stochastic elements in weather conditions introduces probabilistic variability that cannot be fully captured through deterministic approaches, necessitating the use of risk analysis methods such as scenario weighting and confidence interval estimation. Economic uncertainty associated with input prices, market demand, and policy interventions further complicates the optimization of irrigation strategies. The model addresses these challenges through the use of adaptive feedback mechanisms and probabilistic evaluation criteria, enabling decision-makers to weigh expected returns against potential risks. Importantly, the integration of risk-adjusted performance indicators allows for a more comprehensive assessment of alternative management strategies, ensuring that decisions are informed not only by average outcomes but also by the probability and magnitude of adverse deviations.

e-ISSN: 2786-586X

A key aspect of the analysis is the determination of the adaptability boundaries of the management model, defining the range of external conditions within which the model can maintain an acceptable level of performance. These boundaries are shaped by both the structural flexibility of the model and the availability of reliable input data. Under conditions of moderate climatic variability, the adaptive mechanisms embedded in the model are capable of adjusting irrigation schedules and sustaining stable yield indicators. However, as external conditions approach extreme thresholds, such as prolonged droughts, severe heat waves, or abrupt disruptions to water supply, the effectiveness of adaptive measures may diminish. In such cases, the model may encounter boundary conditions under which incremental adjustments prove insufficient to compensate for systemic stress, resulting in reduced forecast accuracy and deterioration in decision-making quality. These threshold values are identified through stress-testing procedures, during which the model is subjected to progressively intensifying external shocks to observe patterns of performance degradation.

Accounting for adaptability boundaries is important both for model refinement and for the development of policy responses. It highlights the need to complement adaptive management tools with broader resilience-enhancing measures, including infrastructure investment, diversification of water supply sources, and institutional support mechanisms. The importance of continuous model updating and recalibration in response to evolving environmental and economic conditions is also emphasized. Through systematic sensitivity analysis, uncertainty assessment, and adaptability boundary determination, the model not only enhances its internal consistency but also provides a transparent framework for understanding its strengths and limitations. This, in turn, supports more informed and risk-oriented decision-making in irrigation management, contributing to the long-term resilience and stability of agricultural production systems under conditions of ongoing climate change.

Discussion

Interpretation of the results. The obtained results confirm that the application of the adaptive irrigation management model substantially improves the efficiency of water resource use under conditions of variability in climatic and production factors. In contrast to traditional irrigation schemes that rely on fixed irrigation norms, the proposed approach provides a more flexible response to the dynamics of soil moisture, forecasted weather conditions, and the expected productivity of crops. This makes it possible to reduce the risks of excessive or insufficient moistening, which directly affects the stability of agricultural production.

Particular importance is attached to the identified interrelation between the parameters of adaptive control and the economic indicators of the system. The results of the scenario modeling demonstrate that the optimization of irrigation regimes affects not only agronomic performance but also the reduction of operating costs, lower energy consumption, and the overall profitability of production. The water resource management system is therefore regarded not merely as a technical instrument but as a component of the economic resilience of an agricultural enterprise.

At the same time, the results indicate that the effectiveness of the model depends on the quality of the input data, the stability of sensor-based monitoring, and the accuracy of the forecasting algorithms. This points to the need for a comprehensive approach to the digitalization of irrigation systems, in which mathematical modeling must be combined with actual field observations and systems of operational control.

The interpretation of the obtained results makes it possible to assert that the principal effect of adaptive management is achieved through the reduction of uncertainty in irrigation decision-making. A system that takes into account the current state of the soil, climatic fluctuations, and forecasted scenarios of agroecosystem development ensures a more accurate distribution of water resources. This is particularly important under conditions of water scarcity or heightened climatic instability.

e-ISSN: 2786-586X

The positive yield dynamics observed in the modeled scenarios indicate that adaptive irrigation supports the maintenance of an optimal plant water balance during the critical phases of the growing season. In this case, the increase in productivity should be interpreted not as a direct consequence of higher water consumption, but as the result of a more efficient spatial and temporal distribution of irrigation events.

The economic indicators demonstrate that the greatest effect is achieved with medium-term and long-term use of the system. The initial costs of introducing digital monitoring tools can be offset by reductions in water and electricity expenses and by the decrease in yield losses. This makes it possible to treat the model as an instrument not only of operational management but also of strategic resource planning.

Comparison with other studies. The obtained results are consistent with the conclusions of contemporary studies in the field of precision agriculture and intelligent irrigation management systems, which emphasize the importance of adaptive algorithms in improving water productivity. In line with other works, it has been established that the use of forecasting models and sensor-based monitoring makes it possible to reduce unproductive water losses and to improve the stability of agrotechnological processes.

At the same time, the proposed approach is distinguished by a more comprehensive integration of economic analysis and scenario modeling. In many previous studies, the main attention was focused predominantly on the agronomic or technical parameters of irrigation, whereas the economic feasibility of adaptive management was assessed only in a fragmentary manner. In the present study, the model makes it possible to treat the effectiveness of the system as a multifactorial indicator that encompasses productivity, resource conservation, and financial sustainability.

In addition, in contrast to approaches oriented toward static climatic conditions, the present model takes into account the variability of external factors and potential risk scenarios. This broadens its applied value for regions with unstable hydrometeorological conditions and enhances the adaptability of management decisions.

Scientific novelty. The scientific novelty of the study lies in the development of an integrated adaptive irrigation management model that combines elements of mathematical forecasting, scenario analysis, and economic efficiency assessment. In contrast to traditional approaches, in which irrigation decisions are formed predominantly on the basis of normative values or individual indicators of soil moisture, the proposed model takes into account the interdependence among climatic, agronomic, and economic parameters.

A substantial scientific contribution is the application of the scenario approach to modeling the behavior of the system under various conditions of resource availability and changes in the external environment. This makes it possible to analyze not only the current efficiency of irrigation but also to forecast the stability of the system under conditions of heightened uncertainty. Such an approach broadens classical methods of optimizing water use, which often do not take into account the multiplicity of risk variants.

An additional element of novelty consists in the combination of the technical efficiency of irrigation control with economic criteria for decision-making. The proposed model makes it possible to assess not only the agronomic result but also the impact of management decisions on costs, energy efficiency, and the profitability of production. This forms an interdisciplinary approach to irrigation management with the potential for further development within systems of digital farming.

Practical significance. The practical significance of the study lies in the possibility of implementing the adaptive irrigation management model within actual agricultural production systems in order to enhance the efficiency of water resource use. The proposed approach can be applied to optimize irrigation regimes under conditions of limited water supply, seasonal climatic variability, and rising energy costs.

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For agricultural enterprises, the model provides a basis for reducing operating costs through more accurate irrigation planning, the elimination of excessive water use, and a lower load on pumping equipment. This produces a direct economic effect by decreasing the costs of infrastructure operation and by improving the stability of crop yields. The practical value also consists in the possibility of integrating the model with sensor platforms, remote monitoring systems, and elements of automated control.

At the level of strategic planning, the results of the study can be used in shaping resource-conservation policies, in the modernization of irrigation networks, and in the implementation of digital technologies in agriculture. The model thus has significance not only for individual farms but also for the broader development of sustainable water use and for enhancing the adaptability of the agricultural sector to climate change.

Conclusions

The study synthesizes the theoretical and methodological foundations of adaptive irrigation management under climate change and substantiates the rationale for transitioning from conventional approaches to flexible, data-driven decision-making models. Effective water resource management in the agricultural sector requires the integration of yield forecasting, scenario analysis, and economic assessment into a unified analytical system. An adaptive irrigation management model has been developed and formalized, grounded in the interaction among climatic, agronomic, and economic parameters and incorporating iterative algorithms for the adaptation of management decisions. The key parameters of the model have been substantiated, their influence on system performance outcomes has been determined, and the importance of informational support has been demonstrated, including the use of remote sensing data, meteorological monitoring, and statistical sources. The applicability of the scenario-based approach to evaluating irrigation system performance under uncertainty has been analyzed, enabling the identification of critical risk factors and the delineation of alternative development trajectories.

The economic efficiency assessment of the proposed model confirms its advantages over conventional approaches, particularly in terms of improved water use efficiency, yield stabilization, and reduced irrigation costs. The application of the adaptive approach is shown to contribute to increased agricultural profitability and enhanced resilience to climatic variability. The sensitivity analysis conducted enabled the determination of the influence of key climatic parameters on modeling outcomes and the identification of the system's adaptability boundaries under conditions of extreme environmental change. The highest model effectiveness is achieved when data are updated in a timely manner and responses to changing external factors remain flexible, underscoring the need for continuous improvement of informational and analytical support. Directions for further research include expanding the functional capabilities of the model through the integration of artificial intelligence methods, improving yield forecast accuracy, and adapting the model to diverse agroecological conditions.

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