PAN
POLSKA AKADEMIA NAUK

JOURNAL OF WATER AND LAND DEVELOPMENT

e-ISSN 2083-4535

ITP-PIB

Polish Academy of Sciences (PAN) Institute of Technology and Life Sciences – National Research Institute (ITP – PIB)

JOURNAL OF WATER AND LAND DEVELOPMENT
DOI: 10.24425/jwld.2026.158699
2026, No. 69 (IV–VI): 50–61

Sustainable management of agricultural water resources in Kazakhstan

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RECEIVED 29.09.2025 ACCEPTED 23.01.2026 AVAILABLE ONLINE 25.05.2026

Abstract: Ensuring the sustainable use of water resources is one of Kazakhstan's key development priorities. The country faces limited availability of freshwater, uneven spatial distribution of water resources, deteriorated irrigation infrastructure, and the growing impacts of climate change. These factors pose significant risks to food security and the long-term resilience of the agricultural sector. The aim of this study is to conduct a comprehensive assessment of agricultural water use in Kazakhstan, identify the key constraints limiting the efficiency of water management, and develop a theoretically grounded, integrated model of sustainable water resource management adapted to the country's climatic, institutional, and technological conditions. The methodology is based on a mixed-methods approach, combining structured surveys (521 respondents) with an analysis of statistical data covering the period from 1960 to 2023. The study examines irrigation practices, water availability, levels of digitalisation, and institutional mechanisms of water governance across different agro-climatic zones of the country. The results show that 68% of farms experience water supply disruptions, 72% face deterioration of irrigation systems, and 65% incur substantial water losses. Only 23% of farmers employ water-saving technologies, primarily due to financial and informational constraints. The study concludes by recommending accelerated modernisation of irrigation infrastructure, the implementation of digital monitoring and water-management systems, expansion of state support measures, and the promotion of innovative technologies in the agricultural sector.

Keywords: climate change, irrigation, Kazakhstan, sustainable development goals (SDGs), sustainable agriculture, water policy, water resources

INTRODUCTION

Sustainable management of agricultural water resources is a priority for achieving the UN sustainable development goals (SDGs) by 2030 (Resolution, 2015). The SDG 6 emphasises not only universal access to water and sanitation but also water-use efficiency, integrated management, infrastructure modernisation, and ecosystem preservation. Agriculture accounts for nearly 70% of global freshwater withdrawals (UNESCO, 2024), and water scarcity is acute in arid countries such as Kazakhstan, where limited resources, deteriorated irrigation, and low adoption of water-saving technologies hinder sustainability. Under climate change and growing food demand, sustainable water use becomes critical for food security and rural resilience.

Kazakhstan's agricultural potential is considerable: of its 217 mln ha of land, 35 mln ha are arable (10th globally and 2nd in the world in arable land per capita), while 13 mln ha are classified as fallow (Halyk Finance, 2023). However, the country faces acute water scarcity: only 2.8% of its territory is covered by water, whereas two-thirds consist of arid zones. Agriculture accounts for approximately 60% of total national water withdrawals, yet only 30% of the 75% of land suitable for agricultural production is currently utilised (ITA, 2023), and irrigation covers merely 6% of this area (1.4 mln ha). Crop yields are twice as low as those of the European Union, water-use efficiency is 6–8 times lower, and nearly 40% of available water is lost due to severely degraded infrastructure. According to the United Nations Development Programme (UNDP), climate change could lead to a twofold reduction in wheat yields and a decline of up to 6% of gross domestic product (GDP) by 2050 (UNDP, 2021), as all major economic sectors depend on water resources.

In the Presidential Addresses to the Nation – "The economic course of a just Kazakhstan" (President of the Republic of Kazakhstan, 2023) and "Kazakhstan in the era of artificial intelligence: Current challenges and their solutions through digital transformation" (President of the Republic of Kazakhstan, 2025) – it is underscored that sustainable water use constitutes a fundamental prerequisite for economic growth and national security.

These priorities reflect the particular importance of the water factor for Kazakhstan's agriculture, especially in the southern and southeastern regions, where the arid climate makes water resources a critical component of the production process. Research confirms its strategic role in food security, climate adaptation, and ecosystems (Zhupankhan, Tussupova and Berndtsson, 2018). Studies point to uneven distribution, outdated irrigation, and low digitalisation (Tursunova *et al.*, 2022), calling for smart irrigation and remote sensing (Singh, 2024), canal rehabilitation and incentives (Yespolov, Tireuov and Kerimova, 2022; Adamov, Kusainov and Yesbergen, 2025). Ecological risks in Lake Balkhash (Propastin, 2012; Yapiyev *et al.*, 2017; Yegizbayeva *et al.*, 2024) and rising aridity confirmed by satellite monitoring (Yegizbayeva *et al.*, 2024) further underscore the urgency. International studies (Minhas and Qadir, 2024; Yadav *et al.*, 2024) stress integrating economic, institutional, and ecological factors.

The approaches presented in the works of international and domestic researchers undoubtedly possess substantial scientific and practical relevance for Kazakhstan. However, the majority of these approaches were developed within the context of different climatic, institutional, and infrastructural conditions. This necessitates their adaptation to the specific characteristics of Kazakhstan, which is marked by an arid climate, a high degree of deterioration of irrigation systems, and a limited level of digitalisation in the water sector.

The analysis of existing studies reveals several critical gaps. First, there is no comprehensive model of sustainable water management that integrates economic, environmental, institutional, and digital components. Second, there is an insufficient amount of empirical data reflecting regional differences in water-use efficiency and the impacts of climatic factors. Third, existing research rarely addresses social and governance aspects – such as farmer participation, the role of water user associations, and state policy instruments aimed at promoting rational water use.

Under these conditions, the relevance of the present study is determined by the need to develop a comprehensive, scientifically grounded, and technologically supported model of sustainable water management in Kazakhstan's agricultural sector. Such a model should ensure the rational use of water resources, minimise losses, and enhance the adaptive capacity of the agricultural sector to climatic and socio-economic changes.

Accordingly, the aim of this study is to conduct a comprehensive analysis of water use in Kazakhstan's agricultural sector, identify the key factors that limit water-management efficiency, and develop and theoretically substantiate an integrated model of sustainable water-resource management tailored to the country's climatic, institutional, and technological characteristics.

The scientific novelty of the research lies in the development of an integrated model of sustainable water use based on four interrelated principles: economic efficiency, social equity, ecological sustainability, and digital transparency. In contrast to existing approaches, the proposed model incorporates both Food and Agriculture Organization (FAO) international standards and the regional specifics of Kazakhstan. This approach enables a transition from fragmented regulation to a systemic framework of water-resource governance aligned with the objectives of the country's new water policy and the provisions of the Water Code of the Republic of Kazakhstan.

The practical significance of the study is reflected in the applicability of the proposed model for improving state water policy and ensuring the effective implementation of the new Water Code of the Republic of Kazakhstan (Vodnyy kodeks, 2025). The findings can be used to enhance the performance of irrigation systems, introduce digital tools for monitoring and planning water use in the agricultural sector, and develop national programs for rational water use as well as for adapting international methodologies to Kazakhstan's natural-climatic and institutional conditions.

MATERIALS AND METHODS

DESCRIPTION OF THE AREA

Kazakhstan, the world's ninth-largest country, covers 2.7 mln km^2 in Central Asia with a small part in Eastern Europe, sharing borders with Russia, China, Kyrgyzstan, Uzbekistan, and Turkmenistan (World Bank, 2024). Its territory spans diverse zones, including steppes, deserts such as Kyzylkum and Betpak-Dala, the Tien Shan and Altai mountains, and the Caspian Sea coast (Zhupankhan, Tussupova and Berndtsson, 2018). Hydrologically, it comprises eight water basins, with the Ili, Irtysh, Syrdarya, and Ural among 39,000 rivers (FAO, 2013). Lake Balkhash faces salinisation and pollution (Propastin, 2012; Yapiyev *et al.*, 2017; Yegizbayeva *et al.*, 2024). Agriculture consumes ~70% of withdrawals (FAO, 2024a; FAO, 2025). The sharply continental climate, low precipitation, and desertification heighten vulnerability, exemplified by the Aral Sea disaster (Micklin, 2016; Zhupankhan, Tussupova and Berndtsson, 2018; FAO, 2024a).

METHODOLOGICAL FRAMEWORK OF THE STUDY

The methodological framework of the study is designed to ensure a comprehensive and multi-level analysis of sustainable water-resource management in Kazakhstan's agricultural sector. The research process is structured into four interrelated stages that combine theoretical justification, empirical observation, statistical analysis, and conceptual modelling.

Stage 1 – Preparatory. At this stage, a systematic literature review was conducted, covering theoretical approaches and leading international practices in integrated water-resource management and sustainable agriculture. Based on this analysis, a conceptual foundation was developed, incorporating the key dimensions of water governance: economic, institutional, environmental, and digital.

Stage 2 – Empirical. This stage focused on collecting primary and secondary data describing the current state of water use in Kazakhstan's agricultural sector. Primary data were obtained through a structured survey of 521 farmers across three water-scarce regions (Kyzylorda, Turkestan, and Zhambyl oblasts). Secondary data covered the period from 1960 to 2023 and were sourced from national and international institutions (the Ministry of Water Resources and Irrigation of Kazakhstan, Food and Agriculture Organization (FAO), the World Bank, and United Nations Development Programme (UNDP)). This enabled the creation of a representative empirical dataset for statistical and comparative analysis.

Stage 3 – Analytical. At this stage, both quantitative and qualitative analyses of the collected data were performed. Descriptive statistics were applied to summarise key indicators, while Spearman's correlation analysis and multiple linear regression were used to identify relationships between technical, institutional, and behavioural factors affecting water-use efficiency. Data processing was carried out using IBM SPSS Statistics 26.0, ensuring the reliability, precision, and international comparability of the results.

Stage 4 – Interpretive and modelling. The final stage involved synthesising empirical and analytical findings to develop an integrated model of sustainable water-resource management tailored to Kazakhstan's agricultural context. The model is grounded in four interrelated principles: economic efficiency, social equity, environmental sustainability, and digital transparency. It serves as a conceptual foundation for shaping state water policy and adaptive management strategies under conditions of climatic and socio-economic change.

Overall, the proposed methodological framework ensures a coherent connection between empirical data and theoretical conclusions, combining analytical rigor with practical applicability. This approach aligns with the global agenda for sustainable water-resource management and contributes to the development of evidence-based solutions for Kazakhstan's agricultural sector.

PARTICIPANTS AND SAMPLE REPRESENTATIVENESS

Within the fieldwork stage of the study, a survey was conducted among 521 farmers engaged in crop production on irrigated lands. The sample was distributed across the regions as follows: Kyzylorda Region – 160 respondents (30.7%), Turkestan Region – 190 respondents (36.5%), Zhambyl Region – 171 respondents (32.8%) (Tab. 1).

The regional breakdown of the sample makes it possible to account for the specific agro-climatic conditions and the state of infrastructure, and provides a foundation for developing differentiated recommendations for optimising water use.

Table 1. Sectoral specialisation by region

Region	Number of farmers cultivating				
	grain crops	forage crops	vegetables and melons	fruit and berry crops	total
Kyzylorda	54	45	40	21	160
Turkestan	76	49	40	25	190
Zhambyl	67	46	34	24	171

Source: own study.

RESULTS AND DISCUSSION

RESULTS

Comprehensive assessment of the current state of water resources in the Republic of Kazakhstan. According to the SDG 6.4.2 methodology, Kazakhstan is classified as a country with a medium-high level of water stress (Kuzma, Saccoccia and Chertock, 2023). Food and Agriculture Organization (FAO) AQUASTAT data indicate that in 2022, the level of water stress reached 34.6% (FAO, 2024b).

The situation in Kazakhstan appears vulnerable, as a significant share of pastures and rainfed lands regularly experience moisture deficits, while irrigated lands are exposed to high levels of water stress – similar to other Central Asian countries (see Tab. 2).

Water stress in Kazakhstan is strongly influenced by sectoral abstraction patterns. Agriculture accounts for around 60% of total water consumption, while industry and households share the rest. Total abstraction remained stable at 24.9 km^3 in 2020, 24.5 km^3 in 2021, 25.0 km^3 in 2022, and 24.9 km^3 in 2023, though growth is possible due to oil, gas, and mining expansion (Government of the Republic of Kazakhstan, 2024). On average, 14.8 km^3 was abstracted annually for agriculture in 2020–2022, with 77% used for regular irrigation over 1.18 mln ha. The remaining 3.61 km^3 supported flood irrigation, hayfield flooding, and pasture watering. Notably, 98.8% of abstraction originated from surface water (see Tab. 3).

Irrigation remains the main agricultural water user, though since 2020 both abstraction volumes and irrigated land area have declined. Relative water losses persist, while climate change has raised crop water demand and irrigation frequency. Inefficiencies driven by outdated infrastructure, limited water-saving technology, and weak accounting highlight the urgent need for irrigation modernisation and wider adoption of efficient practices to mitigate salinisation and desertification risks.

Prospects for improving the efficiency of irrigated farming are inextricably linked to the widespread application of water-saving irrigation technologies. In 2023, the area of irrigated land under water-saving technologies amounted to 312.3 thous. ha (see Tab. 4).

According to the Concept for the transition of the Republic of Kazakhstan to a Green Economy (Decree, 2013), irrigated land with water-saving technologies is expected to reach 1,040 thous. ha by 2030, 1,800 thous. ha by 2040, and 2,300 thous. ha by 2050. Despite progress with sprinkler and drip irrigation, significant barriers remain: deteriorated systems, outdated equipment, and fragmented institutional responsibility. These

Table 2. Area (ha) and share of land by production systems under conditions of water scarcity and shortage in Central Asian countries

Country / territory	Irrigated agricultural land under high / very high water stress		Rainfed agricultural land with minimal resources exposed to high / very high drought frequency		Rainfed agricultural land with intensive resource use exposed to high / very high drought frequency		Pastures exposed to high / very high drought frequency	
	thous. ha	%	thous. ha	%	thous. ha	%	thous. ha	%
Central Asia	9,214	95.9	11,979	58.0	1,459	37.2	27,502	23.7
Kazakhstan	1,577	79.9	11,753	58.6	1,036	33.7	21,940	23.8
Kyrgyzstan	1,064	100.0	32	20.2	39	19.7	255	2.9
Tajikistan	705	100.0	30	18.7	36	20.9	283	7.3
Turkmenistan	1,742	100.0	44	82.4	88	80.3	3,259	61.9
Uzbekistan	4,126	100.0	120	58.2	260	70.0	1,766	30.7

Source: FAO (2020).

Table 3. Irrigation water withdrawal trends by basin in Kazakhstan

River basin	2020			2021			2022			2023		
	irrigated land (thous. ha)	water with-drawal (mln m^3)	specific water use (thous. $m^3 \cdot ha^{-1}$)	irrigated land (thous. ha)	water with-drawal (mln m^3)	specific water use (thous. $m^3 \cdot ha^{-1}$)	irrigated land (thous. ha)	water with-drawal (mln m^3)	specific water use (thous. $m^3 \cdot ha^{-1}$)	irrigated land (thous. ha)	water with-drawal (mln m^3)	specific water use, (thous. $m^3 \cdot ha^{-1}$)
Aral-Syrdarya	642	7,456	11.6	536	6,920	12.9	590	6,781	11.5	694	7,126	10.2
Balkhash-Alakol	456	3,401	7.5	453	3,310	7.3	312	3,347	10.7	291	3,229	11.1
Ertis	49	165	3.4	48	158	3.3	52	174	3.3	63	187	2.96
Esil	6	10	1.8	9	14	1.5	8	5	0.6	12	11	0.92
Oral-Caspian	12	46	3.9	12	48	4.1	15	47	3.2	13	48	3.69
Nura-Sarysu	24	74	3.1	9	74	7.9	20	74	3.7	25	92	3.68
Tobyl-Torgai	6	13	2.2	7	13	2.0	8	20	2.3	8	210	2.63
Shu-Talas	84	936	11.2	104	936	9.0	139	1,040	7.5	122	1,002	8.21
Total	1,277	12,101	9.5	1,177	12,101	10.3	1,144	11,489	10.0	1,228	11,905	9.69

Source: Government of the Republic of Kazakhstan (2024).

Table 4. Irrigated land and irrigation methods (thous. ha)

Indicator	Value in year					Change in 2019–2023 (%)
	2019	2020	2021	2022	2023	
Permanently irrigated lands	2,224.6	2,234.2	2,243.4	2,302.7	2,333.8	+4.91
Utilised irrigated land area	1,486.0	1,451.4	1,557.6	1,612.8	1,472.5	−0.91
Furrow irrigation	1,275.4	1,229.9	1,298.8	1,333.2	1,160.2	−9.04
Drip irrigation	49.8	60.4	73	79.5	84.9	+70.48
Sprinkler irrigation	160.8	161.1	185.8	200.1	227.4	+41.37
Area of pastures with flood irrigation	864.2	864.2	864.2	864.5	858.9	−0.61

Source: own elaboration according to data of Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan (2024).

factors constrain agricultural productivity, especially in southern Kazakhstan, and highlight the urgency of adopting precision and automated irrigation supported by digital monitoring.

To obtain empirical validation of the identified challenges, as well as to more accurately assess regional differentiation in the factors influencing sustainable water use and the effectiveness of government support, a sociological survey was conducted among farmers in key agricultural regions of Kazakhstan. The data collected provide an opportunity to move beyond generalised analysis toward a more nuanced interpretation of behavioural and institutional dimensions of water use at the micro level. The findings of this field study are presented below, structured according to key performance indicators.

Empirical data from the farmer survey: Factors of sustainable water use and perceptions of state support. The results of a survey conducted among farmers in three water-stressed regions of Kazakhstan – Kyzylorda, Turkestan, and Zhambyl – illustrate the main challenges and factors influencing the sustainability of water use. For analytical clarity, each aspect has been assessed separately and is presented in the form of tables with both quantitative and qualitative indicators (see Tab. 5).

An analysis of water availability in the southern regions of Kazakhstan reveals systemic instability and pronounced regional disparities in agricultural water provision. Only 2.7% of farmers in the Kyzylorda region and 9.6% in the Zhambyl region reported a stable and fully sufficient water supply. These figures indicate that efficient water use remains an exception rather than the norm, significantly constraining productivity improvements in the agricultural sector. The situation appears particularly alarming in the Turkistan region, where nearly one in five respondents (17.85%) experience regular water supply disruptions. This is likely driven by a combination of high water demand, uneven distribution of resources, and chronic infrastructure degradation.

Critically unstable water supply – marked by levels of scarcity that threaten crop yields – is most pronounced in the Kyzylorda region (8.83%), underscoring its hydrological vulnerability as the downstream segment of the transboundary Syr Darya River basin. In this context, competition for water arises not only domestically but also across national borders, rendering the region highly sensitive to seasonal fluctuations in inflow and inefficiencies in water regulation.

The data point to the emergence of persistent asymmetries in agricultural productivity across regions, rooted in the degree of water supply stability. When fewer than 10% of farms can rely on predictable and uninterrupted access to irrigation water, the adoption of precision irrigation technologies, digital water management platforms, or even basic irrigation planning becomes highly challenging. This not only limits technological transformation in the agri-sector but also exacerbates investment and social risks in rural areas.

The observed disparities in water access have direct implications for the design of adaptive and regionally specific water policies. They support:

- prioritising infrastructure modernisation based on vulnerability levels;
- establishing regional indicators of water-use sustainability;
- justifying targeted subsidies for vulnerable categories of farmers;
- developing climate adaptation scenarios informed by current water scarcity conditions.

From an academic perspective, the identified patterns offer a robust empirical foundation for interregional comparisons, spatial modelling of water deficit, and analysis of transboundary instability. These findings are relevant not only in the context of Kazakhstan but also for other countries in the arid belt of Eurasia facing similar challenges (see Tab. 6).

An analysis of irrigation infrastructure conditions in the southern regions of Kazakhstan reveals a large-scale and persistent infrastructural deficit that poses a systemic threat to the stability of agricultural water supply. The share of facilities in good condition and requiring minimal maintenance is extremely low – ranging from 1.92% in the Kyzylorda region to 4.99% in the Zhambyl region. These figures indicate that the overwhelming majority of canals and distribution nodes fail to meet operational standards and cannot ensure effective and equitable water delivery without substantial reinvestment.

Coupled with widespread degradation of infrastructure – where 20–27% of facilities require major repairs or are entirely non-operational – the situation assumes crisis proportions. The problem is particularly acute in the Turkistan region, where intensive water use coincides with the highest share of deteriorated systems (over 27%). This results in a structural mismatch between water demand and the technical capacity to supply it, inevitably leading to increased losses, supply interruptions, and competition over resources.

Regional differences in infrastructure deterioration also highlight disparities in management models and budgetary

Table 5. Water availability

Category	Region					
	Kyzylorda		Turkestan		Zhambyl	
	N	%	N	%	N	%
Stable and fully sufficient water supply	14	2.69	34	6.53	50	9.60
Moderately unstable water supply	22	4.22	39	7.48	40	7.68
Unstable supply with regular interruptions	66	12.67	93	17.85	66	12.67
Critically unstable and deficient water supply	46	8.83	27	5.18	24	4.61

Explanations: N = number.
Source: own elaboration based on field survey data (2025).

Table 6. Condition of irrigation infrastructure

Category	Region					
	Kyzylorda		Turkestan		Zhambyl	
	N	%	N	%	N	%
Good condition (minimal maintenance)	10	1.92	18	3.46	26	4.99
Satisfactory (requires modernisation)	26	4.99	34	6.52	34	6.52
Poor (needs major repair/replacement)	85	16.31	106	20.35	74	14.20
Non-operational (unfit for use)	41	7.87	35	6.72	32	6.14

Explanations: N as in Tab. 5.
Source: own elaboration based on field survey data (2025).

priorities. In areas where regular diagnostics and repair planning are absent, deterioration progresses rapidly to an irreversible phase, rendering rehabilitation on the basis of existing infrastructure unfeasible. Furthermore, the high proportion of non-operational systems reflects not only technical obsolescence but also an institutional withdrawal from maintaining entire segments of the water management complex.

The empirical data obtained from field surveys enable both quantitative assessment of infrastructure vulnerability and its application as a foundation for:
- developing regional indices of water infrastructure degradation;
- spatial modelling of investment priorities;
- designing technical standards and retrofitting protocols for irrigation systems under scarcity conditions.

From a scientific standpoint, these findings offer a solid empirical basis for interdisciplinary research that combines hydraulic engineering, water economics, and digital infrastructure modelling. In addition, the observed regional variation allows for the creation of comparative case studies to evaluate the institutional effectiveness of water infrastructure governance (see Tab. 7).

An analysis of water losses in irrigation systems across three key agricultural regions of Kazakhstan reveals a persistent trend of inefficient water use that undermines both hydrological and agricultural sustainability. The share of farms experiencing minimal losses (up to 10%) is extremely low – ranging from 1.15% in the Kyzylorda region to 4.03% in the Zhambyl region. This indicates that efficient water distribution remains an exception rather than the norm, posing major challenges for crop productivity in an arid climate.

Table 7. Water losses (%)

Category	Region					
	Kyzylorda		Turkestan		Zhambyl	
	N	%	N	%	N	%
Minimal losses (≤10)	6	1.15	15	2.88	21	4.03
Moderate losses (10; 25]	33	6.33	50	9.60	50	9.60
Significant losses (25; 50]	77	14.78	92	17.65	64	12.28
Critical losses (>50)	44	8.44	35	6.72	34	6.52

Explanations: N as in Tab. 5.
Source: own elaboration based on field survey data (2025).

Most farms report moderate (10–25%) or significant (25–50%) losses. The situation is particularly acute in the Turkistan region, where 17.65% of farmers lose up to half of the supplied water. This may result not only from the physical degradation of main and intra-field canals, but also from the lack of sealing systems and the absence of targeted water monitoring solutions – such as pressure sensors, metering devices, and automated gate controls.

Critical losses (exceeding 50%), reported by 6.5–8.4% of respondents, indicate both physical degradation and institutional dysfunctions. These include inadequate tariff structures, weak distribution oversight, and low penetration of water management technologies. The concentration of such losses in the Kyzylorda region highlights its hydrological vulnerability and ineffective network operations under conditions of resource scarcity and limited access to modernisation.

The findings have high applied and academic relevance.
- From a practical standpoint, they justify the urgent transition from open, inefficient canal systems to more sustainable piped or drip irrigation systems supported by automated monitoring platforms.
- In terms of water policy, the results support the case for targeted subsidies and flexible regional support programs based on actual loss levels.
- From a research perspective, the data provide a basis for:
  - comparative analysis of water productivity (input–output water efficiency);
  - construction of regional infrastructure leakage indices;
  - development of return-on-investment models for water-saving technologies (see Tab. 8).

An analysis of the adoption of water-saving technologies across three southern regions of Kazakhstan reveals a limited and fragmented transition toward efficient water use models, despite high levels of resource vulnerability. Full implementation of solutions such as drip and tape irrigation, automated water delivery systems, and digital monitoring is observed in only 5.18% of farms in Kyzylorda and 9.79% in Zhambyl. These figures indicate an extremely low degree of technological transformation in the irrigation sector – a particularly alarming trend given the growing water deficit and critical deterioration of infrastructure.

The share of farms with partial implementation (5–7%) reflects isolated modernisation efforts. However, the lack of access to the full technological cycle points to systemic barriers – most likely including limited capital, insufficient service infrastructure,

Table 8. Adoption of water-saving technologies

Category	Region					
	Kyzylorda		Turkestan		Zhambyl	
	N	%	N	%	N	%
Full adoption	27	5.18	42	8.06	51	9.79
Partial adoption	27	5.18	35	6.72	32	6.14
Plans for adoption	50	9.60	59	11.32	53	10.17
No adoption/plans	58	11.13	53	10.17	34	6.52

Explanations: N as in Tab. 5.
Source: own elaboration based on field survey data (2025).

Table 9. Barriers to adoption

Category	Region					
	Kyzylorda		Turkestan		Zhambyl	
	N	%	N	%	N	%
Full adoption	131	25.14	136	26.11	87	16.70
Partial adoption	57	10.94	81	15.55	96	18.43
Plans for adoption	37	7.10	44	8.45	39	7.49
No adoption/plans	29	5.56	34	6.53	31	5.95

Explanations: N as in Tab. 5.
Source: own elaboration based on field survey data (2025).

and risks associated with deploying innovations in conditions of unstable water supply. Simultaneously, about 10–11% of respondents report intentions to adopt such technologies in the future, highlighting not only an awareness of their importance but also the existence of latent demand constrained by financial and institutional limitations.

Particularly concerning is the proportion of farms without any adoption or intention to adopt – ranging from 6.52% in Zhambyl to 11.13% in Kyzylorda. Under conditions of water scarcity and high losses, this suggests significant institutional inertia, a lack of adaptive mechanisms, and an absence of behavioural incentives for transforming water use practices. The findings confirm that technological modernisation is hampered by a combination of structural, organisational, and behavioural constraints.

The results provide a compelling rationale for shifting from fragmented support measures to a coherent policy framework for the accelerated deployment of water-saving technologies. This should include:
– the development of flexible subsidy and concessional financing programs;
– establishment of regional service clusters (technical support, installation, maintenance);
– education and demonstration projects in water-scarce areas;
– institutional support at the regional governance level.

Moreover, the observed interregional disparities lay the groundwork for differentiated incentive programs based on regional vulnerability indices and levels of institutional maturity.

From an academic perspective, the findings offer a robust empirical foundation for studying technological adaptation under climate and water stress. Specifically, they:
– enable the construction of behavioural models of farmer decision-making;
– support evaluation of the effectiveness of policy interventions;
– provide comparative insights for cross-national analyses of water sector transformation in transition economies (see Tab. 9).

An analysis of constraints hindering the adoption of water-saving technologies reveals that the most systemic and universally cited barrier across all three regions is the shortage of financial resources. A lack of investment was reported by 25.14% of respondents in Kyzylorda and 26.11% in Turkestan, highlighting not only limited self-financing capacity, but also the poor accessibility of external support mechanisms such as loans, subsidies, and grants. Although the figure is somewhat lower in Zhambyl (16.7%), financial constraints remain the dominant obstacle, confirming the widespread nature of investment scarcity in the agricultural water sector.

The second most significant barrier is informational in nature, stemming from a lack of knowledge, advisory services, and practical case studies demonstrating the use of water-efficient technologies. This issue is especially pronounced in the Zhambyl region (18.43%), where, despite relatively higher adoption rates, there exists an acute shortage of institutional support and information infrastructure. This paradox may indicate a strong internal demand for innovation that is not being met by educational or extension systems. In Turkestan and Kyzylorda, 15.55% and 10.94% of respondents, respectively, cited information deficits, underscoring the critical importance of educational components within modernisation strategies.

Institutional and infrastructural barriers, while less prevalent, remain significant. These include a lack of technical services (7–8%) and insufficient government support (5–6%). Although these figures appear modest, their persistence across all regions points to a lack of systemic coherence in existing support programs. Farmers report inadequate access to local technical service providers for installation and maintenance, which reduces trust in technologies and increases the transaction costs of transitioning to new practices.

The findings clearly show that the adoption of water-saving technologies is not hindered by a single factor, but rather by a complex interplay of financial, informational, institutional, and service-related constraints. This underscores the need to shift from fragmented subsidy policies toward a multi-level support architecture encompassing financial tools, advisory centres, technician training, and the development of local service markets. Regional differences further emphasise the necessity of tailoring interventions to account for territorial specificities, patterns of water use, and the maturity of local farming communities.

From a scientific perspective, these results contribute to a deeper understanding of the behavioural and structural determinants of water innovation uptake in transition economies. They can inform the development of barrier typologies, comparative models of regional water development, and assessment tools for evaluating the effectiveness of public interventions in the agricultural water sector (see Tab. 10).

The assessment of the effectiveness of government support in the agricultural water use sector reveals the limited impact of existing mechanisms on improving water supply conditions and encouraging innovation adoption. Only 2.69–5.18% of respondents across the three surveyed regions rated government

Table 10. Perception of state support

Category	Region					
	Kyzylorda		Turkestan		Zhambyl	
	N	%	N	%	N	%
Full adoption	14	2.69	22	4.22	27	5.18
Partial adoption	39	7.48	61	11.71	46	8.83
Plans for adoption	63	12.09	68	13.05	51	9.79
No adoption/plans	24	4.61	27	5.18	27	5.18

Explanations: N as in Tab. 5.
Source: own elaboration based on field survey data (2025).

programs as highly effective, meaning they fully address existing issues. This figure highlights either the insufficient reach or low relevance of the provided instruments in relation to the actual needs of agricultural producers.

The majority of respondents characterise support measures as moderately effective, ranging from 7.48% in Kyzylorda to 11.71% in Turkestan. This may indicate a partial alignment between the programs and farmers' real demands, but also suggests systemic shortcomings – such as fragmented implementation, lack of follow-through, and inadequate support during execution. At the same time, a significant proportion of respondents perceive government assistance as either ineffective (9.79–13.05%) or entirely lacking impact (around 5% in each region). These assessments point to a crisis of trust in public policy instruments and a disconnect between program designers and their target beneficiaries.

The issue is especially acute in the Kyzylorda Region, where nearly one in five farmers (16.7%) reported weak or non-existent results from government interventions. This may be attributed to institutional fragmentation in water governance and the high vulnerability of local irrigation infrastructure – factors that undermine the potential benefits of even well-intentioned support programs.

From a practical standpoint, these results underscore the urgent need to restructure the architecture of government support in the agricultural water sector. Key priorities should include the following.

1. Targeting programs based on regional characteristics and degrees of water vulnerability.
2. Integrating financial and informational tools into a unified support system.
3. Introducing performance metrics grounded in beneficiary feedback. Additionally, the regional differences in perceived effectiveness can serve as a foundation for designing adaptive policy instruments – such as differentiated subsidy schemes, support for demonstration farms, and digital platforms for application and reporting processes.

From a research perspective, these findings provide a solid empirical basis for analysing the relationship between perceived policy effectiveness and actual changes in farmers' behaviour regarding irrigation modernisation. These results can also inform models for evaluating policy interventions and the effectiveness of water governance systems in agricultural regions.

To better understand the relationships between the key variables, a Spearman correlation analysis was conducted. It allowed for assessment of the direction and strength of associations between water availability, the condition of irrigation infrastructure, water losses, adoption of water-saving technologies, barriers to adoption, and government support. The correlation coefficients are presented in Table 11.

Water losses are negatively correlated with both water availability and the condition of irrigation infrastructure. Technology adoption shows positive associations with resource availability and infrastructure quality, and negative associations with barriers, while state support has only a moderate positive effect. To refine the analysis, multiple regression was conducted, allowing a quantitative assessment of the relative impact of availability, infrastructure, technology, barriers, and support on overall water losses. The results are presented in Table 12.

The main driver of water losses is the poor condition of irrigation infrastructure ($\beta = -0.41$, $p < 0.001$), while improved water availability ($\beta = -0.22$, $p < 0.01$) and the adoption of water-saving technologies ($\beta = -0.28$, $p < 0.01$) significantly reduce losses. Institutional barriers, primarily financial, increase losses ($\beta = +0.19$, $p < 0.05$), whereas state support shows only a moderate and borderline effect ($\beta = -0.11$, $p \approx 0.09$), underscoring the need for stronger and more targeted policies.

The analysis is limited by aggregated survey data ($n = 521$), which restricts the potential for micro-level modelling and requires the use of partial identification techniques. Moreover, the model incorporates only core factors, while issues such as market incentives, farmer education, institutional coordination, and transboundary dynamics remain beyond the scope of this study and require further examination. In line with international principles of integrated water resources management (FAO, 2020), the findings emphasise the need for a comprehensive

Table 11. Spearman correlation matrix

Variables	Water availability	Irrigation condition	Water losses	Technology adoption	Barriers	State support
Water availability	1.00	0.42**	−0.44**	0.61**	−0.33*	0.28*
Irrigation condition	0.42**	1.00	−0.62**	0.57**	−0.29*	0.25*
Water losses	−0.44**	−0.62**	1.00	−0.55**	0.30*	−0.21
Technology adoption	0.61**	0.57**	−0.55**	1.00	−0.48**	0.32*
Barriers	−0.33*	−0.29*	0.30*	−0.48**	1.00	−0.27*
State support	0.28*	0.25*	−0.21	0.32*	−0.27*	1.00

Explanations: * = $p < 0.05$, ** = $p < 0.01$.
Source: own study.

Table 12. Results of multiple linear regression: factors influencing water losses

Variable	β	p-value
Water availability	−0.22	0.001
Irrigation condition	−0.41	0.000
Technology adoption	−0.28	0.002
Barriers	0.19	0.015
State support	−0.11	0.089
Constant	–	–

Explanations: dependent variable = water losses, β = standardised coefficient; the regression model is statistically significant ($p < 0.01$) and explains about 47% of the variation in the dependent variable (coefficient of determination $R^2 = 0.47$).
Source: own study.

strategy that combines infrastructure modernisation, institutional reform, targeted support mechanisms, and regional coordination in transboundary water use.

Despite the significant findings obtained, the study is subject to several limitations. First, the analysis is based on aggregated data from a sociological survey ($n = 521$), which does not allow for the construction of individualised micro-level models of water use. In the absence of disaggregated data for each respondent, the correlation analysis was carried out within the framework of partial identification, which yields interval-based estimates of relationships. Nevertheless, the direction of the observed associations remains robust across all scenarios and aligns with the results of the regression analysis.

Second, the model considers only the core factors – namely, water availability, infrastructure condition, technology adoption, implementation barriers, and state support. Other important dimensions – such as market incentives, farmers' education level, institutional coordination, and transboundary water governance – were not included in the calculations and require separate investigation.

Based on the findings, a conceptual model for sustainable water resource management in Kazakhstan's agricultural sector was proposed (Fig. 1). This model is consistent with international

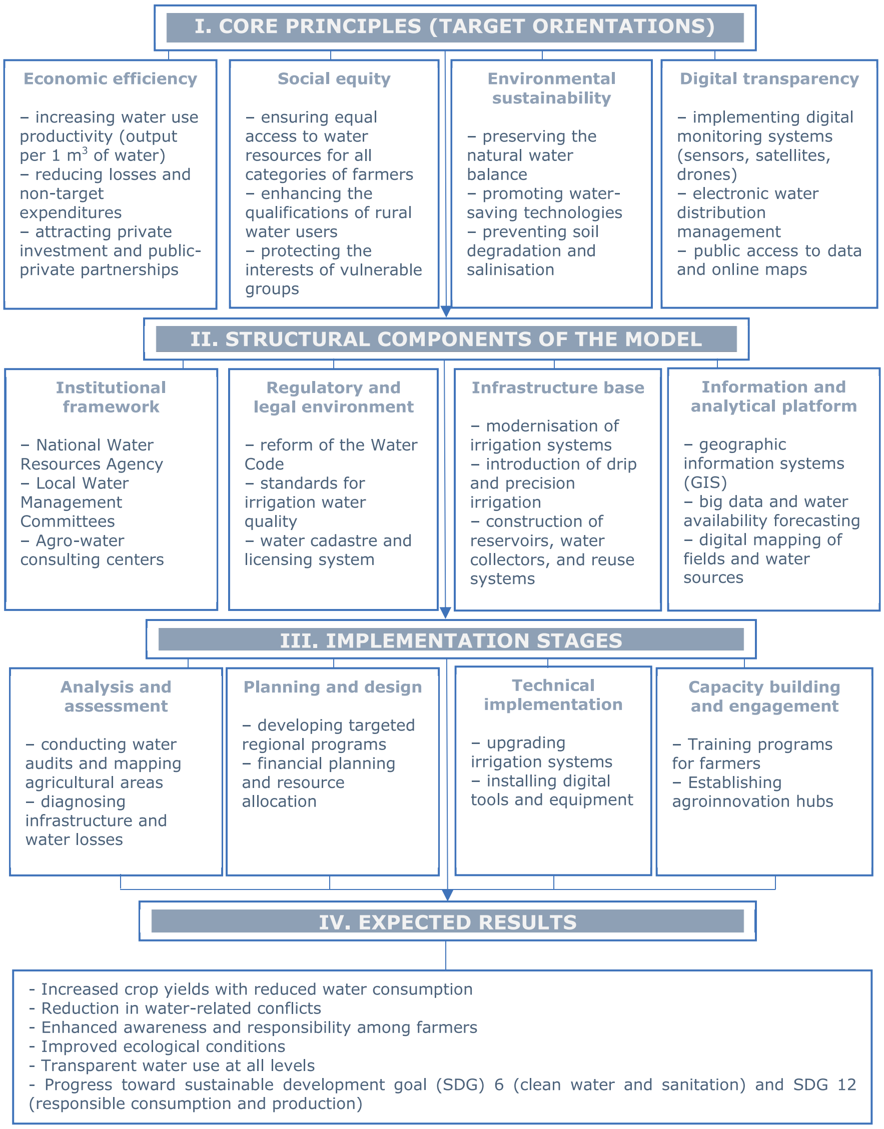

Fig. 1. Model of sustainable water resource management in Kazakhstan's agricultural sector; source: own study

frameworks for integrated water resources management, as outlined in the FAO report "The state of food and agriculture 2020: Overcoming water challenges in agriculture" (FAO, 2020). The model illustrates how the study's results can be applied to develop national strategies for the sustainable development of the agricultural sector. It emphasises the need for a holistic approach in which modernisation of physical infrastructure is combined with institutional reforms, targeted farmer support mechanisms, and regional coordination of transboundary water resource use.

DISCUSSION

Given the agricultural specificities of Kazakhstan, sustainable water management must be grounded in an interdisciplinary and integrated approach that combines institutional reform, digitalisation, rationalisation of water use, and the strengthening of social inclusiveness. In this context, an integrated model of sustainable water management in Kazakhstan's agricultural sector is proposed.

The proposed model is based on four interrelated principles: economic efficiency, social equity, ecological sustainability, and digital transparency. This integrative framework reflects both leading international practices and regional particularities, offering a comprehensive response to the pressing challenges of water scarcity driven by climate change, inefficient usage, and institutional gaps.

First, economic efficiency is achieved through the adoption of water-saving technologies, the reduction of losses along the water supply chain, and the priority allocation of resources to regions and sectors with the highest productivity. This enables increased agricultural yields while simultaneously lowering costs and mitigating environmental impacts.

Second, the principle of social equity aims to ensure fair and inclusive access to water resources, particularly for smallholder farmers and vulnerable rural communities. The model emphasises stakeholder participation, equitable distribution mechanisms, and the mitigation of social tensions.

Third, environmental sustainability underscores the need for the restoration and protection of aquatic ecosystems, the prevention of soil degradation, and the maintenance of hydrological balance. This is particularly relevant for Kazakhstan, where salinisation and soil exhaustion are widespread due to inefficient irrigation practices.

Fourth, digital transparency serves as a cross-cutting element of the model, enhancing openness and accountability in governance. The use of geographic information systems (GIS) technologies, real-time monitoring systems, and open data platforms ensures precision, predictability, and adaptability in decision-making processes.

The logical structure of the model, represented in the form of a block diagram, illustrates the interconnection of key components and their sequential interaction. This facilitates interagency coordination, supports strategic planning, and makes the model scalable and applicable to other arid regions with similar conditions.

In summary, the proposed model goes beyond traditional approaches to water governance by integrating technological, institutional, and ecological dimensions. It constitutes a practical and adaptive tool aimed at building a resilient, inclusive, and digitally supported system of water resource management in agriculture, aligned with the United Nations sustainable development goals (SDG) – specifically, SDG 6 (clean water and sanitation) and SDG 12 (responsible consumption and production).

CONCLUSIONS

This study offers a comprehensive assessment of the current state of water resource management in Kazakhstan's agricultural sector, highlighting systemic inefficiencies amid climatic vulnerability and institutional fragmentation. Empirical findings demonstrate that traditional water use practices remain poorly aligned with sustainable development goals, while infrastructure degradation and governance shortcomings continue to undermine the efficiency and equity of water distribution.

The research substantiates the conceptual and methodological foundations for transitioning toward an integrated and adaptive model of sustainable water resource management in agriculture. The proposed model synthesises economic efficiency, social inclusivity, environmental balance, and digital transparency as interrelated dimensions of sustainability. By establishing an analytical linkage between institutional architecture, technological modernisation, and stakeholder engagement, the study advances theoretical understanding of how governance structures influence water sustainability under conditions of climate risk.

The significance of this work lies not only in the development of a context-specific model for sustainable water governance in arid regions, but also in the formation of a theoretical and methodological framework capable of integrating institutional, technological, and socio-economic dimensions of water management. The proposed approach articulates a systems-based vision of sustainability – bringing together economic viability, environmental integrity, and digital accountability within a unified governance paradigm. This lends the study interdisciplinary relevance and practical utility for researchers, practitioners, and policy institutions concerned with food and water security, sustainable development, and climate adaptation.

The study is subject to certain limitations, including restricted access to statistical data, regional disparities in information availability, and the incomplete representation of innovative irrigation technologies in the current sample. Future research should aim to expand the empirical base, deepen the modelling of interactions among institutional reforms, digital tools, and water use efficiency, and undertake comparative analysis across Central Asian countries. Particular emphasis should be placed on assessing the long-term socio-economic and environmental impacts of integrated and digitalised water governance approaches.

In sum, this work contributes to the evolving academic discourse on sustainable water management in arid regions by bridging theoretical reflection with practical pathways for reform.

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interest.

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