How to cite: S.S. Malikov, Y.G. Zhandiyar, A.E. Aldiyarova, R.S. Bespayeva, Zh. S. Khussainova (2026). Integration of digital technologies into water distribution management in irrigation systems. *Eurasian Agrotechnical Journal*, 2(130), 206-216. DOI: https://doi.org/10.51452/eaj.2026.2(130).2245

UDC631. 46: [631.862:636.2] **Research article**

Integration of digital technologies into water distribution management in irrigation systems

Sungat S. Malikov[1], Yessen G. Zhandiyar[1], Ainura E. Aldiyarova[1]
Roza S. Bespayeva[2], Zhibek S. Khussainova[2]

[1]Kazakh National Agrarian Research University, Almaty, Kazakhstan

[2]S.Seifullin Kazakh Agrotechnical Research University, Astana, Kazakhstan

Corresponding author: Yessen G. Zhandiyar: Essen.zhandiyar@gmail.com
Co-authors: (1: SM): SunGate81@gmail.com; (2: AA) ainura.aldiarova@kaznaru.edu.kz
(3: RB) r.bespayeva@kazatu.edu.kz; (4: ZhKh) zh.khussainova@kazatu.edu.kz
Received: 10.06.2026 **Accepted:** 30.06.2026 **Published:** 30.06.2026

Abstract

Background and Aim. Climate change, growing pressure on water resources, and increasing agricultural demand for water require more efficient irrigation management. The digital transformation of water management improves water-use efficiency and strengthens the resilience of irrigation systems. This study evaluates water distribution efficiency in the Almaty region and substantiates the use of digital technologies for water resources management under stochastic variability in water availability.

Materials and methods. The study was based on statistical data on water use in the Almaty region for 2010–2024, hydrological records of the Ili River basin, and official data from Kazakhstan's authorized water management agencies. Systems analysis, comparative assessment, statistical analysis, correlation analysis, and regression modeling were applied. The coefficients of variation, correlation, and determination were calculated to evaluate water distribution efficiency. The applicability of GIS, IoT, SCADA systems, digital twins, and artificial intelligence toirrigation management was also assessed.

Results. The results indicate an improvement in the efficiency of water resources management. Water withdrawal increased by 20.8%, while the water distribution efficiency coefficient rose from 0.62 to 0.77 and water losses decreased from 38% to 25%. Irrigation water consumption per unit area declined by 22%, resulting in estimated annual water savings of approximately 640 million m^3. A strong negative correlation was found between water losses and system efficiency ($r = –0.89$). The regression model demonstrated high explanatory power ($R^2 = 0.86$), confirming the robustness of the results. The implementation of digital technologies contributes to more efficient water allocation, reduces water losses, and greater resilience of irrigation systems.

Conclusion. Digital technologies enhance the efficiency and sustainability of water resources management by improving water distribution, reducing losses, and the adaptability of irrigation systemsto hydrological variability. The proposed digital–stochastic framework provides a scientific and methodological basis for developing digital water management platforms and decision-support systems, as well as for the practical implementation of adaptive water allocation technologies in irrigation management.

Keywords: digitalization; water distribution; digital technologies; irrigation systems; water resources; Almaty region.

Introduction

Climate change, increasing anthropogenic pressure, and growing agricultural demand for water have become critical factors affecting the sustainability of agricultural production. According to international assessments, agriculture accounts for nearly 70% of global freshwater withdrawals, while water scarcity is increasingly recognized as one of the major threats to food security [1]. This issue is particularly important in regions with extensive irrigated agriculture, where the efficiency of water allocation directly affects crop productivity and the effective use of land resources [2, 3].

The Almaty region is one of Kazakhstan's major irrigated agricultural areas in terms of both irrigated land area and water use. The formation of regional water resources depends on hydrological, climatic, and anthropogenic factors, resulting in considerable interannual variability and an increased probability of water shortages [4, 5]. Ongoing climate change is altering established water supply regimes and intensifying risks to agricultural production systems[6].

Conventional approaches to water distribution management, which rely on fixed water delivery schedules and long-term mean runoff values, have become less effective under current environmental conditions. Such methods do not adequately account for the stochastic nature of water resource formation or the variability of hydrological processes [7, 8]. Therefore, integrated water resources management has gained increasing importance, as it emphasizes the consideration of economic, environmental, and social factors in decision-making[1, 9].

Recent studies indicate that the digital transformation of the water sector offers significant opportunities to improve water-use efficiency. The application of geographic information systems (GIS), Internet of Things (IoT) technologies, SCADA systems, decision-support systems (DSS), artificial intelligence methods, and digital twin concepts enables continuous monitoring of water systems and enhances the quality of water management decisions [10]. In recent years, machine learning approaches have been increasingly used for hydrological forecasting, flood risk assessment, and water resources management [11]. Furthermore, integrated modeling frameworks and decision-support systems facilitate comprehensive analysis of water-useprocesses and contribute to more effective management of water infrastructure [12, 13].

The adoption of digital technologies has demonstrated considerable potential to reduce water losses, improve the accuracy of water demand forecasts, and increase the efficiency of water allocation[14, 15]. However, most previous studies have focused on individual aspects of digitalization and have paid limited attention to the influence of stochastic water availability on irrigation management [7, 11].

In Kazakhstan, the integrated application of digital technologies combined with stochastic modeling of water resources remains insufficiently investigated. At the same time, the digital transformation of the water sector has become one of the strategic priorities of national water policy, as reflected in the Water Resources Management Development Concept of the Republic of Kazakhstan for 2024–2030 and the Comprehensive Water Sector Development Plan of the Republic of Kazakhstan [16].

The present study aims to assess the efficiency of water distribution under conditions of stochastic variability in water availability and to substantiate the application of digital technologies for irrigation system management. The scientific novelty of the research lies in the development of an integrated digital–stochastic approach to water distribution management that combines statistical analysis, assessment of water resource uncertainty, and advanced digital management technologies. The proposed framework makes it possible to account for interannual fluctuations in water availability and adapt water allocation regimes to the challenges associated with climate change and increasing water scarcity.

Materials and Methods

The study was based on a comprehensive assessment of water resources management and water distribution processes in the irrigation systems of the Almaty region, Republic of Kazakhstan. The information base included statistical data on water withdrawal, water consumption, and water losses, official reports of the Ministry of Water Resources and Irrigation of the Republic of Kazakhstan, and hydrological observations from the Ili River basin. The methodological framework combined integrated water resources assessment, hydrological time-series analysis, system modelling, and digital water management approaches, including integrated environmental modelling, artificial intelligence, and digital twin technologies for irrigation management and decision support [7, 8, 12, 13, 14, 15].

The study relied on an integrated systems approach combining water management, statistical analysis, and digital assessment techniques. Systems analysis methods were applied to examine the structure and functioning of water distribution processes as an essential component of water resources management under conditions of variable water availability. Comparative analysis was used to evaluate existing water allocation approaches and identify opportunities for implementing advanced digital technologies in irrigation management [7, 9, 10].

Statistical methods and time-series analysis techniques were used to investigate the variability of water resources. Hydrological observations were analyzed with consideration of the stochastic nature of river runoff formation, which made it possible to assess the influence of climatic and hydrological factors on water supply processes [4, 5, 6]. Descriptive statistics, correlation analysis, and variability assessment methods were applied during data processing.

The coefficient of variation was used to quantify the degree of variability in water resources (1):

$$CV = \left(\frac{\sigma}{\bar{\bar{X}}}\right) \times 100, \quad (1)$$

where

CV – denotes the coefficient of variation (%),

σ represents the standard deviation,

$\bar{X}$ is the mean value of the analyzed indicator.

To determine the strength of the relationship between water losses and the efficiency of water distribution, the Pearson correlation coefficient was applied (2):

$$r = \frac{\Sigma[(x_i - \bar{x})(y_i - \bar{y})]}{\sqrt{[\Sigma(x_i - \bar{x})^2 \Sigma(y_i - \bar{y})^2]}}, \quad (2)$$

where

r is the Pearson correlation coefficient;

x_i and yi are the observed values of the analyzed variables;

$\bar{x}$ and $\bar{y}$ denote their corresponding mean values.

The efficiency of water distribution was evaluated using the following expression (3):

$$\mathrm{E} = \left(\frac{\mathrm{W_u}}{\mathrm{W_s}}\right), \quad (3)$$

where

E is the water distribution efficiency coefficient;

W_u represents the volume of effectively utilized water;

W_s denotes the total volume of supplied water.

The empirical basis of the study consisted of official statistical information and analytical reports issued by the water management authorities of the Republic of Kazakhstan. These data characterize trends in water consumption, the efficiency of water allocation, and the operational condition of irrigation systems. The use of long-term observation records ensured the reliability and representativeness of the obtained results.

The empirical dataset included annual observations for the period 2010–2024 (n = 15), covering indicators of water withdrawal, irrigation water losses, river runoff, and water distribution efficiency in the Almaty region. Statistical processing and regression analysis were performed using IBM SPSS Statistics 27 and Microsoft Excel 365. Prior to model estimation, the data were examined for completeness, consistency, and the absence of significant outliers. The assumptions of linear regression were evaluated through residual analysis, including tests for linearity, homoscedasticity, normality of residuals, and multicollinearity. Model adequacy was assessed using the coefficient of determination (R^2), adjusted R^2, F-statistic, p-value (<0.05), and mean approximation error. Internal validation was performed by comparing predicted and observed values and analyzing residual distributions, confirming the robustness and reliability of the developed regression model.

The assessment of water distribution management efficiency was carried out within the framework of contemporary concepts of integrated water resources management and adaptive management approaches [1, 9]. In addition, probabilistic analysis methods were employed to account for uncertainties associated with water resource formation and to evaluate potential risks of water shortages under varying hydrological conditions [5, 8].

A distinctive feature of the study is the application of an integrated approach that combines stochastic analysis techniques with advanced digital technologies for water management. Particular attention was given to the potential use of geographic information systems (GIS), supervisory control and data acquisition (SCADA) systems, decision-support systems (DSS), Internet of Things (IoT) technologies, artificial intelligence tools, machine learning methods, and digital twin technologies to improve the efficiency of water distribution processes [10–15].

The proposed methodological framework is reproducible and relies on widely accepted analytical approaches recommended in contemporary studies on water resources management and the digital transformation of water systems. The integrated digital–stochastic model developed in this study enables the incorporation of water resource variability into the decision-making process and provides a scientific basis for management strategies aimed at improving the operational performance of irrigation systems.

By combining stochastic analysis with modern digital technologies, the proposed approach makes it possible to account for uncertainties in water availability, support adaptive water allocation, and enhance the resilience of irrigation systems under changing climatic and hydrological conditions.

Results

The conducted study made it possible to identify the principal patterns of water use development and the efficiency of water distribution in the Almaty region. The findings indicate increasing pressure on the regional water management system, considerable variability in water availability, and the growing need for the implementation of digital management technologies.

To evaluate long-term trends in water use, an analysis of water withdrawal dynamics in the Almaty region was carried out. The results of this assessment are presented in Table 1.

Table 1 – Dynamics of Water Withdrawal in the Almaty Region

Year	Water intake, mln m³	Growth rate, %
2010	5200	100.0
2014	5680	104.2
2018	6150	103.9
2020	6030	98.0
2022	6280	104.1

Note: data compiled based on source [17]

As shown in Table 1, the volume of water withdrawal increased from 5.200 to 6.280 mln m^3 during the study period, representing an overall growth of 20.8%. This upward trend reflects the increasing demand for water resources associated with agricultural development in the region.

The growth in water withdrawal volumes was accompanied by the expansion of agricultural production and a rising demand for irrigation water. At the same time, a gradual improvement in water use efficiency was observed.

One of the key indicators of water use efficiency is the amount of water consumed per unit area of irrigated land. During the study period, specific water consumption decreased from 9.100 to 7.100 m^3/ha, corresponding to a reduction of approximately 22%.

The decline in unit water consumption indicates improvements in water use efficiency and the implementation of water-saving measures. Assuming that the irrigated area remained relatively stable, the achieved reduction in water consumption corresponds to annual water savings of approximately 640 mln m^3.

An important outcome of the study was the assessment of water distribution efficiency. The results revealed that water losses within the irrigation network decreased from 38% to 25%, while the water distribution efficiency coefficient increased from 0.62 to 0.77 (Table 2).

Table 2 – Indicators of Water Distribution Efficiency

Indicator	2010	2024
Water intake, mln m^3	3750	4360
Water loss, %	38	25
Efficiency coefficient	0.62	0.77
Efficiency increase, %	–	24.2

Note: data compiled based on source [17]

The statistical analysis revealed a strong inverse relationship between water losses and the efficiency of water distribution. The calculated correlation coefficient reached r = –0.89, indicating that the performance of the irrigation system is highly dependent on the magnitude of water losses within the distribution network.

The analysis of the stochastic behavior of water resource formation in the Ili River basin demonstrated considerable year-to-year fluctuations in river discharge. The maximum runoff volume reached 15.400 mln m3, whereas the minimum value amounted to 10.900 mln m^3. The coefficient of variation was estimated at 11.8%, indicating a moderate level of hydrological variability within the observed series.

To assess the stochastic variability of water resources, an analysis of the interannual dynamics of river runoff in the Ili River basin was performed. The results of the analysis are presented in Figure 1.

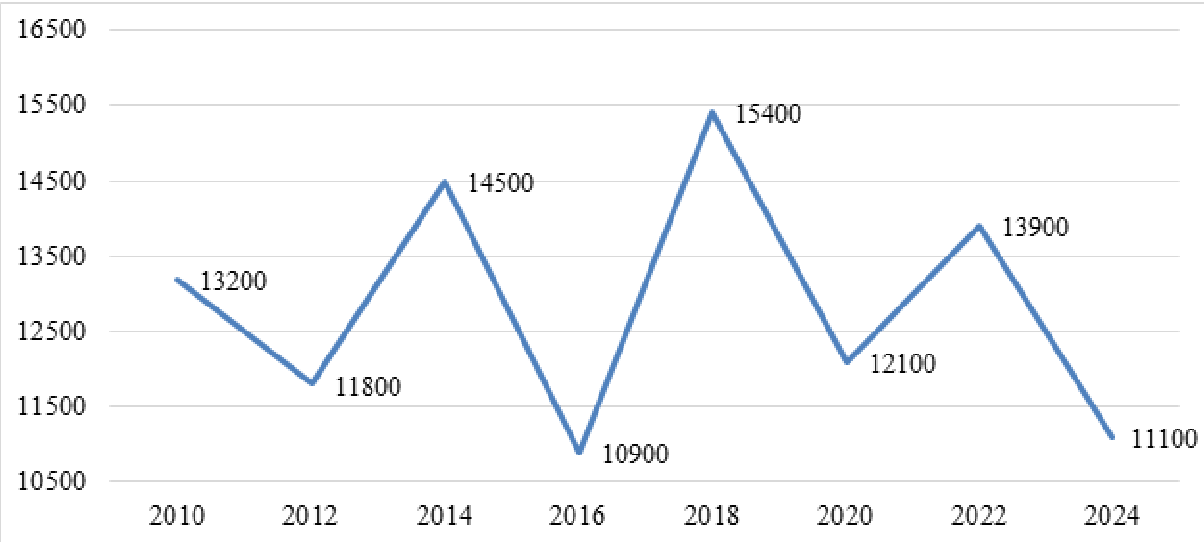

Figure 1 – Interannual variability of river runoff in the Ili River basin

As illustrated in Figure 1, river runoff in the Ili River basin exhibits substantial interannual fluctuations. The lowest recorded runoff volume was 10.900 mln m^3, whereas the highest value reached 15.400 mln m^3. The calculated coefficient of variation of 11.8% indicates a moderate degree of variability in the available water resources.

These findings demonstrate that effective water distribution management cannot rely solely on long-term average standards and fixed allocation schemes. The occurrence of low-water periods significantly increases the probability of water shortages within irrigation systems and creates additional challenges for sustainable water management.

To quantitatively evaluate the influence of the investigated factors on water distribution efficiency, a linear regression model was developed (4):

$$E = a + b_1 L + b_2 Q + \varepsilon, \qquad (4)$$

where

E denotes the water distribution efficiency coefficient;

№ 2 (130)/2026 ISSN 3135-243X, 3135-2448

L represents water losses within the irrigation network;
Q is the volume of water withdrawal;
a is the intercept of the regression model;
b_1 and b_2 are the regression coefficients;
ε denotes the random error term.

The correlation and regression analyses revealed statistically significant relationships among the investigated variables, confirming the influence of the selected factors on the efficiency of water distribution (Table 3).

Table 3 – Results of regression analysis

Indicator	Meaning
Coefficient of Determination (R^2)	0.86
Adjusted R^2	0.83
F-statistic	27.4
Mean Approximation Error, %	5.8
p-value	<0.05

The obtained values of the coefficient of determination indicate a strong explanatory capability of the developed model. The value of $R^2 = 0.86$ demonstrates that approximately 86% of the variation in water distribution efficiency can be explained by the factors included in the regression model. Furthermore, the relatively low approximation error confirms the adequacy and reliability of the proposed model.

Particular attention was given to evaluating the impact of digital technologies on water resources management. The analysis showed that the implementation of geographic information systems, SCADA platforms, Internet of Things technologies, and digital twin solutions contributes to improved operational performance and increased efficiency of irrigation systems.

To estimate the potential benefits of management digitalization, a comparative assessment of contemporary digital technologies was conducted. The corresponding results are presented in Figure 2.

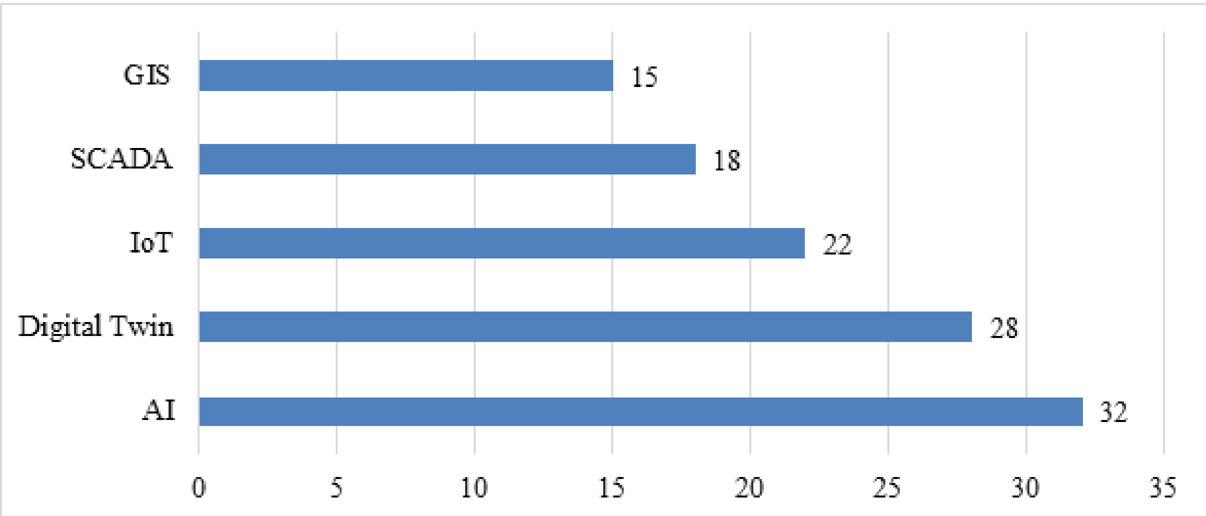

Figure 2 – Impact of digital technologies on water distribution efficiency

According to the results presented in Figure 2, the greatest improvement in water distribution performance was observed under the scenario incorporating artificial intelligence and digital twin technologies. Model simulations indicate that these approaches could improve the operational efficiency of irrigation water distribution by approximately 28–32% compared with conventional management practices.

The findings indicate that the digital transformation of irrigation management can substantially reduce water losses, improve the timeliness and quality of operational decision-making, and increase the adaptability of water allocation under changing hydrological conditions. Unlike conventional rule-based management, digital approaches enable adaptive water distribution based on continuous monitoring, real-time data processing, and predictive analysis.

The proposed framework can be implemented through the development of a digital twin of irrigation systems that integrates hydrological observations, IoT sensor networks, geographic information systems, remote sensing data, and artificial intelligence algorithms. Such an integrated platform would provide real-time monitoring, scenario simulation, and adaptive decision support, thereby increasing the resilience and efficiency of irrigation management under conditions of stochastic water availability.

Discussion

The obtained results are consistent with previous studies demonstrating the effectiveness of digital technologies in water resources management. Recent research has shown that machine learning, artificial intelligence, and integrated digital platforms improve the accuracy of hydrological forecasting, optimize water allocation, and enhance decision-making in irrigation systems.

The obtained results are consistent with recent international studies demonstrating that digital water management technologies can significantly improve irrigation efficiency under conditions of increasing climate variability. Recent research indicates that artificial intelligence enhances operational water management by improving forecasting accuracy, optimizing water allocation, and reducing water losses. In addition, digital twin technologies enable continuous monitoring, scenario simulation, and adaptive decision-making, thereby increasing the efficiency and resilience of irrigation systems under changing hydrological conditions.

Similar findings have been reported in studies conducted in China, Australia, and several European countries, where the implementation of intelligent decision-support systems and digital monitoring technologies reduced irrigation water losses by approximately 15–30% and improved operational efficiency and the reliability of water distribution. These international experiences indicate that advanced digital technologies can be successfully adapted to the irrigation systems in Kazakhstan, taking into account regional hydrological variability and increasing uncertainty associated with climate change.

Compared with previous studies, the present research contributes to the field by integrating stochastic analysis of water availability with a comprehensive assessment of digital technologies within a single methodological framework. While many published studies investigate individual technologies such as GIS, IoT, or artificial intelligence separately, the proposed approach combines statistical modelling, uncertainty assessment, and digital decision-support tools within an integrated irrigation management framework. This integrated methodology provides a more comprehensive basis for adaptive water allocation under conditions of hydrological uncertainty and climate change.

Unlike many existing studies that focus on individual digital technologies or specific components of irrigation management, the proposed approach integrates stochastic assessment of water availability, statistical modelling, and multiple digital technologies within a unified decision-support framework. This integration improves the adaptability of water allocation to hydrological uncertainty and provides a more comprehensive basis for operational water management. Furthermore, the proposed methodology can support the development of national digital water management platforms aligned with current priorities for water sector modernization in Kazakhstan.

Overall, the study confirmed a consistent trend toward improving water distribution efficiency in the Almaty region, identified the stochastic characteristics of water resource formation, and demonstrated the significant potential of digital technologies for enhancing irrigation management. The proposed framework provides a scientific basis for developing digital water management platforms and decision-support systems aimed at increasing the sustainability, efficiency, and resilience of irrigation water allocation under conditions of growing climate uncertainty.

Conclusion

The present study assessed the efficiency of water distribution management under conditions of stochastic variability in water resources in the Almaty region. The findings demonstrated that interannual fluctuations in river runoff significantly affect the reliability of water supply and the operational performance of irrigation systems. Statistical analyses revealed strong relationships among water withdrawal volumes, water losses, and indicators of water distribution efficiency.

The developed regression model demonstrated high explanatory power ($R^2 = 0.86$), confirming the robustness of the results and indicating the potential applicability of the model for predicting water distribution performance under different water availability scenarios.

The study also showed that the implementation of geographic information systems, Internet of Things technologies, automated control systems, digital twin technologies, and artificial intelligence methods can significantly improve water resources management, reduce water losses, and increase the efficiency of operational decision-making.

The proposed digital–stochastic framework can serve as a methodological basis for introducing digital decision-support systems into the activities of water management organizations in the Republic of Kazakhstan. Its implementation may improve the operational planning of irrigation water distribution, enhance monitoring of water-use efficiency, reduce water losses, and support adaptive management under conditions of increasing climate variability. The proposed approach may also be integrated into national programs aimed at the digital transformation of the water sector and modernization of irrigation infrastructure.

The study has several limitations. First, the empirical analysis is based on statistical data from the Almaty region, which may limit the direct transferability of the results to other river basins with different hydrological and institutional conditions. Second, the proposed digital management framework was evaluated using statistical modelling and analytical assessment, whereas its full-scale implementation within operational irrigation systems requires additional pilot testing under real-world conditions.

Future research should focus on validating the proposed framework in other irrigation regions of Kazakhstan and Central Asia, integrating real-time sensor networks and remote sensing data, and developing operational digital twin platforms supported by artificial intelligence. Further investigations should also evaluate the economic efficiency and scalability of digital water management technologies under different climatic and hydrological scenarios.

Authors' Contributions

SS and YeZh: conceptualized and designed the study, developed the research methodology, collected and analyzed the data, and drafted the manuscript. AA: contributed to the interpretation of the results, reviewed the literature, and participated in manuscript preparation. RB and ZhKh: conducted statistical analysis, interpreted the results, critically revised the manuscript, and supervised the research process. All authors read, reviewed, and approved the final version of the manuscript.

Information of funding

This study is 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».

References

1 UNESCO World Water Assessment Programme. (2026). *The United Nations World Water Development Report 2026: Water for All People: Equal Rights and Opportunities.* Paris: UNESCO, 157. DOI: 10.54679/NXCL7067.

2 Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M.A., Kijne, J. (2010). Improving agricultural water productivity: Between optimism and caution. *Agricultural Water Management*, 97(4), 528–535. DOI: 10.1016/j.agwat.2009.03.023.

3 Perry, C., Steduto, P., Allen, R.G., Burt, C.M. (2009). Increasing productivity in irrigated agriculture: Agronomic constraints and hydrological realities. *Agricultural Water Management*, 96(11), 1517–1524. DOI: 10.1016/j.agwat.2009.05.005.

4 Kundzewicz, Z.W., Mata, L.J., Arnell, N.W., Döll, P., Kabat, P., Jiménez, B., Miller, K.A., Oki, T., Şen, Z., Shiklomanov, I. (2007). Freshwater resources and their management. *In: Climate Change 2007: Impacts, Adaptation and Vulnerability.* Cambridge University Press, 173–210.

5 Koutsoyiannis, D. (2011). Hurst-Kolmogorov dynamics and uncertainty. *JAWRA Journal of the American Water Resources Association*, 47(3), 481–495. DOI: 10.1111/j.1752-1688.2011.00543.x.

6 Milly, P.C.D., Betancourt, J., Falkenmark, M., Hirsch, R.M., Kundzewicz, Z.W., Lettenmaier, D.P., Stouffer, R.J. (2008). Stationarity is dead: Whither water management? *Science*, 319(5863), 573–574. DOI: 10.1126/science.1151915.

7 Loucks, D.P., van Beek, E. (2017). *Water Resource Systems Planning and Management: An Introduction to Methods, Models and Applications.* Cham: Springer. DOI: 10.1007/978-3-319-44234-1.

8 Salas, J.D., Delleur, J.W., Yevjevich, V., Lane, W.L. (1980). *Applied Modeling of Hydrologic Time Series.* Littleton: Water Resources Publications. https://ru.scribd.com/doc/314526193/Applied-Modeling-of-Hydrologic-Time-Series.

9 Rahaman, M.M., Varis, O. (2005). Integrated water resources management: Evolution, prospects and future challenges. *Sustainability: Science, Practice and Policy*, 1(1), 15–21. DOI: 10.1080/15487733.2005.11907961.

10 Pahl-Wostl, C., Palmer, M., Richards, K. (2013). Enhancing water security for the benefits of humans and nature – the role of governance. *Current Opinion in Environmental Sustainability*, 5(6), 676–684. DOI: 10.1016/j.cosust.2013.10.018.

11 Mosavi, A., Ozturk, P., Chau, K.W. (2018). Flood prediction using machine learning models: literature review. *Water*, 10(11), 1536. DOI: 10.3390/w10111536.

12 Rizzoli, A.E., Leavesley, G., Ascough, J.C. II, Argent, R.M., Athanasiadis, I.N., Brilhante, V., Claeys, F.H.A., David, O., Donatelli, M., Gijsbers, P., Havlik, D., Kassahun, A., Krause, P., Quinn, N.W.T., Scholten, H., Sojda, R.S., Villa, F. (2008). *Integrated Modelling Frameworks for Environmental Assessment and Decision Support.* In: iEMSs 2008: International Congress on Environmental Modelling and Software. Barcelona, Spain. https://digitalcommons.unl.edu/usgsstaffpub/196.

13 Morain, A., Hawkins, L., Poole, K., Jones, M., Washington, B., Anandhi, A. (2025). Artificial intelligence applications in water management: bibliometric analysis, challenges, and knowledge gaps. *Journal of Water and Climate Change*, 16(12), 3610–3647. DOI: 10.2166/wcc.2025.740.

14 Tao, F., Zhang, M., Liu, Y., Nee, A.Y.C. (2019). Digital Twin Driven Smart Manufacturing. Academic Press, Cambridge. DOI: 10.1016/C2018-0-02206-9.

15 Rashid, M., Saeed, A., Khalid, M., Murtaza, A., Saleem, M.W. (2026). The transformative role of artificial intelligence in water resources engineering: A comprehensive review. *Environmental Modelling & Software*, 197, 106857. DOI: 10.1016/j.envsoft.2026.106857.

16 Ministry of Water Resources and Irrigation of the Republic of Kazakhstan. (2024). *The concept of development of the water resources management system of the Republic of Kazakhstan for 2024-2030.* Astana. https://adilet.zan.kz/rus/docs/P2400000066.

17 Ministry of Water Resources and Irrigation of the Republic of Kazakhstan. (2025). *All materials. Publications.* Astana. https://www.gov.kz/memleket/entities/water/press/article/1?lang=ru.

Суару жүйелеріндегі су бөлуді басқаруға цифрлық технологияларды интеграциялау

Маликов С.С., Жандияр Е.Г., Алдиярова А.Е., Беспаева Р.С., Хусаинова Ж.С.

Түйін

Алғышарттар мен мақсат. Климаттың өзгеруі, су ресурстарына түсетін жүктеме және ауыл шаруашылығының суға деген сұранысының артуы суаруды тиімді басқаруды талап етеді. Су шаруашылығын цифрлық трансформациялау суды пайдалану тиімділігін арттырып, суару жүйелерінің орнықтылығын күшейтеді. Зерттеудің мақсаты – Алматы облысындағы су бөлудің тиімділігін бағалау және су ресурстарының стохастикалық өзгермелілігі жағдайында оларды басқаруда цифрлық технологияларды қолдануды негіздеу.

Материалдар мен әдістер. Зерттеу 2010–2024 жылдардағы Алматы облысындағы су пайдалану жөніндегі статистикалық деректерге, Іле өзені алабының гидрологиялық бақылау материалдарына және Қазақстан Республикасының су шаруашылығы саласындағы уәкілетті органдарының ресми мәліметтеріне негізделді. Жүйелік талдау, салыстырмалы бағалау, статистикалық талдау, корреляциялық талдау және регрессиялық модельдеу әдістері қолданылды. Су бөлудің тиімділігін бағалау үшін вариация, корреляция және детерминация коэффициенттері есептелді.

Сонымен қатар, суаруды басқаруда геоақпараттық жүйелердің (GIS), Заттар интернетінің (IoT), SCADA жүйелерінің, цифрлық егіздердің және жасанды интеллекттің қолданылуы бағаланды.

Нәтижелер. Алынған нәтижелер су ресурстарын басқару тиімділігінің артқанын көрсетті. Су алу көлемі 20,8%-ға ұлғайып, су бөлудің тиімділік коэффициенті 0,62-ден 0,77-ге дейін өсті, ал су шығындары 38%-дан 25%-ға дейін азайды. Суармалы жердің бірлік ауданына шаққандағы су тұтыну 22%-ға төмендеп, жыл сайын шамамен 640 млн м³ су үнемдеуге мүмкіндік берді. Су шығындары мен жүйе тиімділігі арасында күшті теріс корреляция анықталды ($r = –0,89$). Регрессиялық модель жоғары түсіндіру қабілетін көрсетті ($R^2 = 0,86$), бұл алынған нәтижелердің сенімділігін растады. Цифрлық технологияларды енгізу су ресурстарын тиімдірек бөлуге, су шығындарын қысқартуға және суару жүйелерінің орнықтылығын арттыруға ықпал етеді.

Қорытынды. Цифрлық технологиялар су бөлуді жетілдіру, су шығындарын азайту және гидрологиялық өзгермелілік жағдайында суару жүйелерінің бейімделу қабілетін арттыру арқылы су ресурстарын басқарудың тиімділігі мен орнықтылығын қамтамасыз етеді. Ұсынылған цифрлық-стохастикалық тәсіл су ресурстарын басқарудың цифрлық платформаларын, шешім қабылдауды қолдау жүйелерін әзірлеуге және суаруды басқаруда суды бейімделген түрде бөлу технологияларын практикалық енгізуге ғылыми-әдістемелік негіз қалайды.

Кілт сөздер: цифрландыру; су бөлу; цифрлық технологиялар; суару жүйелері; су ресурстары; Алматы облысы.

Интеграция цифровых технологий в управление водораспределением на оросительных системах

Маликов С.С., Жандияр Е.Г., Алдиярова А.Е., Беспаева Р.С., Хусаинова Ж.С.

Аннотация

Предпосылки и цель. Изменение климата, возрастающая нагрузка на водные ресурсы и увеличение потребности сельского хозяйства в воде требуют повышения эффективности управления орошением. Цифровая трансформация управления водными ресурсами способствует повышению эффективности водопользования и устойчивости оросительных систем. Целью исследования является оценка эффективности водораспределения в Алматинской области и обоснование применения цифровых технологий для управления водными ресурсами в условиях стохастической изменчивости водообеспеченности.

Материалы и методы. Исследование основано на статистических данных по водопользованию в Алматинской области за 2010–2024 гг., гидрологических наблюдениях по бассейну реки Или и официальной информации уполномоченных органов Республики Казахстан в сфере водного хозяйства. Применялись методы системного анализа, сравнительной оценки, статистического анализа, корреляционного анализа и регрессионного моделирования. Для оценки эффективности водораспределения рассчитывались коэффициенты вариации, корреляции и детерминации. Оценивались возможности применения геоинформационных систем (GIS), Интернета вещей (IoT), систем SCADA, цифровых двойников и технологий искусственного интеллекта в управлении орошением.

Результаты. Полученные результаты свидетельствуют о повышении эффективности управления водными ресурсами. Объем водозабора увеличился на 20,8 %, при этом коэффициент эффективности водораспределения вырос с 0,62 до 0,77, а потери воды сократились с 38% до 25 %. Удельное водопотребление уменьшилось на 22%, обеспечив ежегодную экономию около 640 млн м³ воды. Выявлена сильная отрицательная корреляция между потерями воды и эффективностью системы ($r = –0,89$). Регрессионная модель продемонстрировала высокую объясняющую способность ($R^2 = 0,86$), подтвердив надежность полученных результатов. Внедрение цифровых технологий способствует более эффективному распределению водных ресурсов, сокращению потерь воды и повышению устойчивости оросительных систем.

Заключение. Цифровые технологии повышают эффективность и устойчивость управления водными ресурсами за счет совершенствования водораспределения, сокращения потерь воды и повышения адаптивности оросительных систем к гидрологической изменчивости. Предложенная цифровая стохастическая модель создает научно-методическую основу для разработки цифровых платформ управления водными ресурсами, систем поддержки принятия решений и практического внедрения технологий адаптивного водораспределения в управление оросительными системами.

Ключевые слова: цифровизация; водораспределение; цифровые технологии; оросительные системы; водные ресурсы; Алматинская область.