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SWOT Assessment of Agricultural Water-Management Systems in Kazakhstan: Infrastructure, Institutional Constraints, and Strategic Development Directions

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Abstract

(1) Background: Kazakhstan's agricultural sector is increasingly exposed to water scarcity, an aging irrigation infrastructure, climate change, and transboundary-water risks. (2) Methods: The study combines a cross-sectional infrastructure inventory as of 1 September 2024 with documentary evidence from 2010–2024. SWOT factors were extracted from infrastructure inventories, official water-sector documents, basin-inspectorate materials, and sector statistics and then screened for relevance and classified according to a consistent rule: strengths and weaknesses represent internal system characteristics, whereas opportunities and threats represent external conditions. Ambiguous factors were reassessed against this rule. The final factors were linked in a traceable TOWS cross-matrix to derive SO, WO, ST, and WT strategic directions. No quantitative weighting or ranking was applied; therefore, the resulting directions are interpreted as qualitative development areas rather than ranked priorities. (3) Results: The analysis identifies substantial regional differences in the scale and condition of reservoirs, hydraulic complexes, canals, pumping facilities, and drainage infrastructure. The main internal constraints are infrastructure deterioration, conveyance losses, limited metering, financing and maintenance constraints, and shortages of technical capacity. External opportunities include public investment, water-saving technologies, digital monitoring, and improved basin governance, whereas climate variability, transboundary dependence, inflationary pressure, and water-quality risks remain key threats. (4) Conclusions: Improving agricultural water security requires a shift from infrastructure expansion alone toward rehabilitation, demand-side efficiency, digital monitoring, basin-level governance, and climate and transboundary risk management.

Keywords: SWOT analysis; agricultural water management; irrigation infrastructure; water-use efficiency; TOWS; digital water management; transboundary water; Kazakhstan

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1. Introduction

Water resource management is a critical component of sustainable agricultural development in Kazakhstan, given the increasing pressure on water resources, the condition of the irrigation infrastructure, and the need to ensure long-term water and food security. The effectiveness of agricultural water-management systems depends not only on the availability of water resources, but also on the technical condition of hydraulic infrastructure, institutional arrangements, financing mechanisms, regulatory frameworks, technological modernization, and the capacity to respond to external environmental and economic pressures.

In this context, a systematic assessment of the internal and external factors affecting agricultural water management is essential for identifying development constraints and opportunities. The relevance of such an assessment is consistent with the priorities established in the Concept for the Development of the Agro-Industrial Complex of the Republic of Kazakhstan for 2021–2030, particularly with regard to national food security [1], and the Concept for the Development of the Water Resource Management System of the Republic of Kazakhstan for 2024–2030 [2].

Previous research on Kazakhstan and Central Asia has addressed individual dimensions of water management, including transboundary governance, climate-related water insecurity, irrigation efficiency, water-saving technologies, groundwater quality, and the condition of hydraulic infrastructure [3,4]. However, these strands are commonly analyzed separately or at the basin/project level. The present study addresses a narrower but distinct gap: it links a national and regional inventory of agricultural water-management assets with an explicitly rule-based SWOT/TOWS synthesis, while distinguishing the complete national infrastructure stock from assets managed by RSE "Kazvodkhoz". The scientific contribution is therefore not the SWOT technique itself, but the transparent integration of the infrastructure condition, institutional evidence, regional differentiation, and external water-security pressures into a reproducible strategic diagnostic for Kazakhstan's agricultural water-management system.

Unlike previous studies that primarily examine individual basins, specific irrigation technologies, or separate institutional and transboundary dimensions, the present study integrates operator-level infrastructure evidence with a rule-based national SWOT/TOWS framework and explicit regional differentiation.

The aim of this study is to assess the current condition and spatial differentiation of agricultural water-management systems in Kazakhstan, identify the principal infrastructural, institutional, economic, technological, and environmental factors affecting their development, and derive qualitative strategic development areas for improving the efficiency, reliability, and sustainability of water-resource use in irrigated agriculture.

The contribution of the study is threefold. First, it separates national water-management statistics from the operational inventory held on the balance sheet of RSE 'Kazvodkhoz', preventing population-level and operator-level data from being conflated. Second, it applies an explicit internal-versus-external classification rule and documents the evidence used to retain each SWOT factor. Third, it links the validated factor set to SO, WO, ST, and WT combinations through a TOWS cross-matrix, allowing readers to trace each strategic direction back to the empirical or institutional evidence from which it was derived.

SWOT analysis is used here as a structured diagnostic framework rather than as a stand-alone causal or optimization method [5–18]. Its methodological role is to organize evidence into four classes—strengths, weaknesses, opportunities, and threats—and then to support a transparent TOWS cross-analysis. The study therefore avoids treating qualitative SWOT outputs as estimates of causal effects or relative weights.

Applications of strategic-assessment frameworks to irrigation and water governance show that SWOT is most useful when factor selection is anchored in technical, institutional, environmental, and economic evidence and when the transition from factors to strategies is made explicit [3–6,19]. In this study, the framework is used to synthesize heterogeneous evidence on the infrastructure condition, resource dependence, regulatory capacity, technological modernization, and climate/transboundary exposure.

The analytical limitation of SWOT is addressed in three ways: (i) every retained factor must be supported by a stated empirical, administrative, regulatory, or peer-reviewed source; (ii) classification follows a fixed internal/external rule; and (iii) the strategic outputs are reported as qualitative development areas, not as quantitatively ranked priorities. Where ranking would require weights, expert elicitation, cost–benefit analysis, or multi-criteria decision analysis, the manuscript explicitly identifies this as a task for subsequent research.

Accordingly, the present assessment does not claim to estimate the magnitude of causal relationships among factors. It provides a structured diagnostic of the current system and a traceable basis for policy-oriented strategic interpretation. This scope is appropriate for a heterogeneous national infrastructure inventory but should not be confused with econometric, optimization, or engineering risk-prioritization models.

The framework also recognizes scale. Internal characteristics are assessed at the level of the Kazakhstan agricultural water-management system and its regional operational components, whereas external conditions include macroeconomic, climatic, transboundary, and policy-environment influences that are not controlled by an individual water-management operator.

This distinction is particularly important in Kazakhstan because regional systems differ markedly in the irrigation intensity, transboundary dependence, infrastructure age, and facility condition. A national SWOT matrix is therefore complemented by regional interpretation rather than treated as evidence of spatial uniformity.

The study consequently uses SWOT/TOWS as a synthesis layer placed after a descriptive and comparative analysis. The empirical inventory establishes what infrastructure exists and in what reported condition, the SWOT stage classifies the system-level implications, and the TOWS stage formulates strategic responses that are explicitly presented as normative interpretations of the evidence.

The aim of the revised analysis is to assess the condition and spatial differentiation of agricultural water-management systems in Kazakhstan, identify evidence-supported internal and external factors affecting their development, and derive transparent, non-ranked strategic development areas for improving water-use efficiency, infrastructure reliability, institutional capacity, and resilience to climate and transboundary risks.

2. Materials and Methods

This study uses a descriptive, comparative, and documentary research design. The phrase '2010–2024' refers to the documentary and policy-evidence window used to contextualize sector development; it does not imply a complete annual panel for every infrastructure variable. The detailed facility inventory is cross-sectional and refers primarily to the status reported as of 1 September 2024. Earlier years are used where source documents provide commissioning dates, historical policy information, selected hydrological statistics, or comparable sector indicators.

The empirical database was assembled from the following: (i) annual and inventory materials of the eight Basin Water Management Inspectorates; (ii) official data of the Ministry of Water Resources and Irrigation of the Republic of Kazakhstan; (iii) regional and consolidated information of RSE 'Kazvodkhoz'; (iv) national strategic and regulatory docu-

ments; and (v) published sector statistics and peer-reviewed studies used for contextual interpretation. Extracted fields included the region, facility type, balance holder, number of facilities, length or capacity where reported, command/serviced area, year or period of commissioning, operational/engineering condition, and selected flow characteristics. No statistical imputation was used for unreported fields: missing values were treated as unavailable rather than as zero. Where the same facility or aggregate appeared in more than one source, records were reconciled using the region, facility type/name, balance-holder information, and the most recent dated report.

The study is based on secondary documentary and administrative data and does not involve laboratory experiments, chemical reagents, commercial cell lines, or physical samples. References to water-management infrastructure, monitoring devices, and hydraulic equipment describe facilities documented in official inventories rather than instruments purchased or operated by the authors. The TALSIM-NG and Tasqyn systems mentioned elsewhere in the manuscript are discussed as examples of sectoral digitalization initiatives; they were not used to generate the analyses or figures reported in this study. The analytical procedures consisted of descriptive calculations, document review, and rule-based qualitative SWOT/TOWS classification; no hydrological simulation or numerical optimization was performed.

The analytical unit is the regional agricultural water-management system; individual facilities are the principal objects of the inventory analysis. Absolute indicators include the facility counts, canal length (km), reservoir capacity (million m^3), reported flow (m^3/s), and command/serviced area (ha). Derived indicators are calculated only where the required denominator is available: regional share (%) = regional value/national or operator total $\times$ 100; condition share (%) = facilities in a stated condition category/facilities with condition data $\times$ 100; lined-canal share (%) = lined canal length/total canal length $\times$ 100; and transboundary dependence (%) = transboundary inflow/average annual surface-water resources $\times$ 100. These indicators are descriptive and are not combined into a composite score.

The SWOT procedure was operationalized as a rule-based evidence-coding process. Candidate factors were first extracted from four evidence blocks: infrastructure condition and operation; institutional/regulatory arrangements; financing and technology; and environmental/transboundary conditions. A candidate factor was retained only when it was directly relevant to agricultural water management and supported by the inventory, an official institutional source, sector statistics, or peer-reviewed literature. Factors were then screened for duplication and reworded at a comparable level of abstraction.

Classification followed a single decision rule. A factor was coded as a Strength (S) or Weakness (W) when it described an existing characteristic, capability, resource, organization, or deficiency within Kazakhstan's agricultural water-management system. A factor was coded as an Opportunity (O) or Threat (T) when it described an external policy, technological, economic, climatic, market, or transboundary condition that could enable or constrain the system. Thus, the deterioration of canals, insufficient metering, maintenance deficits, and ownerless or poorly maintained structures are internal weaknesses, whereas climate change, transboundary-flow uncertainty, macroeconomic inflation, and external financing/technology windows are external factors.

For transparency, the revised manuscript does not claim that the factor set was validated by a Delphi panel or statistically weighted expert survey, because such procedures were not part of the study design. Instead, validation is documentary and logical: each final factor must be traceable to the evidence base and must satisfy the internal/external classification rule. Ambiguous classifications were reassessed and, where necessary, moved to the appropriate quadrant.

The TOWS stage links the final coded factors to four strategy types: SO uses existing strengths to exploit external opportunities; WO uses opportunities to address internal weaknesses; ST uses strengths to reduce exposure to threats; and WT seeks to reduce weaknesses while limiting threat exposure. The cross-matrix in the TOWS cross-matrix presented below identifies the factor codes used for each strategic direction. Because no weights, ranks, pairwise comparisons, or sensitivity analyses were applied, these outputs are interpreted as traceable qualitative strategic directions rather than as ranked priorities.

The SWOT assessment was complemented by an analysis of the technical and operational characteristics of agricultural water-management systems. Water-supply systems in agricultural production constitute a complex of engineering structures, pumping stations, pipelines, and equipment designed for the abstraction, treatment, transport, and distribution of water for domestic, industrial, livestock, and irrigation purposes. Given the substantial share of water resources used by agriculture, the reliability and efficiency of these systems are critical for agricultural production and water security [20].

The water-management complex of the Republic of Kazakhstan is intended to provide the population and economic sectors with water resources, create appropriate conditions for their use, and protect water resources from depletion and pollution [21]. A water-management system comprises hydraulic structures, hydromechanical equipment, measuring and control devices, energy and transport infrastructure, and technical regulation systems designed for water abstraction and the efficient use of natural water resources [22]. Kazakhstan applies a basin-based principle of water-resource management, while water-management systems can be classified according to their morphological structure, functional purpose, and information-management characteristics [3,21,23]. Their morphological organization has a hierarchical character corresponding to territorial and administrative divisions [24,25].

The conceptual hierarchy used to organize these interrelated resource, governance, institutional, and infrastructure conditions is summarized in Figure 1.

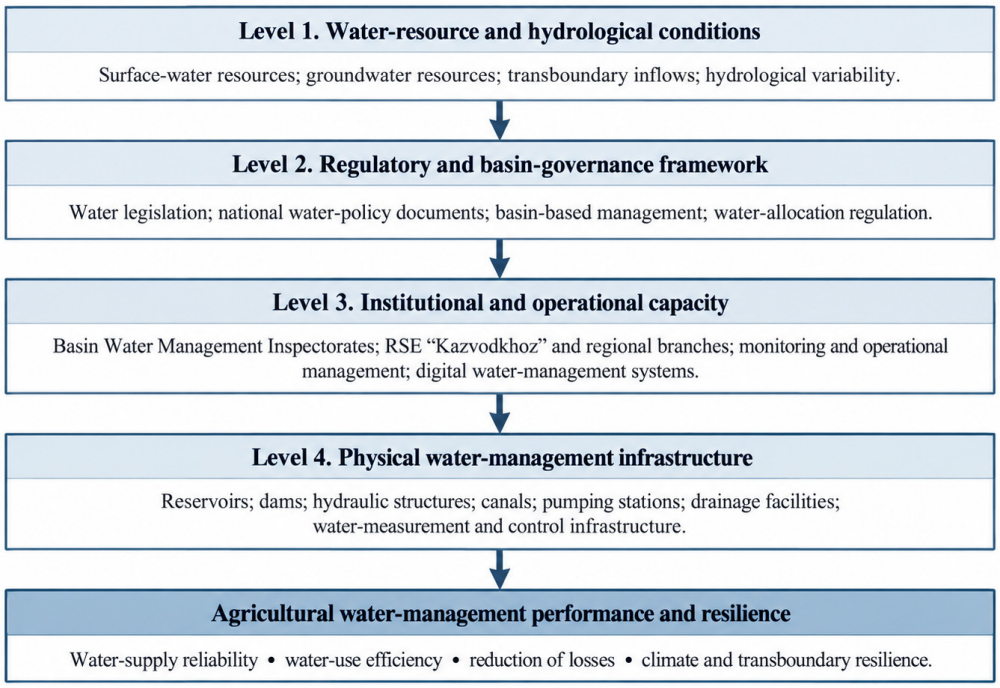


Figure 1. Conceptual hierarchy of conditions supporting agricultural water management in Kazakhstan. Note: authors' synthesis based on the regulatory and institutional framework [3,21–24]. The figure is a qualitative conceptual schematic and does not represent a calculated composite "water-resource potential" index.

Figure 1 summarizes the analytical hierarchy adopted in this study. The four levels are conceptually interrelated but are not aggregated into a composite quantitative index: hydrological conditions define the resource context, the regulatory framework establishes the rules for water allocation and protection, operational institutions implement these arrangements, and the physical infrastructure enables water abstraction, storage, conveyance, distribution, and drainage.

The principal elements of agricultural water-supply systems include water-intake structures such as boreholes, wells, and river or lake intake units; pumping stations used to lift water and maintain the required pressure; treatment and filtration facilities; reservoirs and water towers for storage and pressure regulation; and water-supply networks distributing water to agricultural production facilities and irrigated areas [23]. In the present study, these institutional and infrastructure elements are treated as components of the agricultural water-management system rather than as a calculated measure of national "water-resource potential" [21].

Agricultural water-supply systems can be classified according to their functional purpose into irrigation systems, livestock and poultry water-supply systems, domestic and utility systems, and firefighting systems. Irrigation systems include drip, sprinkler, and surface irrigation technologies. Livestock and poultry systems provide drinking water and water for sanitation and technological operations at agricultural facilities, while domestic and utility systems serve rural settlements, workers, and administrative facilities. Firefighting systems provide the required water reserves for emergency responses.

For conveyance infrastructure, the study uses the conveyance-efficiency coefficient $\eta c = V_{delivered}/V_{diverted}$, where $V_{diverted}$ is the volume entering the canal or conveyance reach and $V_{delivered}$ is the volume reaching the defined delivery point. The reference values cited below are design/regulatory benchmarks for conveyance performance; they are not empirical estimates calculated from the present inventory.

The cited technical guideline reports reference conveyance-efficiency values of approximately 0.90 for earth canals, 0.96 for canals with concrete/geomembrane/asphalt-bitumen lining or reinforced-concrete flumes, and 0.98 for pipelines; an overall irrigation-system efficiency of about 0.75–0.80 is indicated for systems dominated by earth canals [26]. These values are used as engineering benchmarks only, and the manuscript does not infer that individual Kazvodkhoz canals meet them without field measurement.

Measures to reduce water losses can be divided into operational and structural measures. Operational measures include the timely repair and cleaning of canals and their operation under appropriate flow and hydraulic conditions. Structural measures include reducing the length of irrigation canals, optimizing canal cross-sections and flow velocities, reducing the permeability of canal beds, and replacing open conveyance systems with piped distribution networks [27–30]. Unlined earthen canals are particularly vulnerable to deterioration, emergency situations, and other adverse phenomena.

The technical assessment of water-management systems therefore includes the evaluation of the condition and operational performance of water-conveyance infrastructure, the efficiency of water distribution among users, the identification of water losses associated with technical deterioration and operational inefficiencies, and the identification of development areas for modernization. A diagnostic assessment of canals and pipelines should combine visual inspections with instrumental measurements [31]. For reservoirs and other water bodies, the assessment considers water-level dynamics, filling and discharge patterns, water quality, and seasonal hydrological conditions.

Based on the empirical and technical assessment, development areas for reconstruction, repair, modernization, and technological upgrading of water-management systems were identified.

The resulting methodological framework combines a descriptive and comparative assessment of existing agricultural water-management infrastructure with qualitative SWOT analysis. This combination makes it possible to identify the principal internal capabilities and constraints of the systems under examination, assess external opportunities and threats, and formulate strategic development directions for improving the efficiency, reliability, and sustainability of agricultural water management in Kazakhstan.

3. Results

3.1. Water Resources and Agricultural Water-Management Infrastructure in Kazakhstan

The water sector is a critical component of agricultural development in Kazakhstan. The National Development Plan of the Republic of Kazakhstan through 2029 (Presidential Decree No. 611 of 30 July 2024) identifies sustainable infrastructure, resource efficiency, and agricultural development among the country's strategic development priorities [32].

Kazakhstan is divided into eight water-management basins: Aral–Syr Darya, Balkhash–Alakol, Irtysh, Ishim, Zhaiyk–Caspian, Nura–Sarysu, Tobol–Turgai, and Shu–Talas. The frequently cited national estimate of 102.3 km^3 refers to long-term average annual surface-water resources reported in the regional water-sector yearbook: 50.74 km^3 (49.6%) is generated within Kazakhstan and 51.56 km^3 (50.4%) arrives through transboundary rivers. These values are therefore long-term average resource estimates and should not be interpreted as a 2024 observation or as an average calculated from the study's 2010–2024 documentary window [33].

The degree of dependence varies considerably among regions. The highest dependence is observed in the southern, southeastern, and western parts of the country, particularly within the Aral-Syr Darya, Balkhash-Alakol, Shu-Talas, and Zhaiyk-Caspian basins. More than 90% of the water resources available in Kyzylorda and Turkistan regions originate from transboundary flows, compared with approximately 80% in West Kazakhstan and Atyrau regions, more than 75% in Zhambyl region, and approximately 48% in Almaty region [2]. Consequently, the availability and quality of water resources in Kazakhstan are influenced not only by domestic hydrological conditions but also by water use and pollution in upstream countries.

Two infrastructure populations are distinguished throughout the revised manuscript. National sector statistics describe the overall stock of water-management assets in Kazakhstan (for example, national totals for reservoirs, hydraulic structures, canals, and dams), whereas the detailed regional infrastructure inventory presented in the Discussion section covers assets reported on the balance sheet of RSE "Kazvodkhoz". The latter is an operator-level subset and must not be interpreted as the complete national infrastructure stock.

The source documents use several condition concepts that are not identical. In the revised text, 'facility condition' refers to the categorical engineering/operational status (e.g., satisfactory, unsatisfactory, emergency, under reconstruction), while 'depreciation' or 'wear' is used only when the source explicitly reports an accounting or engineering wear percentage. Accordingly, the manuscript avoids converting a statement such as 'wear exceeds 60%' into a share of facilities classified as unsatisfactory unless the underlying source provides that equivalence.

3.2. SWOT Assessment of Agricultural Water-Management Systems

The SWOT assessment in Section 3.2 uses the same evidence blocks specified in the Methods: infrastructure and operational data; institutional and regulatory documents; financing and technology information; and environmental/transboundary evidence. No additional information category is introduced in the Results without being identified in the Methods.

3.2.1. Strengths

The principal strengths of Kazakhstan's agricultural water-management system are associated with the country's substantial agricultural and land-resource potential, the availability of established water-management infrastructure, and the development of an institutional and regulatory framework for water-resource governance. Kazakhstan has diverse soil and climatic conditions that support a wide range of agricultural activities, while diversified organizational forms of agricultural production and the adoption of resource-efficient technologies provide additional capacity for agricultural development [34].

The existing network of reservoirs, canals, hydraulic structures, and other water-management facilities provides an established physical basis for agricultural water supply and irrigation. The entry into force of the Water Code, together with the Concept for the Development of the Water Resource Management System through 2030 and the Comprehensive Plan for the Development of the Water Sector for 2024–2028, provides an institutional and regulatory framework for water-resource management, infrastructure development, and water-resource protection [2,21,35].

An additional institutional strength is the existence of specialized state agencies responsible for water-resource management and established mechanisms for tariff setting and the collection of water-use fees. The application of integrated water-resource management principles provides a basis for coordinating water allocation among agricultural, environmental, and other economic uses.

3.2.2. Opportunities

The principal opportunities for the development of agricultural water-management systems are associated with infrastructure modernization, the expansion of irrigated agriculture, technological upgrading, digitalization, and the improvement of water-use regulation. National plans provide for the modernization of irrigation canals, which is expected to reduce conveyance losses from approximately 50% to 25%, as well as the construction of 42 new reservoirs by 2030, with an additional storage capacity of up to 2.7 billion m^3 [2]. These measures create opportunities to increase the reliability of the agricultural water supply and improve water-use efficiency.

Digital transformation is treated as an external opportunity because national-scale initiatives now provide an enabling technological and financing environment [36]. TALSIM-NG was selected as an illustrative opportunity because it is being adapted for river-basin modeling and runoff forecasting with institutional support and planned basin-scale expansion, while integration with the Tasqyn system is intended to strengthen flood-risk and operational decision support [37]. Its inclusion does not imply that TALSIM-NG is quantitatively more important than every other opportunity; no opportunity ranking was performed.

Digital water accounting and billing provide a second operational example [38]. RSE 'Kazvodkhoz' has introduced a platform for applications, contracts, water-use accounting, invoicing, and payments, with more than 28,000 agreements registered [39]. This initiative is classified as an opportunity for broader digital integration because the present inventory does not demonstrate universal real-time metering across the physical network.

Other external opportunities include automated gates and metering, a national water-data infrastructure, domestic production of water-saving equipment, and investment mechanisms supporting modernization. Their strategic relevance is assessed qualitatively from policy and implementation evidence, not through numerical weighting.

3.2.3. Weaknesses

The principal weaknesses of agricultural water-management systems are associated with the technical deterioration of infrastructure, high conveyance losses, insufficient investment, limited adoption of water-saving technologies, and institutional and human-resource constraints. A substantial share of the hydraulic infrastructure has operated for several decades without major reconstruction or rehabilitation. Some official source materials report wear/depreciation levels exceeding 60% for parts of the infrastructure; because source terminology differs, this figure is treated as a source-reported wear indicator and not as the percentage of facilities classified as unsatisfactory.

The inefficient use of water resources is also associated with outdated and water-intensive irrigation technologies, high conveyance losses in unlined earthen canals, and insufficient installation of water-metering systems at water-intake facilities. The limited availability of effective economic incentives for the adoption of water-saving technologies, water recycling, and sequential water reuse further constrains improvements in water-use efficiency.

Additional weaknesses include insufficient scientific and methodological support, weak links between research institutions and agricultural producers, shortages of qualified personnel, inadequate advisory services, and low returns on some investment projects in the water sector.

3.2.4. Threats

The external environment of agricultural water management is characterized by several significant threats. Climate change is expected to increase variability in precipitation and runoff, intensify drought and flood risks, and increase competition for limited water resources. These changes may reduce the predictability of the agricultural water supply and place additional pressure on the existing infrastructure.

A particularly significant threat is Kazakhstan's dependence on transboundary water resources. A substantial share of the country's water supply originates outside its national borders, making agricultural water availability sensitive to the water-management policies and practices of upstream countries, including China, Russia, and neighboring Central Asian states [40].

Other external threats include the deterioration of source-water quality and ecosystem conditions, inflation and construction-cost escalation, competition among agricultural, municipal, industrial, and environmental water uses, and external shocks that can delay financing, technology supply, or implementation schedules. By contrast, infrastructure deterioration, insufficient maintenance, weak implementation capacity, and ownerless or poorly maintained domestic structures are treated as internal weaknesses rather than external threats.

Taken together, the evidence presented in Sections 3.2.1–3.2.4 was consolidated into the final SWOT factor set shown in Table 1. The classification follows the internal–external rule defined in the Methods and retains only factors supported by empirical, administrative, institutional, or peer-reviewed evidence.

Table 1 shows that the principal internal constraints of Kazakhstan's agricultural water-management system are associated with infrastructure deterioration, conveyance losses, incomplete metering, maintenance limitations, and shortages of technical capacity. At the same time, the system retains important strengths in the form of an established infrastructure base, basin-governance architecture, regulatory mechanisms, and accumulated operational experience.

Table 1. Evidence-based SWOT factors affecting agricultural water-management systems in Kazakhstan (final classified factor set).

Strengths	**Weaknesses**
S1. Established national and regional water-management infrastructure	W1. High physical/engineering deterioration of canals, hydraulic structures, and water-supply networks
S2. Basin-based governance architecture and specialized public institutions	W2. High conveyance losses, incomplete metering, and uneven automation
S3. Existing state support and sector financing mechanisms	W3. Maintenance and rehabilitation financing constraints
S4. Regulatory framework for water allocation, protection, and infrastructure modernization	W4. Shortages of qualified personnel, scientific-methodological support, and advisory capacity
S5. Operational experience and regional asset inventories held by water-management organizations	W5. Limited affordability/collection capacity and high adoption costs for modern irrigation equipment
Opportunities	Threats
O1. Public investment and rehabilitation programs	T1. Climate change, drought/flood variability, and long-term runoff uncertainty
O2. Water-saving irrigation and canal-modernization technologies	T2. Transboundary-flow dependence and upstream water-use decisions
O3. Digital metering, remote sensing, forecasting, and decision-support systems	T3. Deterioration of source-water quality and ecosystem pressures
O4. Additional domestic and international investment/PPP instruments	T4. Inflation and construction-cost escalation affecting capital projects
O5. Integrated use of surface water and groundwater where environmentally justified	T5. Increasing competition for water among agriculture, settlements, industry, and ecosystems
O6. Improved basin-level coordination and data integration	T6. External shocks that delay financing, technology supply, or implementation schedules
O7. Development of domestic water-saving equipment and metering technologies	
O8. International cooperation on transboundary rivers and climate adaptation	
O9. Expansion of training and applied research partnerships	

The external environment combines substantial modernization opportunities—public investment, water-saving technologies, digital monitoring, improved basin coordination, international cooperation, and capacity building—with persistent threats related to climate variability, transboundary dependence, water-quality pressures, inflation, and increasing competition for water. This combination indicates that the development of the sector depends on interactions among technical, institutional, financial, and environmental factors rather than on any single constraint. These interactions are examined in Table 2 through a TOWS cross-matrix linking the coded SWOT factors to qualitative strategic development directions.

Table 2 demonstrates how the diagnostic factors identified in Table 1 are translated into SO, WO, ST, and WT strategic directions. Because no weighting or ranking procedure was applied, these combinations represent qualitative strategic development areas rather than a hierarchy of priorities. The following section interprets each strategy type in greater detail and links it to the empirical and institutional evidence presented above.

Table 2. Traceable TOWS cross-matrix linking the final SWOT factors in Table 1 to qualitative strategic development directions.

TOWS Combination	Factor Links	Strategic Direction and Interpretation
SO	S1–S4 × O1–O3/O6	Use the established infrastructure and basin-governance system to scale rehabilitation, metering, forecasting, and water-saving technologies. This builds on existing institutional and physical capacity to capture modernization opportunities. Qualitative; not ranked.
WO	W1–W4 × O1–O4/O7/O9	Direct investment, technology, training, and digital tools toward deteriorated assets, conveyance losses, weak metering, and capacity gaps. This uses external enabling conditions to address internal deficiencies. Qualitative; not ranked.
ST	S2–S4 × T1–T3/T5	Strengthen basin planning, reservoir operation, monitoring, and transboundary coordination to reduce exposure to climate and water-security risks. This uses internal governance capacity to mitigate external threats. Qualitative; not ranked.
WT	W1–W4 × T1–T6	Emphasize risk-based maintenance, loss reduction, contingency planning, and financially resilient rehabilitation for the most vulnerable assets and regions. This reduces internal vulnerability while limiting exposure to external shocks. Qualitative; not ranked.

To preserve the regional dimension, the subsequent interpretation distinguishes four broad operational contexts: (i) southern and south-eastern irrigated regions, where high irrigation demand and transboundary dependence increase the value of conveyance-loss reduction and metering; (ii) northern and central regions, where aging assets and lower irrigation density make risk-based rehabilitation especially important; (iii) western regions, where transboundary inflow, water-quality pressure, and industrial competition require stronger monitoring and reuse; and (iv) eastern regions, where reservoir regulation and transboundary coordination are central to system resilience. These are analytical typologies rather than administratively fixed clusters.

The resulting TOWS structure provides the analytical basis for the strategic interpretation developed in Section 3.3.

3.3. Strategic Interpretation and Development Areas

3.3.1. SO Strategies: Leveraging Existing Strengths to Capture Development Opportunities

The following SO, WO, ST, and WT sections are strategic interpretations derived from the empirical findings through the TOWS links shown in Table 2. They should not be read as additional empirical results or as a quantitatively optimized policy ranking. Where the text refers to rehabilitation criteria such as deterioration, strategic importance, agricultural coverage, or expected loss reduction, these are proposed decision criteria for future multi-criteria appraisal rather than criteria numerically applied in the present study.

A further SO direction is to use the established water-management network to implement the evolving national infrastructure program. The original 2024 concept and early implementation materials referred to 20 new reservoirs and the reconstruction of 15 existing facilities; subsequent official updates after the 2024 flood period expanded the program to 42 new reservoirs and, in later Ministry reporting, 37 reconstructions by 2030. The revised manuscript therefore cites the dated policy version for each figure rather than presenting these targets as simultaneous or contradictory [2,35].

Another SO direction is the integration of digital technologies into existing water-management institutions. The further development of TALSIM-NG, its integration with the Tasqyn system, and the expansion of digital water accounting and billing can strengthen the capacity of existing institutions to monitor water availability, forecast hydrological conditions, and manage water allocation. The existing institutional framework therefore provides a basis for scaling digital solutions from individual projects to basin-level water management [37,39–41].

The SO strategy also implies greater use of water-saving irrigation technologies in regions where agricultural production already has established irrigation capacity. The combination of existing agricultural potential with drip irrigation, sprinkler systems, improved water metering, and automated distribution can increase the productivity of water resources without relying exclusively on the expansion of water withdrawals.

3.3.2. WO Strategies: Using Opportunities to Overcome Existing Weaknesses

The WO strategy focuses on using available investment, technological, institutional, and digital opportunities to address the structural weaknesses identified in the SWOT assessment. The most significant weaknesses include physical deterioration of the water-management infrastructure, high water losses in irrigation networks, insufficient water metering, limited adoption of water-saving technologies, inadequate investment, and shortages of qualified personnel.

The first WO direction is the targeted rehabilitation of critically deteriorated infrastructure. Where source-reported wear is high or facility condition is deficient, modernization should be guided by technical diagnostics and by proposed decision criteria such as strategic importance, agricultural coverage, and potential effects on water losses. These criteria are presented for future multi-criteria appraisal and were not numerically weighted or ranked in the present study.

The second WO direction is the reduction of water losses through technological modernization. The continued operation of unlined earthen canals and outdated irrigation technologies contributes to significant conveyance losses. The modernization of canals, installation of water-metering equipment, introduction of automated hydraulic structures, and expansion of water-saving irrigation technologies can directly address these weaknesses. National plans to reduce water losses in irrigation networks therefore represent an opportunity to transform an existing structural constraint into a measurable efficiency improvement [2].

The third WO direction is the expansion of digital water accounting. The existing digital billing platform, which already incorporates more than 28,000 water-use agreements, provides an institutional and technological basis for further development of integrated water accounting and monitoring [39]. Extending digital monitoring from billing and contractual processes to the real-time measurement of water abstraction, distribution, and consumption could improve transparency and strengthen incentives for rational water use.

The fourth WO direction concerns the development of human and scientific capacity. The introduction of new forecasting, monitoring, and water-saving technologies requires qualified specialists capable of operating digital systems, managing modern irrigation infrastructure, and interpreting hydrological information. Strengthening cooperation between research institutions, water-management organizations, agricultural producers, and advisory services would therefore be necessary to ensure that technological modernization produces sustained operational effects.

3.3.3. ST Strategies: Using Existing Strengths to Mitigate External Threats

The ST strategy aims to use Kazakhstan's existing institutional, infrastructural, and technological capacities to reduce vulnerability to external threats, particularly climate change, transboundary water dependence, water scarcity, and increasing hydrological variability.

The first ST direction is strengthening basin-level water-resource management. Kazakhstan's division into eight water-management basins provides an institutional basis for coordinating water allocation according to hydrological rather than purely administrative boundaries. This approach can be further strengthened through integrated water-resource management, improved basin-level planning, and systematic coordination among agricultural, environmental, industrial, and municipal water users.

The second ST direction is the development of forecasting and early-warning capacities. Climate variability increases uncertainty in the timing and volume of runoff and creates risks associated with both droughts and floods. The adaptation and expansion of TALSIM-NG, together with its integration with the Tasqyn system, can strengthen the ability of water-management institutions to anticipate hydrological events and adjust reservoir and water-allocation decisions accordingly [37,40,41].

The third ST direction is strengthening the resilience of the agricultural water supply through improved reservoir management. Existing reservoirs represent an important strategic asset because they enable the seasonal regulation of water resources and can partially reduce the effects of fluctuations in natural runoff. Improving reservoir-operation rules, integrating hydrological forecasts into operational decisions, and coordinating reservoir management at the basin level can increase the resilience of irrigated agriculture to climate-related variability.

The fourth ST direction concerns the reduction of exposure to transboundary water risks. Given that 50.4% of Kazakhstan's average annual surface-water resources originate from transboundary inflows, domestic water-management capacity alone cannot eliminate external vulnerability [33]. However, improved monitoring, forecasting, basin-level planning, water-use efficiency, and infrastructure modernization can reduce the sensitivity of agricultural production to fluctuations in transboundary water availability.

3.3.4. WT Strategies: Reducing Weaknesses and Exposure to External Threats

The WT strategy represents the most risk-oriented component of the strategic framework and focuses on minimizing the combined effects of internal weaknesses and external threats. This combination is particularly important for water-management facilities characterized by high physical deterioration, inadequate maintenance, limited investment, and exposure to climate-related or transboundary water risks.

The first WT direction is the rehabilitation or replacement of critically deteriorated hydraulic structures. Infrastructure exposed simultaneously to poor technical conditions and increasing hydrological variability may pose a significant risk to continuity of the agricultural water supply. Technical diagnostics should therefore be used to identify facilities requiring urgent rehabilitation, reconstruction, or replacement; the present study does not calculate engineering failure probabilities.

The second WT direction is the systematic reduction of water losses. Under conditions of increasing water scarcity and climate variability, continued high conveyance losses increase the vulnerability of agricultural water users. Measures aimed at canal rehabilitation, the lining of critical sections, the installation of metering equipment, and the modernization of irrigation technologies should therefore be considered not only as efficiency measures but also as instruments of climate-risk adaptation.

The third WT direction is strengthening operational and maintenance capacity. Aging infrastructure requires regular technical inspection, preventive maintenance,

emergency-response mechanisms, and qualified personnel. Strengthening these functions would reduce the probability that infrastructure deterioration develops into large-scale operational failures, particularly during periods of drought, floods, or abnormal hydrological conditions.

The fourth WT direction is strengthening investment resilience. Inflation, high rehabilitation costs, limited returns on some water-management projects, and competing investment priorities may constrain modernization. Therefore, investment decisions should be based on clearly defined technical, economic, and water-efficiency criteria, with particular attention to projects capable of simultaneously reducing water losses, increasing reliability, and improving agricultural productivity.

3.3.5. Strategic Development Areas for Water Management

Development area 1: Infrastructure modernization and rehabilitation

Development area 1 concerns the modernization and rehabilitation of existing water-management infrastructure. Facilities with high operational significance and substantial potential for reducing water losses should be evaluated through technical diagnostics, risk assessments, and economic and water-saving criteria. The study does not rank these criteria quantitatively.

Development area 2: Water-use efficiency and technological modernization

Development area 2 focuses on increasing water-use efficiency through the modernization of irrigation technologies, reduction of conveyance losses, expansion of water metering, and wider adoption of water-saving irrigation systems. The strategic objective is to increase agricultural output per unit of water used rather than relying primarily on higher water withdrawals.

Development area 3: Digital transformation of water management

Development area 3 concerns an integrated digital water-management system. The further integration of runoff forecasting, reservoir management, water accounting, digital billing, automated hydraulic structures, and real-time monitoring can improve the transparency and responsiveness of water allocation. The expansion of TALSIM-NG, its integration with Tasqyn, and the development of national water-data infrastructure provide an enabling basis for this transformation [37,39–41].

Development area 4: Institutional, financial, and human-resource development

Development area 4 concerns the institutional, financial, and human-resource capacity. This includes the improvement of tariff mechanisms, payment discipline, private investment and public–private partnership instruments, and cooperation among government institutions, research organizations, agricultural producers, and technology providers. Parallel investment in professional training and advisory services is required for the effective operation of modern water-management technologies.

Development area 5: Climate and transboundary water resilience

Development area 5 concerns resilience to climate change and transboundary-water risks. Relevant measures include improved hydrological forecasting, basin-level planning, coordinated reservoir management, more efficient water use, and continued international cooperation on transboundary rivers. Improving water-use efficiency can reduce the sensitivity of agricultural production to fluctuations in both domestic and transboundary water availability.

3.3.6. Overall Strategic Implication

Overall, the SWOT analysis demonstrates that the development of agricultural water-management systems in Kazakhstan requires a transition from predominantly infrastructure-oriented approaches toward an integrated model combining infrastructure

rehabilitation, water-use efficiency, digital transformation, institutional modernization, and climate-risk management. The strategic challenge is therefore not limited to increasing the physical capacity of the water-management system. It also involves improving the efficiency, measurability, reliability, and resilience of existing infrastructure and strengthening the institutional capacity to manage increasingly variable and transboundary water resources.

The proposed strategic framework indicates that the greatest potential for improvement lies at the intersection of infrastructure modernization, digital water management, institutional capacity, and basin/transboundary governance [4,41]. Investment in water-management infrastructure should therefore be accompanied by measurable efficiency indicators, including conveyance-loss reduction, the expansion of metering, the adoption of water-saving technologies, and reliability of the agricultural water supply. Such an integrated approach can provide a more sustainable basis for irrigated agriculture and long-term water and food security in Kazakhstan.

4. Discussion

The results show that Kazakhstan's agricultural water-security challenge is primarily a systems problem rather than a simple shortage of physical water. Infrastructure age, conveyance losses, incomplete metering, maintenance capacity, institutional coordination, and exposure to transboundary and climate variability interact to determine reliability. This interpretation is consistent with recent research from Kazakhstan and Central Asia, which emphasizes that technical modernization alone is insufficient without basin-level governance, demand management, environmental monitoring, and transboundary cooperation [4].

The infrastructure evidence also clarifies why the canal age and lining status matter. Long service lives and large shares of earthen conveyance increase seepage and operational losses, but design-efficiency benchmarks should not be treated as observed performance without field measurements. The practical implication is that rehabilitation decisions require facility-level diagnostics and measured water balances rather than age alone.

Compared with studies that focus on a single basin or a single intervention, the present inventory highlights spatial heterogeneity across the national system. Southern and south-eastern regions combine intensive irrigation with stronger exposure to transboundary inflows; central and northern regions face different asset-density and rehabilitation challenges; western regions require closer attention to water quality and competing uses. This heterogeneity supports differentiated implementation rather than a uniform national package.

Pasture water-supply deterioration is classified in the revised SWOT as an internal weakness because it reflects the condition, maintenance, ownership, and operational status of domestic infrastructure. Potential programs to restore wells, monitor pasture condition, and re-establish seasonal pasture use are treated as opportunities or strategic responses, not as threats.

The long regional inventories that previously occupied the Discussion have been condensed below into comparative patterns supported by Figures 2–7 and Table 3. Detailed facility-level interpretation should be undertaken against the underlying administrative inventory; the Discussion focuses on patterns relevant to strategy.

Figure 2 summarizes the regional distribution of reservoirs recorded on the balance sheet of RSE "Kazvodkhoz" as of 1 September 2024 [33].

As of 1 September 2024, 86 reservoirs were recorded on the balance sheet of RSE "Kazvodkhoz" [33]. Of these, 67 were classified as satisfactory, 9 as unsatisfactory, 5 as emergency facilities, 2 as unfinished, and 3 as undergoing reconstruction. These categories sum to the reported total of 86 facilities and are therefore internally consistent.

The reservoirs represent infrastructure developed over a long historical period, with reported commissioning dates ranging from 1929 to 2011. Forty-one reservoirs, equivalent to approximately 47.7% of the inventory, had been in operation for more than 50 years.

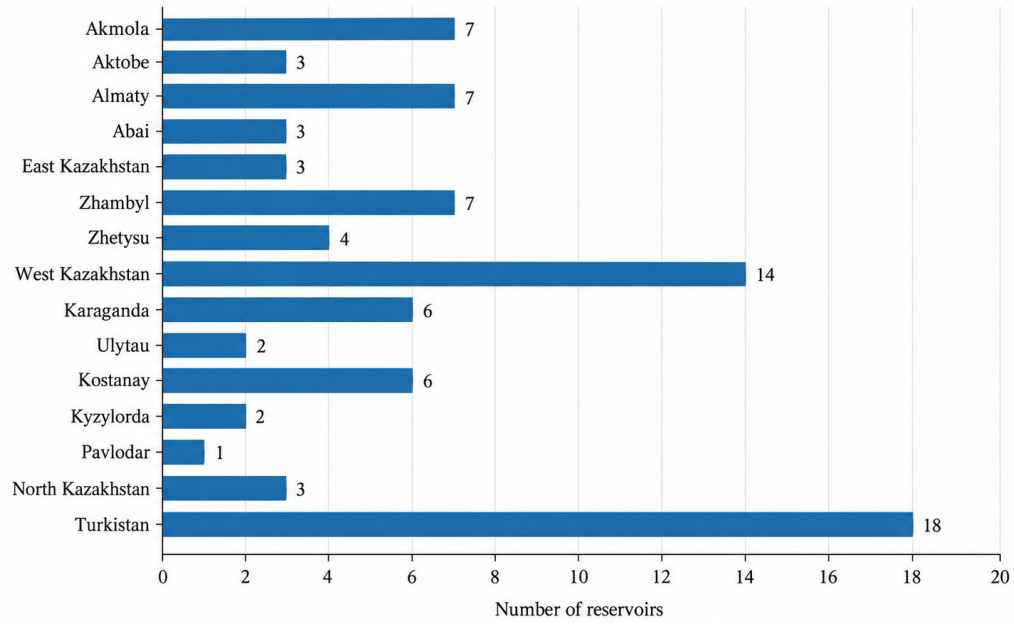


Figure 2. Reservoirs on the balance sheet of RSE "Kazvodkhoz" by region as of 1 September 2024 (number of facilities). Note: RSE "Kazvodkhoz" administrative inventory [32].

The regional distribution of reservoirs is highly uneven. As shown in Figure 2, the number of facilities ranges from one reservoir in Pavlodar Region to 18 in Turkistan Region, while Turkistan and West Kazakhstan Regions together account for 32 of the 86 reservoirs.

The technical-condition data therefore complement the spatial pattern shown in Figure 2. Although the majority of reservoirs are reported as being in satisfactory condition, the presence of unsatisfactory, emergency, unfinished, and reconstructed facilities indicates that infrastructure condition varies substantially across the system. These differences are important because restricted operation or the failure of individual reservoirs may affect water-storage regulation, the irrigation supply, flood management, and the reliability of downstream water delivery.

The regional administrative dataset also contains information on storage capacity, the command area, design and actual discharge, commissioning dates, and multifactorial inspections. However, several entries show inconsistencies in units, decimal separators, or chronological ranges. For this reason, only verified indicators were retained for a comparative interpretation, while uncertain values were excluded from the main analysis pending verification against the original RSE "Kazvodkhoz" inventory.

The regional distribution of reservoirs is highly uneven, ranging from one facility in Pavlodar Region to 18 in Turkistan Region, while Turkistan and West Kazakhstan Regions together account for 32 of the 86 reservoirs. When combined with the reported condition categories, this pattern indicates that rehabilitation needs are spatially differentiated and should be assessed with reference to the technical condition, age, storage function, operational importance, and hydrological exposure rather than facility numbers alone.

The reservoir analysis demonstrates that facility counts should be interpreted together with the technical condition and operational significance. The same analytical approach is applied to dams, whose regional distribution is presented in Figure 3.

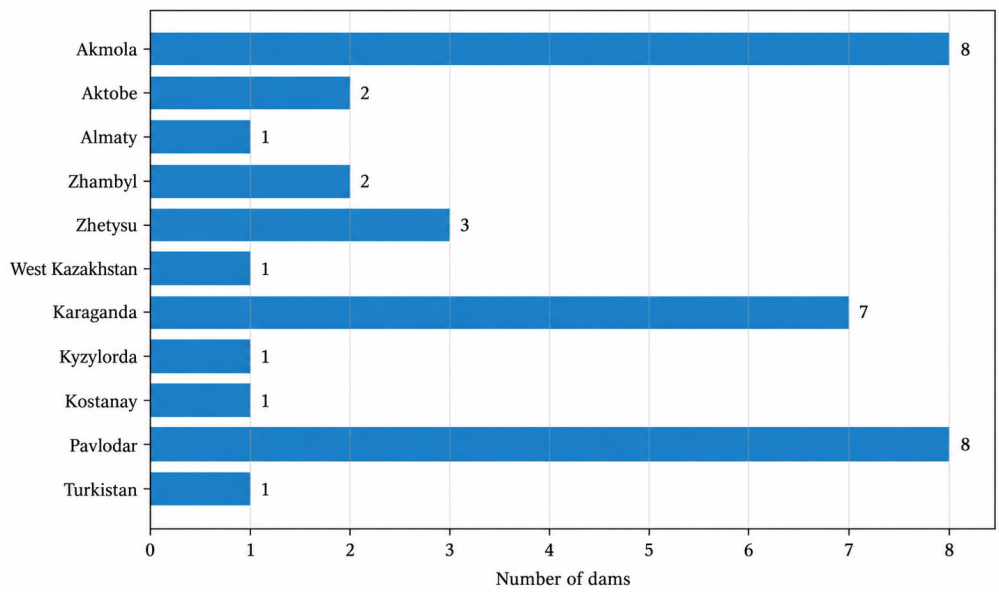


Figure 3. Dams on the balance sheet of RSE "Kazvodkhoz" by region as of 1 September 2024 (number of facilities). Note: RSE "Kazvodkhoz" administrative inventory [33].

Figure 3 illustrates the regional distribution of dams recorded on the balance sheet of RSE "Kazvodkhoz" as of 1 September 2024. According to the administrative inventory, 35 dams were distributed across 11 regions of Kazakhstan. The largest numbers were recorded in Akmola and Pavlodar Regions, with eight facilities each, followed by Karaganda Region with seven. Together, these three regions accounted for 23 dams, or approximately 65.7% of the total inventory. Zhetysu Region had three dams; Aktobe and Zhambyl Regions had two each; and Almaty, West Kazakhstan, Kyzylorda, Kostanay, and Turkistan Regions each had one facility. This distribution demonstrates a substantial spatial concentration of dam infrastructure managed by RSE "Kazvodkhoz" [33].

The technical-condition data further reveal considerable differences among the recorded facilities. Based on the regional inventory, 25 dams (71.4%) were classified as satisfactory, 9 (25.7%) as unsatisfactory, and 1 (2.9%) as being in emergency condition. The largest numbers of unsatisfactory facilities were recorded in Akmola Region (four dams), Aktobe Region (two), and Zhetysu Region (two), while one dam in Kostanay Region was also classified as unsatisfactory. In Pavlodar Region, seven of the eight dams were reported to be in satisfactory condition, whereas one facility was classified as emergency. The reconstruction status reported for some facilities was treated as an operational or rehabilitation status rather than as a separate technical-condition category.

The reported commissioning dates range from 1926 to 2016, illustrating the long development history of the dam infrastructure. However, age alone does not determine the present technical condition. The presence of unsatisfactory and emergency facilities supports a risk-informed rehabilitation approach based on the engineering condition, operational importance, hydraulic function, and potential consequences of failure. Within the SWOT framework, technically deficient dams are therefore treated as an internal weakness rather than an external threat.

The observed regional differences support a risk-informed approach to infrastructure rehabilitation. Particular attention should be given to facilities classified as unsatisfactory or emergency, while subsequent investment decisions should consider the engineering condition, operational importance, hydraulic function, downstream exposure, and the potential consequences of structural failure. Such an approach provides a more transparent basis for identifying rehabilitation needs and strengthening the reliability and resilience of the agricultural water-management infrastructure.

The dam inventory was therefore analyzed as a descriptive assessment of the regional distribution and technical condition, rather than as an independent SWOT analysis. The identified deterioration and maintenance issues were subsequently incorporated into the overall SWOT framework as internal weaknesses of the water-management system. The same analytical principle was applied to the next category of infrastructure.

Because the administrative inventory does not establish an electricity-generation function for all facilities previously labeled as "hydroelectric power plants", the subsequent analysis refers to these objects as hydraulic complexes (hydraulic structures). This terminology more accurately reflects the available administrative evidence and avoids equating multifunctional hydraulic infrastructure with electricity-generating hydropower facilities.

Hydraulic Complexes (Hydraulic Structures): Regional Distribution and Technical Condition. The original administrative classification was reviewed because the available records do not establish an electricity-generation function for all facilities previously described as "hydroelectric power plants". Accordingly, the revised manuscript uses the term hydraulic complexes (hydraulic structures) unless a facility is explicitly identified as an electricity-generating hydropower plant. Figure 4 presents the regional distribution of these facilities in the RSE "Kazvodkhoz" inventory as of 1 September 2024 [33].

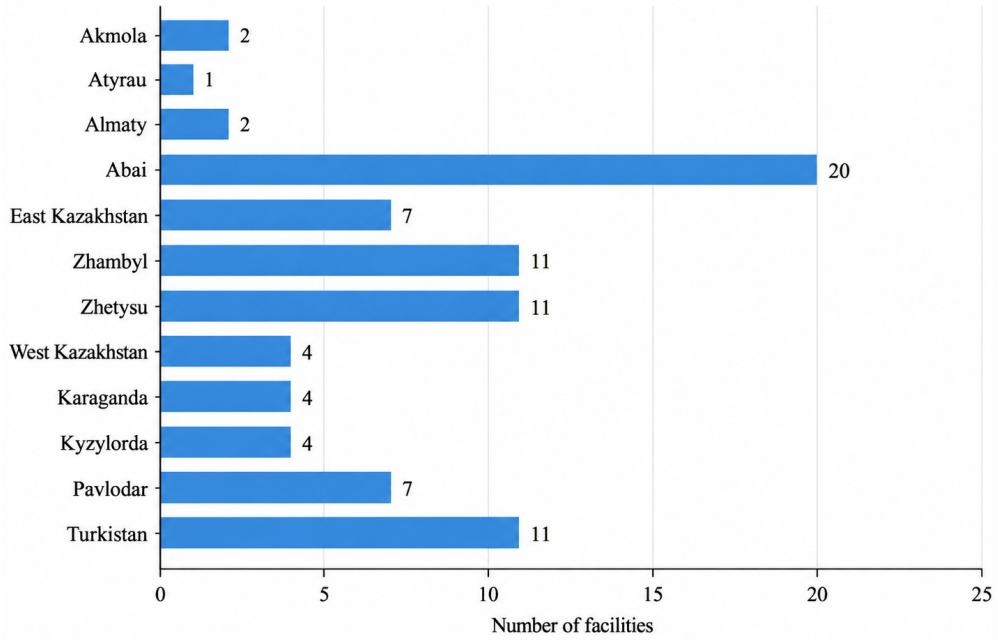


Figure 4. Hydraulic complexes on the balance sheet of RSE "Kazvodkhoz" by region as of 1 September 2024 (number of facilities). Note: RSE "Kazvodkhoz" administrative inventory [33].

Figure 4 shows a pronounced regional concentration of hydraulic complexes within the RSE "Kazvodkhoz" inventory. A total of 84 hydraulic complexes were recorded across 12 regions in the RSE "Kazvodkhoz" administrative inventory. Their regional distribution is highly uneven, with the largest concentration observed in Abai Region (20 facilities), followed by Zhambyl, Zhetysu, and Turkistan Regions (11 facilities each). Together, these four regions account for 53 facilities, or approximately 63.1% of the total inventory.

East Kazakhstan and Pavlodar Regions each contain seven facilities; West Kazakhstan, Karaganda, and Kyzylorda Regions each contain four; Akmola and Almaty Regions each contain two; and Atyrau Region has one. The distribution therefore confirms substantial spatial heterogeneity in the hydraulic infrastructure operated by RSE "Kazvodkhoz". Technically deficient or operationally constrained facilities are treated in the SWOT framework as internal weaknesses, while reconstruction, modernization, improved monitoring, and preventive maintenance represent corresponding strategic responses.

The administrative inventory also reports several categories of the facility condition and operational status, including satisfactory, unsatisfactory, emergency, reconstruction, and repair. These categories are treated as descriptive engineering and operational characteristics rather than as standardized quantitative risk scores. Accordingly, they are used to identify infrastructure weaknesses and rehabilitation needs, but not to estimate failure probabilities or to rank facilities quantitatively by engineering risk.

From a SWOT perspective, technically deficient or operationally constrained hydraulic complexes are classified as an internal weakness of the existing water-management system. At the same time, reconstruction, modernization, improved monitoring, and preventive maintenance represent potential strategic responses to these weaknesses. This distinction maintains consistency between the descriptive infrastructure assessment and the subsequent SWOT interpretation.

The spatial heterogeneity observed for hydraulic complexes is also evident in the canal network, although the scale and functional structure of the canal infrastructure differ substantially across regions. Figure 5 therefore compares the regional distribution of main, inter-farm, and on-farm canals.

Canal Network: Scale, Distribution, and Technical Condition

Technical-condition information was available for a subset of 466 main canals, of which 353 were classified as satisfactory and 113 as unsatisfactory.

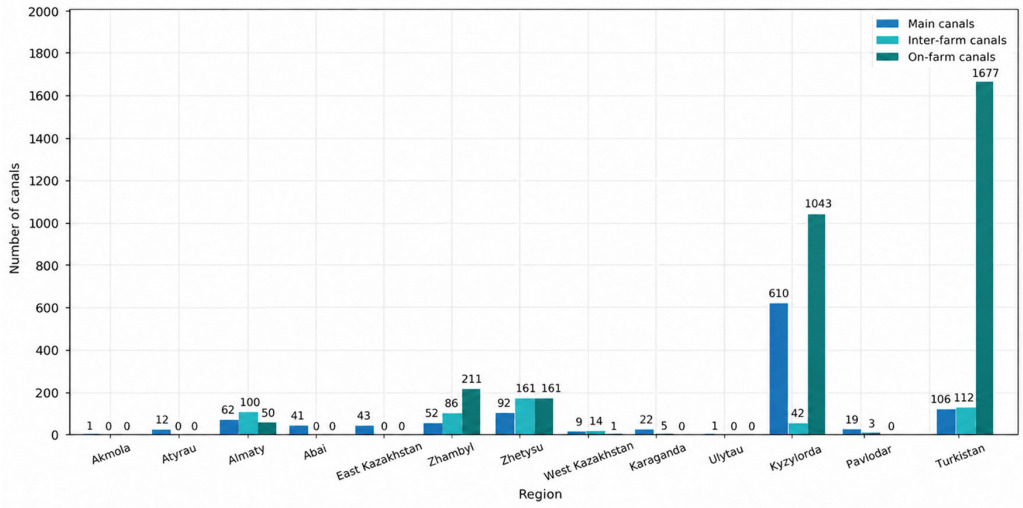


Figure 5. Main, inter-farm, and on-farm canals on the balance sheet of RSE "Kazvodkhoz" by region as of 1 September 2024 (number of facilities). Note: RSE "Kazvodkhoz" administrative inventory [33].

Figure 5 demonstrates pronounced regional heterogeneity in the distribution of canal infrastructure. The regional inventory represented in the figure contains 1070 main canals, 523 inter-farm canals, and 3143 on-farm canals. Main canals are concentrated particularly strongly in Kyzylorda Region, which accounts for 610 facilities, or approximately 57.0% of the total shown for this category. Inter-farm canals display a more dispersed pattern, with the largest numbers recorded in Zhetysu (161), Turkistan (112), Almaty (100), and Zhambyl (86) Regions.

The strongest spatial concentration is observed for on-farm canals. Turkistan Region contains 1677 facilities and Kyzylorda Region 1043; together, these two regions account for approximately 86.5% of all on-farm canals represented in Figure 5. This distribution confirms the particularly high concentration of irrigation infrastructure in southern Kazakhstan and reflects the major role of irrigated agriculture in these regions.

The concentration of canal infrastructure has important operational implications. Regions with extensive canal networks may require proportionally greater maintenance,

metering, automation, and rehabilitation capacity, particularly where earthen or technically deteriorated sections predominate. The benefits of modernization should therefore be assessed using facility-level diagnostics and measured water balances.

The spatial concentration identified in Figure 5 also has operational implications. Modernization, digital metering, automated control, and preventive maintenance in regions with extensive canal networks may affect comparatively large irrigated areas. At the same time, the benefits of such interventions cannot be inferred from facility counts alone and should be assessed using facility-level technical diagnostics and measured water balances.

Facility counts describe the numerical distribution of canal infrastructure but do not reflect the physical scale of the network. To complement Figure 5, Table 3 therefore reports canal length and command (serviced) area by region.

A data-quality issue was identified in the original regional inventory for the commissioning period of Almaty inter-farm canals, where the range was reported as "1929–1912". Because this sequence is chronologically impossible, it was excluded from the revised comparative analysis pending verification against the primary RSE "Kazvodkhoz" administrative record [33]. This prevents an evident transcription or source-formatting error from being reproduced as a valid empirical observation.

Table 3. Canal length and command (serviced) area according to RSE "Kazvodkhoz" data as of 1 September 2024.

Region	Canal Length, km	Command (Serviced) Area, ha
Akmola	12.400	70.0
Atyrau	839.200	15,581.0
Almaty	1563.389	132,320.0
Abai	551.279	70,212.0
East Kazakhstan	531.240	49,609.0
Zhambyl	2177.631	143,470.0
Zhetysu	3908.330	180,437.6
West Kazakhstan	1057.660	47.118
Karaganda	185.260	9792.0
Ulytau	15.812	3028.0
Kyzylorda	6709.840	262,063.1
Pavlodar	306.950	22,446.0
Turkistan	5781.200	331,333.5
Total	23,640.191	1,220,409.318 *

Note: * The total command (serviced) area is calculated as the sum of the regional values reported by RSE "Kazvodkhoz". The aggregate is provisional and subject to verification because the reported value for West Kazakhstan Region (47.118 ha) may reflect an inconsistency in decimal or thousands separators. The original reported value has been retained without adjustment.

Table 3 demonstrates substantial regional variation in both the canal length and command area. Based on the reported values, the total canal length across the included regions amounts to 23,640.191 km. The provisional sum of the reported command (serviced) areas is approximately 1.22 million ha; however, this aggregate remains subject to verification because the West Kazakhstan value (47.118 ha) may reflect a decimal/thousands-separator inconsistency. Therefore, the aggregate command-area value should be interpreted with caution until the original administrative record is confirmed.

The largest reported canal lengths are observed in Kyzylorda Region (6709.84 km), Turkistan Region (5781.2 km), and Zhetysu Region (3908.33 km). Together, these three regions account for more than two-thirds of the reported canal length, confirming the strong spatial concentration of irrigation infrastructure in southern and south-eastern Kazakhstan. Large command areas are also reported for Turkistan, Kyzylorda, Zhetysu, and Zhambyl Regions, indicating the major role of these regions in irrigated agricultural production.

The earlier wording stating that "19.4 km are in earthen channels and 4.1 km are lined" was inconsistent with the reported total canal length of approximately 23,640 km. These figures most likely refer to values expressed at the thousand-kilometer scale, but because the original source units require verification, the revised manuscript does not reproduce these values as precise kilometer estimates. This avoids presenting an unverified unit conversion as an established result.

A further data-quality issue concerns the West Kazakhstan Region command area reported as 47.118 ha. Given the formatting of other regional values, this entry may represent a decimal/thousands-separator inconsistency and should be verified against the primary administrative inventory before final publication. For this reason, the total command-area figure should also be presented as approximate unless the original source record is confirmed.

Because canal length alone does not indicate the agricultural area served by the network, Figure 6 complements Table 3 by visualizing the regional distribution of the command (serviced) area associated with the reported canal infrastructure.

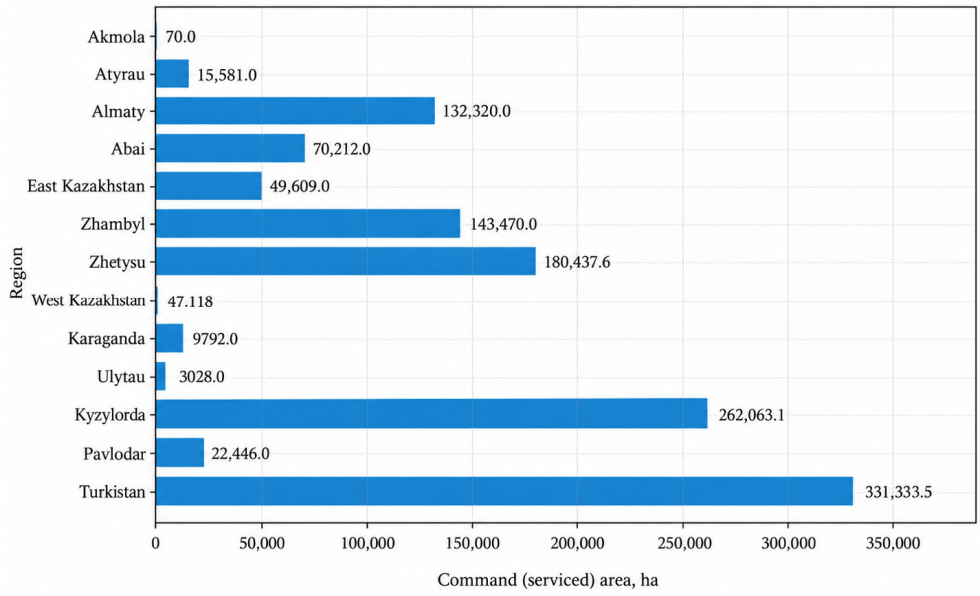


Figure 6. Command (serviced) area associated with the reported canal inventory by region as of 1 September 2024 (ha).

Figure 6 shows substantial regional variation in the command (serviced) area associated with the reported canal inventory. The largest serviced area is recorded in Turkistan Region (331,333.5 ha), followed by Kyzylorda Region (262,063.1 ha) and Zhetysu Region (180,437.6 ha). Considerable serviced areas are also reported for Zhambyl Region (143,470.0 ha) and Almaty Region (132,320.0 ha). Together, these five regions account for the dominant share of the command area represented in the inventory.

The spatial pattern confirms the concentration of irrigation infrastructure in the southern and south-eastern parts of Kazakhstan, where irrigated agriculture has a particularly important role. By contrast, the reported command areas in northern and central regions are substantially smaller. For example, Akmola, Ulytau, Karaganda, and Pavlodar Regions account for comparatively limited serviced areas within the reported inventory.

The concentration of serviced areas in Turkistan, Kyzylorda, Zhetysu, Zhambyl, and Almaty Regions indicates that the modernization of canal rehabilitation, metering, automation, and loss reduction in these regions may affect comparatively large irrigated areas. At the same time, this concentration increases the potential consequences of infrastructure failure and supports differentiated, risk-based investment planning.

The pronounced concentration of serviced areas in Turkistan, Kyzylorda, Zhetysu, Zhambyl, and Almaty Regions has practical implications for infrastructure modernization. Improvements in canal rehabilitation, water metering, automation, and loss reduction in these regions may affect large, irrigated areas and therefore generate substantial system-level benefits. At the same time, the scale of serviced areas also increases the potential consequences of infrastructure failure or inefficient water distribution, reinforcing the need for differentiated, risk-based investment planning.

Data-quality caution is required for West Kazakhstan Region, where the reported value of 47.118 ha appears inconsistent with the scale and formatting of the other regional entries. This figure should be verified against the original RSE "Kazvodkhoz" administrative inventory before being used in comparative calculations or aggregate totals.

Taken together, Figures 5 and 6 characterize the scale and spatial concentration of the canal infrastructure. The final infrastructure comparison considers collectors and pumping stations, which perform different drainage and water-lifting functions within regional irrigation systems. Their distribution is presented in Figure 7.

Figure 7 compares collectors and pumping stations on the balance sheet of RSE "Kazvodkhoz" as of 1 September 2024.

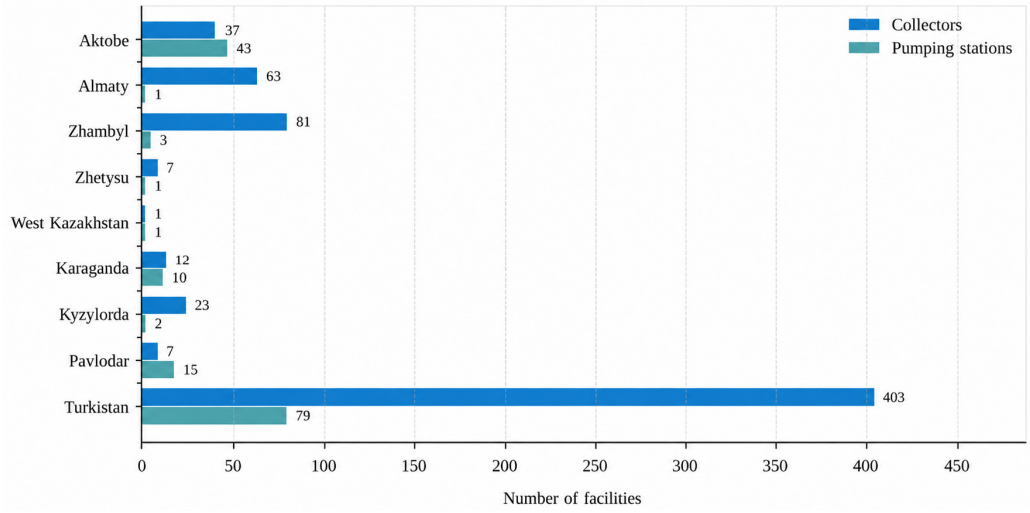


Figure 7. Collectors and pumping stations on the balance sheet of RSE "Kazvodkhoz" by region as of 1 September 2024 (number of facilities). Note: RSE "Kazvodkhoz" administrative inventory [33].

Figure 7 demonstrates a highly uneven regional distribution of collectors and pumping stations within the RSE "Kazvodkhoz" administrative inventory. A total of 634 collectors and 155 pumping stations are represented across the nine regions included in the dataset. Turkistan Region has by far the largest infrastructure stock, with 403 collectors and 79 pumping stations, corresponding to approximately 63.6% of all collectors and 51.0% of all pumping stations shown in Figure 7. This concentration distinguishes Turkistan as the most infrastructure-intensive region within this subset of the national water-management system.

Outside Turkistan Region, the largest numbers of collectors are recorded in Zhambyl Region (81 facilities) and Almaty Region (63), followed by Aktobe Region (37) and Kyzylorda Region (23). Smaller collector inventories are reported in Karaganda (12), Zhetysu (7), Pavlodar (7), and West Kazakhstan (1) Regions. The spatial pattern of pumping stations differs. After Turkistan Region, the largest number is recorded in Aktobe Region (43 stations), followed by Pavlodar Region (15) and Karaganda Region (10); the remaining regions have between one and three pumping stations.

The contrasting regional distributions of collectors and pumping stations reflect differences in the functional configuration of the water-management infrastructure. Collectors

are associated primarily with drainage and the regulation or removal of excess irrigation water, whereas pumping stations support water abstraction, lifting, conveyance, and redistribution where gravity-based delivery is insufficient.

Within the SWOT framework, the deterioration, insufficient maintenance, and inefficient operation of collectors and pumping stations are treated as internal weaknesses, whereas the modernization of pumping equipment, automation, digital monitoring, improved energy efficiency, and drainage rehabilitation represent development opportunities or strategic responses.

The regional concentration of collectors is also consistent with the reported distribution of the vertical drainage infrastructure. According to the operator-level administrative data, RSE "Kazvodkhoz" recorded 1416 vertical drainage wells, including 1208 in Turkistan Region, 162 in Kyzylorda Region, and 46 in Zhambyl Region [33]. These figures further indicate that drainage requirements are spatially concentrated, particularly in the southern irrigated regions. However, because these data relate only to facilities recorded by RSE "Kazvodkhoz", they should not be interpreted as national totals covering all ownership categories.

These regional interpretations are qualitative and should not be regarded as a quantitative ranking of regions. They are used to inform the subsequent SWOT/TOWS analysis by linking observed infrastructure patterns to internal weaknesses, external opportunities, and strategic development options.

Taken together, Figures 2–7 demonstrate substantial spatial heterogeneity in the scale, composition, and reported condition of agricultural water-management infrastructure. Facility counts should not be interpreted as direct measures of hydraulic performance, reliability, or water-use efficiency. Regional comparisons therefore require consideration of the technical condition, canal length, command area, lining status, operational function, and measured hydraulic performance where such data are available. This evidence supports differentiated rather than uniform rehabilitation and modernization strategies across Kazakhstan's regions.

Artificial intelligence, satellite monitoring, automated metering, and advanced analytics are therefore treated in the revised SWOT framework as opportunities, rather than as existing strengths, unless their large-scale operational deployment is documented. Their potential contribution lies in improving water accounting, anomaly detection, drought and flood monitoring, infrastructure inspection, and operational decision-making when integrated with verified field data and institutional management systems.

The manuscript also distinguishes between policy targets adopted at different stages of sector development. Earlier policy documents referred to the construction of 20 new reservoirs and reconstruction of 15 existing facilities, whereas subsequent official updates expanded these objectives to 42 new reservoirs and 37 reconstructed reservoirs by 2030. These figures are therefore presented as dated policy targets rather than as simultaneous or contradictory study results. The same principle is applied to targets concerning water-loss reduction, irrigated-area expansion, water reuse, and digitalization: such numerical values are identified explicitly as government program objectives rather than empirical findings of the present study.

Overall, the regional infrastructure analysis supports an integrated approach combining facility diagnostics, measured water balances, real-time metering, maintenance planning, digital data integration, basin-level governance, and transboundary cooperation. The principal implication is that technological modernization alone is unlikely to produce sustained improvements unless it is accompanied by institutional capacity, reliable data, appropriate maintenance systems, and effective adoption by water-management organizations and agricultural users.

5. Conclusions

This study provides a national and regional diagnostic of agricultural water-management systems in Kazakhstan by combining a cross-sectional infrastructure inventory (primarily as of 1 September 2024) with documentary evidence from 2010–2024 and a transparent SWOT/TOWS synthesis. The main empirical finding is strong spatial heterogeneity in infrastructure scale and condition, together with a recurring set of internal constraints: aging assets, conveyance losses, incomplete metering and automation, maintenance and financing limitations, and capacity gaps.

The external environment creates both enabling conditions and significant risks. Public rehabilitation programs, water-saving irrigation, digital forecasting and accounting, improved basin governance, and international cooperation provide opportunities for modernization. At the same time, climate variability, transboundary-flow dependence, water-quality pressure, inflationary construction costs, and competition among water users increase system vulnerability.

The methodological contribution is the explicit separation of internal and external factors and the traceable linkage of the final SWOT factors to SO, WO, ST, and WT strategic directions. Because the study does not apply factor weights, expert scoring, cost–benefit ranking, or multi-criteria optimization, the five development areas identified—infrastructure rehabilitation, water-use efficiency, digital water management, institutional/financial/human-capacity development, and climate/transboundary resilience—should be understood as qualitative strategic directions rather than ranked priorities.

The analysis also clarifies the data boundary: national infrastructure totals and the detailed RSE 'Kazvodkhoz' balance-sheet inventory represent different populations. Operator-level statistics should therefore not be generalized to the entire national infrastructure stock without additional ownership-level data. Similarly, categorical facility condition, physical/engineering wear, and accounting depreciation are distinct concepts and should not be used interchangeably.

Policy targets cited in the manuscript—such as reservoir construction/reconstruction, reductions in conveyance losses, digitalization, or reuse—are government program objectives and not measured outcomes of this study. The revised text dates these targets where policy versions changed and avoids unsupported statements that Kazakhstan currently has 'sufficient' water for all sectors; the evidence instead indicates national resource potential combined with substantial regional scarcity, seasonality, transboundary dependence, and future climate risk.

The study has several limitations. The infrastructure inventory is not a complete annual panel for 2010–2024, some variables are missing or reported with inconsistent terminology across regional sources, no independent engineering inspection was conducted, and the SWOT/TOWS stage is qualitative. Future research should develop a harmonized open asset-level dataset, verify questionable commissioning dates and units against primary records, combine measured water balances with remote sensing and sensor data, and apply multi-criteria decision analysis or cost–benefit methods to rank rehabilitation projects under alternative climate and transboundary-water scenarios.

Within these limitations, the evidence supports a clear strategic implication: Kazakhstan's agricultural water security will depend less on infrastructure expansion alone and more on the coordinated modernization, measurement, maintenance, and governance of existing systems, reinforced by water-saving technology and basin-level resilience planning.

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