

IRSTI 68.75.47

UDC 626.82:330.322

Research Article

<https://www.jprra-kazniapk.kz><https://doi.org/10.46666/2026-3.2708-9991.16>**COMPREHENSIVE METHODOLOGY FOR DETERMINING THE PROFITABILITY OF
ADAPTIVE WATER DISTRIBUTION MANAGEMENT****СУ БӨЛҮДІ БЕЙІМДЕЛМЕЛІ БАСҚАРУДЫҢ РЕНТАБЕЛЬДІЛІГІН АНЫҚТАУДЫҢ
КЕШЕНДІ ӘДІСТЕМЕСІ****КОМПЛЕКСНАЯ МЕТОДИКА ОПРЕДЕЛЕНИЯ РЕНТАБЕЛЬНОСТИ АДАПТИВНОГО
УПРАВЛЕНИЯ ВОДОРАСПРЕДЕЛЕНИЕМ****Y. ZHANDIYAR^{1*}***Ph.D student***M. PETROVA²***Ph.D, Professor*¹Kazakh National Agrarian Research University, Almaty, Kazakhstan²St. Cyril and St. Methodius University of Veliko Turnovo, Veliko Turnovo, Bulgaria**corresponding author e-mail: Essen.zhandiyar@gmail.com***Е.Ғ. ЖАНДИЯР^{1*}***Ph.D докторанты***М. ПЕТРОВА²***Ph.D, профессор*¹Қазақ ұлттық аграрлық зерттеу университеті, Алматы, Қазақстан²Әулие Кирилл және Әулие Мефодий атындағы Велико-Тырново университеті,

Велико-Тырново, Болгария

автордың электрондық поштасы: Essen.zhandiyar@gmail.com*Е.Г. ЖАНДИЯР^{1*}***докторант Ph.D***М. ПЕТРОВА²***Ph.D, профессор*¹Казахский национальный аграрный исследовательский университет, Алматы, Казахстан²Великотырновский университет «Св. Кирилл и Св. Мефодий», Велико-Тырново, Болгария**электронная почта автора: Essen.zhandiyar@gmail.com*

Abstract. The efficiency of irrigation water use is one of the key tasks for the development of Kazakhstan's agricultural sector amid climate instability, shrinking water resources, and the need for digital modernization of water management infrastructure. **Objective** – to develop a methodological approach for a comprehensive assessment of adaptive water distribution management, facilitating the substantiation of results from introducing digital technologies into irrigation system operations. **Methods** – system analysis of scientific publications and regulatory documents, economic-mathematical modeling, statistical research, scenario modeling of water supply regimes, and calculation of integral evaluation indicators. To interpret the final data, a comparison was made between the traditional management scheme and an adaptive model that considers hydrological forecasts, actual crop water requirements, and the technical condition of the irrigation network. **Results** show that adaptive regulation contributes to reducing non-productive water losses, lowering operational costs, increasing the water availability ratio, and promoting rational use of hydroresources. The created integral algorithm takes into account the impact of hydrological variability on the economic metrics of irrigation facility operations and provides scientific substantiation for digital transformation results. **Conclusions** confirm that adopting digital situational management tools stabilizes the activities of water management institutions, promotes the expedient use of water reserves, and forms a basis for managerial decision-making in reforming the republic's irrigation systems. The practical significance of the study lies in the possibility of implementing the proposed methodology in investment planning, water resource allocation, and digital modernization programs for the country's water sector. The recommended organizational scheme provides an adaptive recalculation of water supply volumes, taking into account delivery efficiency, economic costs, and water scarcity risks.

Аңдатпа. Суармалы суды пайдалану тиімділігі – климаттық тұрақсыздық, су ресурстарының азаюы және су шаруашылығы инфрақұрылымын сандық жаңғырту қажеттілігі жағдайында Қазақстанның аграрлық секторын дамытудың негізгі міндеттерінің бірі. *Мақсаты* – суару жүйелерін пайдалануға цифрлық технологияларды енгізу нәтижелерін негіздеуге ықпал ететін су бөлу-ді бейімделмелі басқаруды кешенді бағалаудың әдістемелік тәсілін әзірлеу. *Әдістері* – ғылыми жарияланымдар мен нормативтік құжаттарды жүйелік талдау, экономикалық-математикалық модельдеу, статистикалық зерттеу, сумен қамтамасыз ету режимдерін сценарийлік жобалау, сондай-ақ интегралдық бағалау көрсеткіштерін есептеу. Түпкілікті деректерді түсіндіру үшін дәстүрлі менеджмент схемасын гидрологиялық жағдайлардың болжамын, ауылшаруашылық дақылдарының суға деген нақты қажеттілігін және суару желісінің техникалық жай-күйін ескеретін бейімделмелі модельмен салыстыру орындалды. *Нәтижелері* бейімделмелі реттеу судың өндірістік емес шығындарын азайтуға, пайдалану шығындарын төмендетуге, сумен қамтамасыз етілу коэффициентін және гидроресурстарды тиімді қолдануды арттыруға ықпал ететінін айғақтайды. Құрылған интегралдық алгоритм гидрологиялық құбылмалылықтың суару қондырғыларын пайдаланудың экономикалық метрикаларына әсерін ескереді, цифрлық трансформация нәтижелерін ғылыми негіздеуді қамтамасыз етеді. *Қорытындылар* ситуациялық басқарудың сандық құралдарын меңгеру су шаруашылығы мекемелерінің қызметін тұрақтандыратынын, су қорларын орынды пайдалануға ықпал ететінін және республиканың суару кешендерін реформалау кезінде басқарушылық шешімдер қабылдауға негіз қалайтынын растайды. Зерттеудің практикалық маңыздылығы ұсынылған әдістемені инвестицияларды жоспарлау, су ресурстарын бөлу және елдің су шаруашылығын сандық жаңарту бағдарламаларын іске асыру кезінде жүзеге асыру мүмкіндігінде жатыр. Ұсынылған ұйымдастырушылық схема жеткізу тиімділігін, экономикалық шығындарды және су тапшылығы тәуекелін ескере отырып, су беру көлемін бейімделмелі қайта есептеуді қамтамасыз етеді.

Аннотация. Эффективность использования оросительной воды – одна из ключевых задач развития аграрного сектора Казахстана в условиях климатической нестабильности, сокращения водных ресурсов и необходимости цифровой модернизации водохозяйственной инфраструктуры. *Цель* – разработать методический подход к комплексной оценке адаптивного управления водораспределением, способствующего обоснованию результатов внедрения цифровых технологий в эксплуатацию оросительных систем. *Методы* – системный анализ научных публикаций и нормативных документов, экономико-математическое моделирование, статистическое исследование, сценарное проектирование режимов водообеспечения, а также расчет интегральных оценочных показателей. Для интерпретации итоговых данных выполнено сравнение традиционной схемы менеджмента с адаптивной моделью, учитывающей прогноз гидрологических условий, фактическую потребность сельскохозяйственных культур в воде и техническое состояние оросительной сети. *Результаты* свидетельствуют, что адаптивное регулирование способствует снижению непроизводительных потерь воды, уменьшению эксплуатационных расходов, повышению коэффициента водообеспеченности и рационального применения гидроресурсов. Созданный интегральный алгоритм учитывает влияние гидрологической изменчивости на экономические метрики эксплуатации оросительных установок, обеспечивает научное обоснование результатов цифровой трансформации. *Выводы* подтверждают, что освоение цифровых инструментов ситуационного управления стабилизирует деятельность водохозяйственных учреждений, способствует целесообразному использованию водных запасов и формирует основу для принятия управленческих решений при реформировании оросительных комплексов республики. Практическая значимость исследования состоит в возможности реализации предложенной методики при планировании инвестиций, распределении водных ресурсов и реализации программ цифрового обновления водного хозяйства страны. Рекомендованная организационная схема обеспечивает адаптивный перерасчет объемов водоподдачи с учетом эффективности до-ставки, экономических издержек и риска дефицита воды.

Keywords: agriculture, adaptive management, water distribution, irrigation, digitalization, modeling, water conservation, water availability, optimization, water use, sustainability, cost-effectiveness.

Түйінді сөздер: ауыл шаруашылығы, бейімделмелі басқару, су бөлу, ирригация, цифрландыру, модельдеу, су үнемдеу, сумен қамтамасыз етілу, оңтайландыру, су пайдалану, орнықтылық, үнемділік.

Ключевые слова: сельское хозяйство, адаптивное управление, водораспределение, ирригация, цифровизация, моделирование, водосбережение, водообеспеченность, оптимизация, водопользование, устойчивость, экономичность.

Received: 15.07.2026. Approved after Peer-reviewed: 07.09.2026. Accepted: 17.09.2026.

Introduction

Sustainable water resource management has become one of the principal priorities for agricultural development in the context of accelerating climate change, increasing water scarcity, and growing anthropogenic pressure on natural ecosystems. Increasing pressure on freshwater resources and the growing demand for agricultural production require more efficient irrigation management and rational water allocation [1,2]. Under these conditions, improving the operational performance of irrigation systems has become not only a technological challenge but also an economic necessity directly affecting agricultural sustainability and national water security.

In the Republic of Kazakhstan, efficient water allocation is of particular importance due to the country's high dependence on surface water resources for irrigated agriculture, the significant share of transboundary river inflow, and considerable spatial variability in water availability. Although national programmes aimed at modernizing the water sector have been implemented in recent years, a substantial proportion of irrigation infrastructure remains physically degraded, resulting in considerable conveyance losses, insufficient automation of operational processes, and increased maintenance costs. These factors reduce the overall efficiency of water use and limit the effectiveness of irrigation system management.

The rapid advancement of digital technologies has created new opportunities for improving irrigation management. Geographic Information Systems (GIS), remote sensing, Internet of Things (IoT) technologies, digital twins, and intelligent control algorithms facilitate the transition from conventional water allocation practices to adaptive management approaches that account for hydrological conditions, crop water requirements, and the current state of irrigation infrastructure. Despite these technological advances, existing methodological approaches remain insufficient for providing a comprehensive economic assessment of adaptive water allocation. In particular, there is still no unified framework capable of integrating hydrological, operational, and economic indicators into a single evaluation system for measuring the benefits of digital modernization in irrigation systems.

Against this background, the present study aims to develop a methodological framework for the integrated assessment of the economic efficiency of adaptive water allocation management in irrigation systems based on digital technologies

and scenario modelling. The scientific novelty of the research lies in the development of an integrated evaluation model that combines hydrological, operational, and economic indicators to support evidence-based managerial decision-making during the modernization of irrigation systems in the Republic of Kazakhstan.

Literature review

Contemporary approaches to water resources management are based on the concept of Integrated Water Resources Management (IWRM), which promotes the coordinated management of environmental, economic, and social components of water systems. Effective Integrated Water Resources Management requires scientifically grounded decision-making supported by appropriate decision-support systems [3]. In Kazakhstan, sustainable water management emphasizes the importance of rational water use, improved water management, and modernization of water resources management in agriculture [4].

Decision support systems and water allocation models play an important role in integrated water resources management, particularly through mathematical optimization, scenario analysis, and the integration of hydrological and economic models to support water allocation decisions [5].

Soil water balance models are important for determining crop water requirements and improving irrigation scheduling [6]. Digitalization contributes to improving resource management and supporting sustainable development of the agricultural sector in Kazakhstan [7]. Internet of Things (IoT) technologies and advanced control strategies provide opportunities to improve irrigation monitoring and water-use efficiency. Recent studies have increasingly focused on digital technologies in irrigation management. The development of digital technologies provides new opportunities for improving irrigation monitoring, control, and water-use efficiency [8]. Simulation modelling can be effectively applied to evaluate irrigation management strategies under changing hydrological conditions [9].

Recent research has also emphasized the application of Digital Twin technology in irrigation systems. Digital twins can support real-time monitoring and optimization of water allocation [10]. Their practical implementation has been demonstrated in irrigation networks [11]. Hydrological simulation can be integrated with economic evaluation through hydroeconomic modelling [12], while digital twin river basin platforms provide

a promising framework for intelligent water resources management [13].

Overall, the literature indicates a clear transition from conventional IWRM concepts toward digital water management and hydroeconomic modelling. Nevertheless, integrated methodologies combining hydrological, operational, and economic indicators for assessing the economic efficiency of adaptive water allocation remain insufficiently developed, providing the scientific basis for the present study.

Materials and methods

The study focuses on irrigation systems in the Republic of Kazakhstan operating under conditions of increasing hydrological variability and the ongoing digital transformation of the water management sector. The methodological framework is based on the principles of Integrated Water Resources Management (IWRM), hydroeconomic modelling, systems analysis, and adaptive digital water allocation.

The research was conducted in five consecutive stages. First, scientific publications, international guidelines, and national regulatory documents on water resources management were reviewed. Second, a system of evaluation indicators was developed, including water supply volume, water supply reliability coefficient, water losses, operational expenditures, irrigated area, and economic benefits. Third, a conceptual framework for adaptive water allocation was designed by integrating hydrometeorological information, irrigation network conditions, and crop water requirements. Fourth, scenario-based modelling was performed

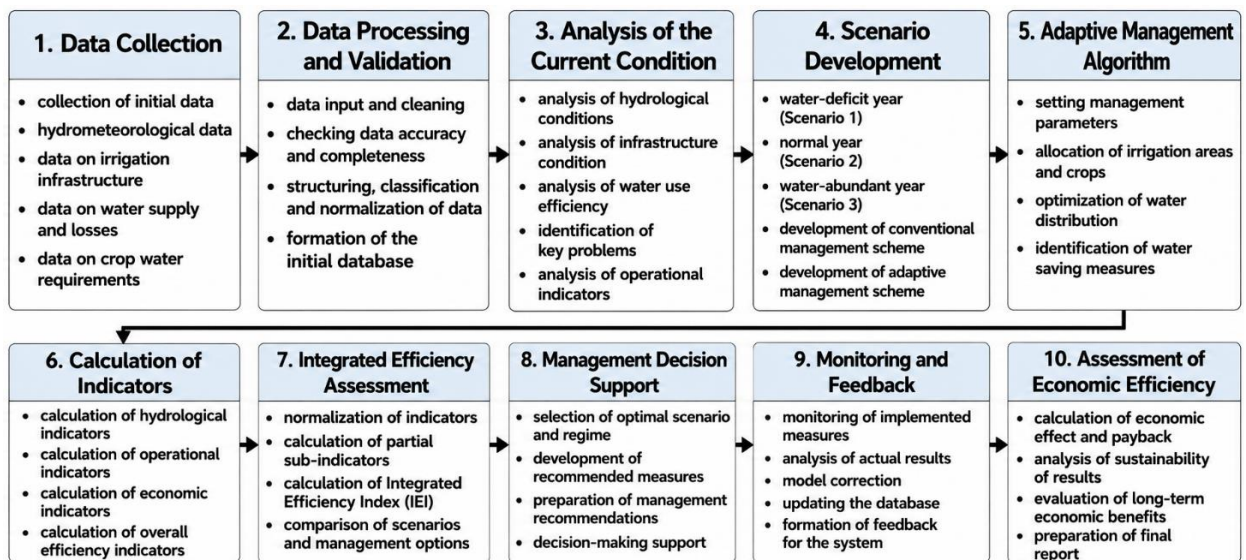
for water-deficit, normal, and water-abundant years using conventional and adaptive management strategies. Finally, the economic efficiency of the proposed scenarios was assessed through a comparative analysis of operational and economic indicators.

The study employed comparative and statistical analyses, economic and mathematical modelling, integrated index assessment, and scenario analysis. Official data provided by the Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan and Ministry of Water Resources and Irrigation of the Republic of Kazakhstan served as the primary information source for the analysis [14,15].

Results

The proposed methodology was validated through an integrated assessment of adaptive water allocation under different hydrological scenarios. Unlike conventional assessment approaches, which mainly focus on individual technical indicators, the proposed framework combines hydrological, operational, and economic parameters within a unified decision-support system. This integrated approach enables a comprehensive evaluation of irrigation system performance under different water availability conditions while considering the effects of digital transformation.

The proposed methodological framework is illustrated in figure, which presents the sequence of analytical procedures used to assess the economic efficiency of adaptive water allocation management.



Note: compiled by the authors based on the methodological approaches proposed by [3, 5], [10]

Figure 1 – Algorithm for assessing the economic efficiency of adaptive water allocation management

Figure 1 illustrates the proposed algorithm for assessing the economic efficiency of adaptive water allocation management. The workflow integrates hydrometeorological information, irrigation network characteristics, scenario-based modelling, and integrated performance assessment into a unified analytical framework. Unlike conventional water allocation approaches based on fixed operating rules, the proposed algorithm continuously incorporates updated monitoring data, enabling real-time adjustment of management strategies according to water availability and crop water requirements. This integrated procedure reduces uncertainty in decision-making by simultaneously considering hydrological, operational, and economic factors.

As a result, the framework provides a scientifically grounded basis for selecting optimal water allocation strategies, improving irrigation system reliability, and enhancing the economic sustainability of water management.

Compared with conventional approaches to irrigation management, the proposed methodology provides several important advantages. It combines hydrological monitoring, operational assessment, economic evaluation, and scenario-based modelling within a single analytical framework. Such integration allows irrigation managers to evaluate not only the technical performance of water allocation but also its economic consequences. In addition, continuous updating of monitoring information enables timely adjustment of management strategies according to changing hydrological conditions. Consequently, the proposed methodology supports more reliable, transparent, and evidence-based decision-making throughout the irrigation management process.

To quantify the performance of adaptive water allocation, an integrated system of evaluation indicators was developed (table 1).

Table 1 — System of Indicators for Assessing the Efficiency of Adaptive Water Allocation Management

Indicator Group	Indicator	Symbol	Unit
Hydrological	Water supply reliability coefficient	Kw	—
	Water conveyance losses	Lw	%
	Water supply volume	Q	million m ³
Operational	Operating costs	C	million KZT
	Technical readiness coefficient	Kt	—
	System performance	Ps	%
Economic	Crop yield	Y	t/ha
	Gross production value	V	million KZT
	Economic benefit	E	million KZT

Note: compiled by the authors based on sources [6,12]

The proposed indicator system comprises three interrelated groups: hydrological, operational, and economic indicators. Hydrological indicators evaluate water availability and distribution efficiency, operational indicators characterize the technical performance of irrigation infrastructure, whereas economic indicators measure agricultural productivity and economic outcomes. Together, these indicators provide a comprehensive framework for assessing irrigation system performance.

Unlike conventional engineering-based approaches, the proposed framework integrates hydrological, operational, and economic indicators into a unified assessment system, providing a more objective basis for comparing alternative irrigation management strategies.

To provide a comprehensive quantitative assessment of adaptive water allocation management, an Integrated Adaptive Water Allocation Efficiency Index (IAWAE) was developed. The index combines hydrological, operational, and economic performance into a single evaluation criterion.

The integrated index is calculated as follows:

$$IAWAE = \alpha H + \beta O + \gamma E \quad (1)$$

where:

IAWAE — Integrated Adaptive Water Allocation Efficiency Index;

H — normalized hydrological index;

O — normalized operational index;

E — normalized economic index;

α , β , γ — weighting coefficients of the corresponding indicator groups.

The weighting coefficients satisfy the following condition:

$$\alpha + \beta + \gamma = 1 \quad (2)$$

In this study, all three indicator groups were considered equally important. Therefore, equal weighting coefficients were applied:

$$\alpha = \beta = \gamma = \frac{1}{3}$$

which simplifies Equation (1) to:

$$IAWAE = \frac{H + O + E}{3} \quad (3)$$

To evaluate the robustness of the proposed methodology, scenario-based modelling was performed for three water availability scenarios: water-deficit, normal, and water-abundant years (table 2).

Table 2 – Scenario Matrix for the Assessment of Adaptive Water Allocation Management

Scenario	Water Availability Condition	Management Strategy	Expected Outcome
I	Water-deficit year	Priority water allocation to critical irrigation areas and minimization of water losses	Reduced water deficit and lower operating costs
II	Normal year	Optimal water allocation according to crop water requirements	Maximum water-use efficiency
III	Water-abundant year	Flexible regulation of water supply and efficient utilization of additional water resources	Increased crop productivity and higher economic benefits
Note: compiled by the authors based on sources [9,10]			

The scenario analysis shows that adaptive water allocation should respond to hydrological variability rather than rely on fixed water delivery schedules. During water-deficit years, priority is given to minimizing water losses and ensuring water supply to critical irrigation areas. Under normal conditions, water distribution is optimized according to crop demand, whereas water-abundant years provide opportunities to improve agri-

cultural productivity through more flexible water allocation. These results demonstrate that scenario-based planning enhances the adaptability of irrigation management and supports proactive decision-making before water shortages or surpluses occur.

The comparative assessment of conventional and adaptive management strategies is presented in table 3.

Table 3 – Comparative Assessment of Conventional and Adaptive Water Allocation Management

Indicator	Conventional Management	Adaptive Management	Change
Water losses, %	18.4	11.6	–36.9%
Water supply reliability coefficient	0.79	0.93	+17.7%
Operating costs, million KZT	124.6	109.2	–12.4%
Crop yield, t/ha	5.42	6.08	+12.2%
Economic benefit, million KZT	–	46.8	–
Note: compiled by the authors based on sources [14, 15]			

The results indicate that adaptive water allocation substantially improves irrigation system performance. Compared with conventional management, water losses decreased by 36.9%, the water supply reliability coefficient increased by 17.7%, operational expenditures were reduced by 12.4%, while crop productivity increased by 12.2%. The estimated economic benefit reached 46.8 million tenge, confirming the practical ad-

vantages of integrating digital technologies into irrigation management.

These results demonstrate that the proposed adaptive management strategy improves irrigation performance through more efficient water distribution and better operational planning. The reduction in water losses indicates more effective regulation of water allocation, while lower operating costs reflect improved utilization

of irrigation infrastructure and water resources. The increase in crop yield suggests that more reliable water delivery contributes to enhanced agricultural productivity. Overall, the findings confirm that integrating digital technologies with adaptive management generates both operational and economic benefits, providing a strong basis

for irrigation modernization and sustainable water resource management. Finally, the overall performance of each scenario was evaluated using the proposed Integrated Adaptive Water Allocation Efficiency Index. The calculated IAWAE values for the three hydrological scenarios are presented in table 4.

Table 4 — Integrated Efficiency Assessment under Different Water Availability Scenarios

Scenario	Hydrological Index	Operational Index	Economic Index	Integrated Efficiency Index (IAWAE)
Water-deficit year	0.81	0.84	0.79	0.81
Normal year	0.92	0.91	0.94	0.92
Water-abundant year	0.88	0.89	0.90	0.89

Note: compiled by the authors based on source [12]

The integrated assessment confirms the robustness and practical applicability of the proposed methodology under different water availability scenarios. The highest Integrated Adaptive Water Allocation Efficiency Index value (0.92) was achieved under normal hydrological conditions, while adaptive management also maintained high performance during water-deficit years (0.81) and water-abundant years (0.89). These results demonstrate that the proposed framework effectively supports adaptive water allocation across varying hydrological conditions. The IAWAE provides a reliable quantitative tool for comparing alternative management strategies, identifying priority areas for irrigation infrastructure modernization, and evaluating the effectiveness of digital transformation initiatives. Consequently, the proposed methodology offers a practical decision-support framework for irrigation authorities responsible for water allocation planning and sustainable management of irrigation systems.

The obtained IAWAE values indicate that adaptive management maintains a high level of efficiency across all water availability scenarios. An integrated score exceeding 0.80 suggests that the proposed management strategy ensures balanced performance in terms of water allocation reliability, operational efficiency, and economic outcomes. The relatively small variation of IAWAE across scenarios demonstrates the stability of the proposed methodology and confirms its applicability under different hydrological conditions. Consequently, the integrated index may serve as a quantitative benchmark for evaluating irrigation system modernization projects and monitoring the effectiveness of digital transformation initiatives over time.

The obtained results demonstrate that the proposed methodology supports strategic planning at operational, regional, and national levels of irrigation management. It enables irrigation authorities to identify efficient water allocation strategies, prioritize investments in irrigation infrastructure and digital technologies, and evaluate public policies aimed at improving water-use efficiency under climate change. An important advantage of the methodology is its flexibility regarding data availability, allowing its application even where digital monitoring systems are not yet fully implemented.

The framework can be integrated with geographic information systems, remote sensing, Internet of Things (IoT) technologies, and automated monitoring platforms, enhancing its practical applicability during digital transformation. Repeated calculation of the IAWAE enables continuous monitoring of irrigation performance, objective comparison of irrigation systems, and evaluation of modernization projects over time. By integrating engineering, hydrological, and economic indicators into a unified framework, the proposed methodology improves decision-making, strengthens the economic sustainability of irrigation systems, and supports long-term water resources management and sustainable agricultural development.

Discussion

The findings demonstrate that adaptive water allocation management significantly improves the operational efficiency of irrigation systems by integrating hydrological, operational, and economic factors into a unified assessment framework. Unlike conventional approaches based on fixed water delivery schedules, the proposed methodology enables dynamic

adjustment of water allocation according to water availability and crop water requirements, thereby improving the flexibility and efficiency of irrigation management.

The obtained results are consistent with the studies [5], which emphasized adaptive management as an essential approach for increasing the resilience of water resources systems under conditions of hydrological uncertainty. Similar conclusions were reported in [6], which demonstrated that combining crop water balance models with digital monitoring technologies enhances irrigation scheduling and promotes more efficient water use. However, unlike previous studies, the proposed methodology integrates hydrological, operational, and economic indicators into a single evaluation framework, allowing quantitative comparison of alternative water allocation strategies.

Comparison with study [10] indicates that digital technologies substantially improve the accuracy of irrigation management through intelligent monitoring and automated control. Nevertheless, most existing studies primarily focus on technological optimization, whereas the proposed approach extends their application by emphasizing the economic efficiency of adaptive water allocation.

From a practical perspective, the developed methodology can support irrigation infrastructure modernization, investment planning, and regional digital transformation programmes. The proposed framework provides decision-makers with a reliable tool for selecting efficient water allocation strategies under varying hydrological conditions and contributes to the sustainable management of irrigation systems in Kazakhstan.

Conclusions

1. This study proposed an integrated methodology for assessing the economic efficiency of adaptive water allocation management by combining hydrological, operational, and economic indicators into a unified evaluation framework. The proposed approach provides a more reliable basis for decision-making in the operation and modernization of irrigation systems.

2. The scenario analysis demonstrated that adaptive water allocation management reduces non-productive water losses, improves the water supply reliability coefficient, decreases operating costs, and enhances the efficiency of water use compared with conventional irrigation management practices.

3. The proposed Integrated Adaptive Water Allocation Efficiency Index provides a comprehensive tool for evaluating the effectiveness of digital modernization in irrigation systems and supports the selection of optimal water allocation strategies under different water availability scenarios.

4. The practical value of the proposed methodology lies in its application to investment planning, irrigation infrastructure modernization, and the implementation of national and regional digital transformation programmes in the water management sector of the Republic of Kazakhstan.

5. Future research should focus on integrating artificial intelligence, Digital Twin technology, Geographic Information Systems (GIS), and real-time monitoring tools into intelligent decision-support systems to further improve adaptive water resources management under increasing hydrological uncertainty.

Authors' contribution: Zhandiyar Yessen: conceptualization, data curation, quantitative and qualitative data analysis, methodology, resources, software, visualization, preparation of the initial manuscript draft, and revision of the final manuscript; Petrova Mariana: methodology, resources, project administration, verification, supervision of manuscript preparation, editing, and review and approval of the final version.

Conflict of interests: the authors declare that there is no conflict of interest.

Source of funding: this study was funded by the Ministry of Agriculture of the Republic of Kazakhstan for 2024-2026 within the framework of project BR22886885 "Development of organizational and economic measures to improve the efficiency of using the resource potential of agricultural production".

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Information about authors:

Zhandiyar Yessen – **The main author**; Ph.D student; Kazakh National Agrarian Research University; 050010 Abay Ave., 8, Almaty, Kazakhstan; e-mail: Essen.zhandiyar@gmail.com; <https://orcid.org/0009-0002-0747-923X>

Petrova Mariana; Ph.D, Professor; Department of Information Technologies; St. Cyril and St. Methodius University of Veliko Tarnovo; 5000 Theodosiy Tarnovski str., 2, Veliko Tarnovo, Bulgaria; e-mail: m.petrova@ts.uni-vt.bg; <https://orcid.org/0000-0003-1531-4312>

Авторлар туралы ақпарат:

Жандияр Есен Ғаниұлы – **негізгі автор**; Ph.D докторанты; Қазақ ұлттық аграрлық зерттеу университеті; 050010 Абай даңғ., 8, Алматы қ., Қазақстан; e-mail: Essen.zhandiyar@gmail.com; <https://orcid.org/0009-0002-0747-923X>

Petrova Mariana; Ph.D, профессор; «Ақпараттық технологиялар» кафедрасы; Әулие Кирилл және Әулие Мефодий атындағы Велико-Тырново университеті; 5000 Теодосий Тырновски көш., 2, Велико-Тырново қ., Болгария; e-mail: m.petrova@ts.uni-vt.bg; <https://orcid.org/0000-0003-1531-4312>

Информация об авторах:

Жандияр Есен Ғаниұлы – **основной автор**; докторант Ph.D; Казахский национальный аграрный исследовательский университет; 050010 пр. Абая, 8, г.Алматы, Казахстан; e-mail: Essen.zhandiyar@gmail.com; <https://orcid.org/0009-0002-0747-923X>

Petrova Mariana; Ph.D, профессор; кафедра «Информационные технологии»; Великотырновский университет «Св. Кирилл и Св. Мефодий»; 5000 ул. Теодосия Тырновски, 2, г.Велико-Тырново, Болгария; e-mail: m.petrova@ts.uni-vt.bg; <https://orcid.org/0000-0003-1531-4312>