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OPTIMISING THE USE OF IRRIGATED LANDS IN KAZAKHSTAN: SYSTEM ANALYSIS AND RESOURCE MANAGEMENT

This article explores the challenges and opportunities in optimizing the use of irrigated lands in Kazakhstan, focusing on system analysis and resource management. The research purpose is to identify strategic improvements in irrigation practices and regional water governance, while aiming to enhance water resource management efficiency and sustainability in agriculture. The main directions of the study involve analyzing Kazakhstan's reliance on external water sources, infrastructural inefficiencies, and region-specific strategies for sustainable agricultural practices. Methodologically, the research relies on regional case studies, national statistical data, and quantitative analyses, including correlations and descriptive statistics. It also applies frameworks like Integrated Water Resources Management, Socio-Ecological Systems, Water-Energy-Food Nexus, and Participatory Water Management.

The research results highlight Kazakhstan's vulnerability due to its significant dependence on external water sources, accounting for 46% of its water supply, and inefficiencies in its aging irrigation infrastructure. The practical value of this research is in offering comprehensive, actionable recommendations to policymakers, agricultural stakeholders, and local communities for improving infrastructure, adopting efficient irrigation techniques, and fostering international collaboration. The research novelty lies in its interdisciplinary application of multiple strategic frameworks to develop tailored strategies addressing the unique challenges across Kazakhstan's economic districts, balancing agricultural productivity with sustainable water management practices.

Key words: water resource management in Kazakhstan, agricultural water efficiency and sustainability, impact of external water sources, innovation in irrigation practices, economic problems in agriculture.

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Қазақстандағы суармалы жерлерді пайдалануды оңтайландыру: жүйелік талдау және ресурстарды басқару

Бұл мақала жүйені талдау мен ресурстарды басқаруға баса назар аудара отырып, Қазақстандағы суармалы жерлерді пайдалануды оңтайландырудағы қиындықтар мен мүмкіндіктерді зерттейді. Зерттеу мақсаты ауыл шаруашылығындағы су ресурстарын басқару тиімділігі мен тұрақтылығын арттыруға бағытталған суару тәжірибесі мен аймақтық суды басқарудағы стратегиялық жақсартуларды анықтау болып табылады. Зерттеудің негізгі бағыттары Қазақстанның сыртқы су көздеріне тәуелділігін, инфрақұрылымдық тиімсіздігін және тұрақты ауылшаруашылық тәжірибесі үшін аймаққа тән стратегияларды талдауды қамтиды. Әдістемелік тұрғыдан зерттеу аймақтық жағдайлық зерттеулерге, ұлттық статистикалық деректерге және сандық талдауларға, соның ішінде корреляциялық және сипаттамалық статистикаға сүйенеді. Ол сондай-ақ су ресурстарын біріктірілген басқару, әлеуметтік-экологиялық жүйелер, су-энергия-азық-түлік байланысы және бірлескен суды басқару сияқты құрылымдарды қолданады.

Зерттеу нәтижелері Қазақстанның сумен қамтамасыз етудің 46% құрайтын сыртқы су көздеріне айтарлықтай тәуелділігіне және ескірген суару инфрақұрылымының тиімсіздігіне байланысты осалдығын көрсетеді. Бұл зерттеудің практикалық құндылығы саясаткерлерге, ауылшаруашылық мүдделі тараптарына және жергілікті қауымдастықтарға инфрақұрылымды жақсарту, суарудың тиімді әдістерін қабылдау және халықаралық ынтымақтастықты ынталандыру бойынша жан-жақты, әрекет етуге болатын ұсыныстарды ұсынуда. Зерттеудің жаңалығы оның Қазақстанның экономикалық аудандарындағы бірегей міндеттерді шешуге арналған бейімделген стратегияларды әзірлеу, ауыл шаруашылығы өнімділігін тұрақты су ресурстарын басқару тәжірибесімен теңестіру үшін көптеген стратегиялық негіздерді пәнаралық қолдануында жатыр.

Түйін сөздер: Қазақстандағы су ресурстарын басқару, ауылшаруашылық су тиімділігі мен тұрақтылығы, сыртқы су көздерінің әсері, суару тәжірибесіндегі инновациялар, ауыл шаруашылығындағы экономикалық мәселелер.

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Оптимизация использования орошаемых земель Казахстана: системный анализ и управление ресурсами

В данной статье исследуются проблемы и возможности оптимизации использования орошаемых земель в Казахстане, уделяя особое внимание системному анализу и управлению ресурсами. Целью исследования является определение стратегических улучшений в практике орошения и регионального управления водными ресурсами с целью повышения эффективности и устойчивости управления водными ресурсами в сельском хозяйстве. Основные направления исследования включают анализ зависимости Казахстана от внешних источников воды, неэффективности инфраструктуры и региональных стратегий устойчивого ведения сельского хозяйства. Методологически исследование опирается на региональные тематические исследования, национальные статистические данные и количественный анализ, включая корреляции и описательную статистику. Он также применяет такие концепции, как интегрированное управление водными ресурсами, социально-экологические системы, взаимосвязь воды, энергии и продовольствия и совместное управление водными ресурсами.

Результаты исследования подчеркивают уязвимость Казахстана из-за его значительной зависимости от внешних источников воды, на долю которых приходится 46% его водоснабжения, а также неэффективности стареющей ирригационной инфраструктуры. Практическая ценность этого исследования заключается в предложении всеобъемлющих и практических рекомендаций политикам, заинтересованным сторонам в сельском хозяйстве и местным сообществам по улучшению инфраструктуры, внедрению эффективных методов орошения и развитию международного сотрудничества. Новизна исследования заключается в междисциплинарном применении множества стратегических рамок для разработки индивидуальных стратегий, направленных на решение уникальных проблем в экономических районах Казахстана, балансируя производительность сельского хозяйства с практиками устойчивого управления водными ресурсами.

Ключевые слова: управление водными ресурсами в Казахстане, эффективность и устойчивость использования воды в сельском хозяйстве, влияние внешних источников воды, инновации в ирригационной практике, экономические проблемы в сельском хозяйстве.

Introduction

The topic "Optimizing the use of irrigated lands in Kazakhstan: system analysis and resource management" is chosen for understanding how the country can improve its agricultural productivity and sustainability through effective water resource management. The nation is characterized by significant reliance on transboundary rivers, with 46% of its water supply coming from neighboring countries. Consequently, this external dependency poses challenges to water security and highlights the need for international cooperation, infrastructure upgrades, and efficient irrigation practices.

The justification for this topic stems from Kazakhstan's complex water resource situation, with around 60% of the country's water being consumed by agriculture. Previous studies have identified the importance of international collaboration in managing shared resources. However, there is a dearth of region-specific data on how water-efficient practices could be implemented in different economic districts. This gap is critical, as it affects agricultural productivity and sustainable development.

The relevance of this study is underpinned by the growing importance of water resource management in an era of climate change and increasing competition for shared resources. Practically, the findings are expected to aid policymakers, agricultural stakeholders, and local communities in developing comprehensive water strategies that are tailored to the distinct needs of each region.

The object of this study is the irrigation network and management practices across Kazakhstan's economic districts. The goal is to identify challenges and opportunities to optimize water usage in agriculture. This entails analyzing regional water usage patterns, infrastructural needs, and the effects of transboundary river agreements on irrigation.

The research objectives include:

- evaluating water usage trends in different economic districts;
- assessing the efficiency of current irrigation infrastructure;
- identifying challenges posed by transboundary water agreements;
- developing tailored frameworks for sustainable irrigation management.

The methodology used regional case studies and quantitative analyses, such as descriptive statistics and correlations, to understand the distribution of irrigated lands and identify infrastructural inefficiencies across the economic regions of Kazakhstan. Strategic frameworks like Integrated Water Resources Management, the Socio-Ecological Systems approach, the Water-Energy-Food Nexus, and Participatory Water Management were applied to address these challenges and optimize water resource management across the country's diverse regions. The research aim is to provide a detailed assessment of Kazakhstan's irrigation landscape and propose strategic based on the mentioned strategic frameworks.

The hypothesis is that significant dependence on external sources and infrastructural inefficiencies are primary contributors to water scarcity. By adopting modern irrigation techniques, upgrading infrastructure, and fostering international collaboration, Kazakhstan can improve its water resource sustainability.

The significance of this work lies in offering a comprehensive approach to managing irrigated lands and understanding the specific needs of each region. It aims to provide actionable recommendations that balance agricultural productivity with water sustainability. The research novelty lies in its interdisciplinary application of Integrated Water Resources Management, Socio-Ecological Systems, the Water-Energy-Food Nexus, and Participatory Water Management frameworks to develop tailored strategies that address regional water challenges and optimize the management of irrigated lands in Kazakhstan.

Literature review

Globalization and climate change are significantly transforming agricultural landscapes across the world. The study by Brown and Funk (2008) has highlighted this transformation, revealing a direct correlation between increased global warming and the reduction in agricultural productivity, especially in regions relying heavily on rain-fed agriculture. These findings underscore the urgency of adapting agricultural practices to rapidly changing climatic conditions. Lobell et al. (2008) further elucidate this issue, demonstrating the adverse impacts of rising temperatures and shifting precipitation patterns on crop yields. This situation becomes more critical when viewed in the context of the global population, which as of February 2024 stands at 8 billion and is projected to rise to 9.8 billion by 2050. Such growth intensifies the demand for food, exacerbating the challenges posed by declining agricultural productivity. The Food and Agriculture Organization of the United Nations (2024) reports that over 783 million people are currently suffering from hunger, thereby emphasizing the dire need for sustainable and efficient food production systems. In response to these challenges, the focus has shifted towards innovative water resource management frameworks. Water resource management involves diverse theoretical frameworks that shape different policy recommendations and assumptions. For instance, the Integrated Water Resources Management (IWRM) is a comprehensive approach that emphasizes coordinated management of water, land, and related resources to maximize economic and social welfare without compromising environmental sustainability. The model recognizes that water resource management requires a holistic and adaptive approach, considering environmental, economic, and social interactions (Grigg, 2016).

The IWRM is grounded in four key principles: economic efficiency, environmental sustainability, social equity, and policy coordination (Vieira, Sandoval-Solis, Pedrosa, & Ortiz-Partida, 2020). Economic efficiency involves maximizing the benefits of water use while recognizing it as a scarce economic good. Environmental sustainability emphasizes the balance between water use and renewal to maintain the integrity of ecosystems. Social equity ensures that all stakeholders have fair access to water resources and a voice in decision-making. Policy coordination aligns water management strategies across different sectors for a unified approach.

Kazakhstan, a water-scarce nation with unique geographical challenges, stands to benefit significantly from the IWRM. In the agricultural sector, which consumes about 60% of the nation's water supply, implementing the IWRM can optimize water use by incorporating efficient irrigation techniques and reducing wastage (Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, 2024; Grigg, 2016). Drip irrigation, precision farming, and groundwater monitoring could improve water efficiency, particularly in the key regions of Turkestan and Almaty, where agricultural output heavily relies on irrigated lands (Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, 2024; Evett et al., 2020).

The country's reliance on transboundary rivers such as the Syr Darya, Talas, and Ili presents environmental challenges, as upstream activities impact downstream ecosystems (Radelyuk, Zhang, & Tussupova, 2022). The IWRM's focus on environmental sustainability calls for international cooperation to manage these resources responsibly. Enhanced collaboration with neighbouring countries like China, Kyrgyzstan, and Uzbekistan is crucial for safeguarding vital basins such as the Balkhash-Alakol while maintaining the ecological balance.

Social equity is a critical concern in Kazakhstan due to the uneven distribution of water resources. Many rural communities, especially in arid regions like Mangystau and Aktobe, lack sufficient access to water. The IWRM principles aim to address this issue by empowering the local Water User Associations (WUAs), providing them with the necessary capacity and resources to advocate for their water needs and participate in decision-making. This approach ensures that marginalized communities receive equitable access to water.

On the other hand, the Socio-Ecological Systems (SES) approach recognizes that human societies and ecological environments are deeply intertwined and should be analyzed as complex, adaptive systems. This theoretical framework helps to understand how interactions between ecological and social components shape each other over time, influencing outcomes like resource sustainability, ecosystem health, and community resilience (Berkes, Colding, & Folke, 2008).

In the SES, the emphasis is placed on studying the dynamic feedback loops between natural and human systems (Biggs et al., 2022). Human activities affect ecological conditions and, conversely, environmental changes reshape human behaviors and decisions. This reciprocal relationship demands holistic management strategies that incorporate environmental, economic, and social factors.

In Kazakhstan, the Socio-Ecological Systems (SES) framework provides essential insights into water resource management challenges, considering the influence of both natural climatic conditions and human activities such as agriculture, industry, and urban development. The SES model offers a holistic analysis of these interconnected factors.

In contrast to Integrated Water Resources Management (IWRM) and SES, two other prominent frameworks are the Water-Energy-Food Nexus and Participatory Water Management, each providing distinct insights into water management priorities.

The Water-Energy-Food (WEF) Nexus framework acknowledges the tight interconnection between water, energy, and food, advocating for their holistic management (Muthu, 2021). Each resource affects the others, creating dependencies where decisions in one sector impact the others. For example, expanding water-intensive crops increases irrigation needs and energy consumption for pumping. This framework promotes balancing trade-offs between sectors, such as biofuel production impacting food supply or hydropower production affecting agricultural water availability. It encourages systems thinking to capture broad impacts and optimize resource use across sectors. Cross-sectoral coordination is crucial to align strategies and avoid conflicting objectives.

Applying the WEF Nexus framework in Kazakhstan leads to policy recommendations such as increasing irrigation efficiency through advanced technologies, managing water allocation between agriculture and industry, and developing alternative energy sources to reduce reliance on hydropower. Improved data collection across water, energy, and food sectors is essential for evidence-based decision-making. However, this framework assumes strong institutional mechanisms for cross-sectoral collaboration and resources for policymakers to analyze complex trade-offs (Mabhaudhi et al., 2022).

Participatory Water Management emphasizes the active involvement of stakeholders, particularly local communities, in water resource decision-making (Soncini-Sessa, Castelletti, & Weber, 2007). It prioritizes inclusivity and equity, ensuring marginalized groups like smallholder farmers have a voice (von Korff et al., 2012). Local communities possess valuable knowledge about water resources that should inform decisions. Decentralizing water management by empowering Water User Associations (WUAs) helps create local solutions tailored to unique needs.

In Kazakhstan, each framework offers valuable insights. IWRM is relevant due to the country's dependence on transboundary rivers and the need for cross-sectoral coordination. SES is critical due to socio-economic disparities across regions and the ecological challenges of climate change and desertification. The WEF Nexus is essential given Kazakhstan's reliance on hydropower and irrigation-based agriculture, requiring trade-offs between water, energy, and food. Participatory Water Management ensures marginalized stakeholders receive equitable access and can contribute their knowledge to policymaking.

These frameworks provide complementary perspectives to guide Kazakhstan's water management strategies. IWRM and SES ensure holistic, adaptive management, while the WEF Nexus balances trade-offs across sectors. Participatory Water Management promotes inclusivity. Applying these frameworks will help Kazakhstan navigate its unique water challenges and balance economic, environmental, and social priorities for sustainable development.Kazakhstan faces unique water management challenges due to its heavy reliance on transboundary rivers, arid climate, and outdated infrastructure. By examining the water resource management methodologies in countries like Australia and the Netherlands, we can better understand the adaptability and limitations of their approaches in Kazakhstan's specific geographic and cultural context.

Australia, particularly the Murray-Darling Basin, has faced severe water scarcity due to prolonged droughts and growing agricultural demands (Easter & Huang, 2014). To tackle this, Australia introduced a water trading system, which allows water rights holders to buy, sell, or lease their water entitlements (Garrick, 2015). This system incentivizes efficient water use by letting farmers allocate water to high-value crops and sell surplus allocations to others. It helps distribute scarce water resources more equitably across the agricultural sector.

However, implementing water trading in Kazakhstan presents challenges. The system relies heavily on robust legal frameworks and accurate measurement of water flows, something Kazakhstan currently lacks due to outdated irrigation infrastructure. Furthermore, water trading in Australia required significant investment in monitoring technology and administrative systems to ensure transparent and accurate transactions (Easter & Huang, 2014).

On the other hand, the Netherlands is a world leader in sustainable agriculture despite its limited land area. Dutch high-tech greenhouse systems can recycle up to 90% of their water, allowing crops to thrive with minimal waste. These greenhouses utilize hydroponics (growing plants without soil), sophisticated climate control, and advanced nutrient delivery systems to optimize plant growth and reduce water use significantly (Bakker et al., 2023).

Implementing such high-tech greenhouses in Kazakhstan could drastically improve water efficiency and agricultural productivity, especially in regions like Turkestan or Almaty where irrigated agriculture is concentrated. However, the high upfront costs of greenhouse infrastructure could hinder adoption, particularly for smallholder farmers who dominate the agricultural sector.

Methodology

The research focuses on understanding water resource management in Kazakhstan, particularly for irrigated agriculture, and identifying ways to improve efficiency and sustainability in light of climate change, population growth, and regional political factors.

The primary research question guiding this study was: how can Kazakhstan improve the efficiency and sustainability of its water resource management for irrigated agriculture, given its significant reliance on external water sources and aging infrastructure? The central hypothesis is that Kazakhstan's reliance on external water sources and inefficiencies in irrigation infrastructure contribute to water scarcity. Enhancing infrastructure, adopting efficient irrigation techniques, and fostering international collaboration could lead to more sustainable agricultural practices.

In the initial phase, a comprehensive literature review was conducted to identify gaps in current knowledge and existing challenges. This was followed by data collection from national and regional databases to understand water usage, irrigation patterns, and agricultural output. Analysis of this data helped identify patterns, inefficiencies, and the impact of transboundary water agreements on overall water management.

Regional case studies provided deeper insights into specific challenges faced by different economic districts, including water availability, agricultural practices, and governance structures. The strategic frameworks, like Integrated Water Resources Management (IWRM) and Socio-Ecological Systems (SES), were developed based on each district's unique needs.

Quantitative analysis, including descriptive statistics and correlation analysis, was used to evaluate trends in water usage and relationships with agricultural productivity. Qualitative content analysis of policy documents and stakeholder interviews provided valuable insights into ground-level impacts. Comparative analysis of Kazakhstan's water management practices against those of neighboring countries offered additional context.

By developing strategic frameworks such as IWRM, SES, Water-Energy-Food Nexus, and Participatory Water Management, the study provides actionable recommendations to optimize water distribution, improve infrastructure, and involve local communities in water management. These frameworks can help address Kazakhstan's unique challenges and ensure sustainable agricultural development.

Results and discussion

The research results demonstrate that Kazakhstan's water resources are heavily reliant on external sources. A significant portion, approximately 46%, of its water supply originates from neighbouring countries, flowing into Kazakhstan through transboundary rivers (Official Information Source of the Prime Minister of the Republic of Kazakhstan, 2023). These include (Radelyuk, Zhang, & Tussupova, 2022):

- the Irtys and Ile rivers from the People's Republic of China (PRC);
- the Syr Darya, Talas, and Shu rivers from Central Asian countries such as Kyrgyzstan, Uzbekistan, and Tajikistan;
- the Edil (Volga) and Zhayik (Ural) rivers from Russia;

Kazakhstani agriculture, which utilizes about 60% of the country's water resources, is particularly impacted by these inefficiencies. Despite the limited rainfall and challenges in water supply, the adoption of water-efficient technologies in agriculture remains low. This is reflected in the changes in agricultural practices over the years. For instance, from 1991 to 2023, there has been a significant decrease in the area of irrigated arable land. This decline–529.5 thousand hectares or 22.9 percent–over the last 33 years, illustrates the challenges faced by the agricultural sector in terms of water availability and efficient usage.

Table 1 – Area of irrigated arable lands by the regions of the Republic of Kazakhstan in 2023, thousand ha.

№	Regions	Area of irrigated arable lands		Place
		Area, thousand ha	Share from the total, %	
1	Abai	75.5	4.2	7
2	Akmola	17.2	0.9	12
3	Aktobe	12.3	0.7	15
4	Almaty	263.8	14.8	2
5	Atyrau	9.1	0.5	14
6	West Kazakhstan	27.4	1.5	10
7	Zhambyl	206.3	11.6	4
8	Zhetysu	215.2	12.1	3
9	Karaganda	66.3	3.7	8
10	Kostanay	9.1	0.5	16
11	Kyzylorda	187.0	10.5	5
12	Mangystau	0.8	0.04	18
13	Pavlodar	130.0	7.3	6
14	North Kazakhstan	13.6	0.8	13
15	Түркістан	458.8	25.8	1
16	Turkestan	64.1	3.6	9
17	Ulytau	1.3	0.07	17
	3 megalopolis cities	21.1	1.2	11
Total for Kazakhstan		1778.9	100	
Note – compiled by the authors based on the information from the Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan.				

Given the data from Table 1, which details the area of irrigated arable lands by region in the Republic of Kazakhstan for the year 2023, let's clarify and expand upon the current situation and future goals for the country's agricultural land:

As of 2023, the total area of irrigated agricultural lands in Kazakhstan amounts to approximately 1.77 million hectares (Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, 2024). The government has set ambitious goals to expand this to around 3 million hectares by 2025-2030. This expansion is crucial for enhancing agricultural productivity and sustainability, given the varying climatic conditions and water resource challenges in the region.

A significant concentration, about 80%, of these irrigated lands is found in five regions within the southern economic district: Zhetysu, Almaty, Zhambyl, Turkestan, and Kyzylorda. These regions are pivotal in Kazakhstan's agricultural sector due to their favorable climate and available water resources, making them ideal for intensive agriculture.

Analyzing the data from Table 1:

- Turkestan leads with the largest region under irrigation (458.8 thousand ha), contributing a substantial 25.8% to the national total;

- Almaty region follows with 263.8 thousand ha (14.8%), Zhetysu region with 215.2 thousand ha (12.1%), Zhambyl region with 206.3 thousand ha (11.6%), and Kyzylorda region with 187.0 thousand ha (10.5%).

In terms of statistical analysis, we can calculate the median (or middle value) and quartiles (which divide the data into four equal parts) from Table 1:

- the median area: sorting the regions by the area of irrigated land and finding the middle value, the median region is Pavlodar with 130 thousand ha;

- the first quartile (Q1): the lower quartile, or the 25th percentile, is around West Kazakhstan with 27.4 thousand ha;

- the third quartile (Q3): the upper quartile, or the 75th percentile, lies close to Zhambyl with 206.3 thousand ha.

These statistical measures give us a sense of how irrigated land is distributed across the regions of Kazakhstan, with a substantial skew towards the southern economic district. This distribution has direct implications for regional water resource management and agricultural policies.

Further discussions and strategies regarding the allocation and usage of irrigated lands are likely detailed in Table 2, which presents the share of irrigated arable land in economic districts. This table would provide a more macroscopic view of how irrigated land is distributed across the broader economic regions of Kazakhstan.

Table 2 – Area of irrigated arable lands by the economic districts of the Republic of Kazakhstan in 2023, thousand ha.

№	Economic districts	Regions	Area of irrigated arable lands	
			Area, thousand ha	Share from the total, %
1	South	Almaty	263.8	74.8
		Zhambyl	206.3	
		Zhetysu	215.2	
		Kyzylorda	187.0	
		Turkestan	458.8	
		Total for the Southern economic district	1331.1	
2	West	Aktobe	12.3	2.8
		Atyrau	9.1	
		West Kazakhstan region	27.4	
		Mangystau	0.8	
		Total for the Western economic district	49.6	
3	North	Akmola	17.2	9.6
		Kostanay	9.1	
		Pavlodar	130.0	
		North Kazakhstan region	13.6	
		Total for the Northern economic district	169.9	

Table continuation

№	Economic districts	Regions	Area of irrigated arable lands	
			Area, thousand ha	Share from the total, %
4	Central	Karaganda	66.3	3.8
		Ulytau	1.3	
		Total for the Central economic district	67.6	
5	East	Abai	75.5	7.8
		East Kazakhstan region	64.1	
		Total for the Eastern economic district	139.6	
6	Megapolises	Almaty	1.6	1.2
		Astana	0.1	
		Shymkent	19.4	
		Total for 3 megapolises	21.1	
Total for Kazakhstan			1778.9	100
Note – compiled by the authors based on the information from the Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan.				

To elucidate the current state and future objectives for irrigated land in Kazakhstan, while considering the information in Table 2, let's delve deeper into the context of water resource management and agricultural development:

Kazakhstan, facing the challenges of limited water resources and a declining trend in glacier stocks due to climate change, emphasizes the need for efficient water use in agriculture. The total area of irrigated land in the country currently stands at 1.77 million hectares, with a plan to expand this to 3 million hectares by 2025-2030. A significant 80% of these irrigated lands are concentrated in five regions of the southern economic district: Zhetysu, Almaty, Zhambyl, Turkestan, and Kyzylorda.

Table 2 provides a breakdown of irrigated arable lands by economic districts in 2023:

- the Southern economic district, encompassing regions like Almaty, Zhambyl, Zhetysu, Kyzylorda, and Turkestan, collectively accounts for a substantial portion of the total irrigated area, amounting to 1331.1 thousand hectares;

- other districts, such as the Western, Northern, Central, and Eastern economic districts, together with the three megapolises, contribute the remaining 25.2% of the irrigated land.

In the broader context, Kazakhstan is characterized as an industrial-agrarian country. With approximately 24 million hectares of arable land, the nation annually harvests around 17-20 million tons of grain, of which 7 million tons cater to domestic needs, and 8-10 million tons are earmarked for export. This agricultural output is underpinned by significant research and development efforts. Across the country, 17 experimental stations are actively engaged in research in plant and animal husbandry, yielding tangible results for production. The development of new agricultural breeds and varieties, such as sheep and vegetables, is a time-intensive process, often spanning a decade or more.

The combined data from Tables 1 and 2 offer a comprehensive understanding of the current state of irrigated agriculture in Kazakhstan, highlighting regional strengths and indicating potential areas for development and investment, particularly in the context of efficient water usage and sustainable agricultural practices amidst environmental challenges. The Integrated Water Resources Management (IWRM) framework offers structured guidance to optimize irrigated land usage across Kazakhstan's economic districts. By focusing on economic efficiency, environmental sustainability, social equity, and policy coordination, IWRM can help address the unique challenges faced by each region.

In the southern district (Almaty, Zhambyl, Zhetysu, Kyzylorda, and Turkestan regions), irrigation is crucial, covering 75% of the nation's irrigated lands. Reliance on transboundary rivers like the Syr Darya and Ili necessitates international collaboration with China and Uzbekistan. Infrastructure in Turkestan, with 25.8% of the irrigated area, requires modernization to reduce water loss. Efficient irrigation methods and precision farming should be supported by government subsidies. Empowering Water User Associations (WUAs) is vital for equitable water distribution.

The western district (Aktobe, Atyrau, West Kazakhstan, and Mangystau regions) faces arid conditions and limited surface water, contributing only 2.8% to irrigated land. Diversifying water sources through groundwater extraction and desalination, adopting efficient irrigation techniques, and cultivating drought-resistant crops are essential. Upgrading infrastructure and expanding water storage are also needed. Training local water managers will improve governance.

The northern district (Akmola, Kostanay, Pavlodar, and North Kazakhstan regions) is noted for grain farming and contributes 9.6% of irrigated land. Pavlodar has 130,000 hectares of this. Modernizing infrastructure, using automated irrigation controls, and employing precision farming will optimize water use. Enhanced data collection and sharing across ministries can improve water allocation.

The central district (Karaganda and Ulytau regions) has limited water, requiring efficient use and alternative sources like groundwater and wastewater reuse. Investments in groundwater exploration, desalination, and modern irrigation techniques are crucial. Strengthening local water management and WUAs will ensure equitable access.

The eastern district (Abai and East Kazakhstan regions) holds 7.8% of irrigated land, relying on the Irtysh and Ile rivers. Cross-border agreements with China are needed for sustainable use. Expanding reservoir capacity and monitoring water levels will support adaptive management. Promoting efficient irrigation and precision farming will optimize water use.

The IWRM framework aims to improve water management by upgrading infrastructure, empowering local institutions, and adopting efficient irrigation practices. Enhanced data collection, cross-border collaboration, and policy coordination are key for sustainable agriculture. The SES framework provides insights into the interaction between ecological systems and human societies, offering a nuanced approach to addressing region-specific challenges and solutions.

In the southern district (Almaty, Zhambyl, Zhetysu, Kyzylorda, and Turkestan regions), irrigation is crucial, covering nearly 75% of Kazakhstan's irrigated lands and relying on rivers like the Syr Darya and Ili. This area faces socio-ecological challenges due to upstream water usage and downstream degradation. An SES approach advocates for international cooperation with China and Uzbekistan to ensure equitable water access through joint conservation and water-sharing agreements.

Modernizing irrigation infrastructure is essential to reduce water wastage and maintain groundwater reserves. Efficient practices like drip irrigation and precision farming should be promoted to minimize ecological impact. Monitoring river flows, soil health, and aquifer levels will aid adaptive policymaking. Social equity is critical, especially in Turkestan and Kyzylorda, where outdated infrastructure and socio-economic vulnerabilities hinder clean water access. Empowering Water User Associations (WUAs) with resources and support will enable equitable water distribution and improved governance.

The western district (Aktobe, Atyrau, West Kazakhstan, and Mangystau regions) faces severe water scarcity due to arid conditions, contributing only 2.8% of irrigated lands. Diversifying water sources, such as groundwater extraction, desalination, and rainwater harvesting, is vital. Modernizing irrigation infrastructure and adopting drought-resistant crops and advanced techniques will reduce water wastage and ecological degradation. Building local water management capacity is essential for resource monitoring, adaptive policy development, and equitable distribution.

In the northern district (Akmola, Kostanay, Pavlodar, and North Kazakhstan regions), extensive grain farming dominates, with 9.6% of irrigated lands. Pavlodar holds the largest share. Modernizing infrastructure to maintain soil health, regulate groundwater, and reduce water loss is crucial. Strengthening data management systems for water flow monitoring and optimizing irrigation schedules is recommended. Cross-sector collaboration ensures equitable water access between agriculture and industry. Empowering local institutions and WUAs improves governance and participation.

The central district (Karaganda and Ulytau regions) has limited water availability and fragile ecosystems. The SES framework emphasizes managing alternative water sources, such as groundwater extraction and wastewater reuse. Investments in groundwater exploration and desalination will support irrigation. Strengthening institutional capacity and WUAs will improve groundwater monitoring, equitable water allocation, and decision-making. Promoting modern irrigation technologies and drought-resistant crops will reduce water usage and maintain ecological balance.

The eastern district (Abai and East Kazakhstan regions) relies on transboundary rivers like the Irtysh and Ile, accounting for 7.8% of irrigated land. Cross-border agreements with China are vital for sustainable water management. Expanding reservoir capacity supports adaptive water management and stable supplies during dry periods.

Promoting efficient irrigation techniques will reduce the ecological impact on river ecosystems. Enhanced data collection will allow policymakers to effectively monitor water availability, soil quality, and groundwater levels. Collaborative conservation programs can ensure that agriculture balances environmental needs.

The Socio-Ecological Systems (SES) framework provides a comprehensive understanding of the interplay between socio-economic vulnerabilities and environmental stress in Kazakhstan. Managing these interactions holistically will align water management strategies with ecological conditions, improving irrigation efficiency, empowering local stakeholders, and safeguarding natural resources. Adaptive management strategies will balance agricultural productivity and environmental sustainability, fostering resilient socio-ecological systems across the country.

The Water-Energy-Food (WEF) Nexus framework emphasizes the interdependence of water, energy, and food resources. This holistic approach is crucial for managing irrigated lands, as agricultural productivity relies on efficient water and energy use. The WEF Nexus framework helps identify trade-offs and synergies between these sectors to guide policies that balance competing demands.

In the southern economic district (Almaty, Zhambyl, Zhetysu, Kyzylorda, and Turkestan regions), agriculture is the backbone of the economy, with nearly 75% of Kazakhstan's irrigated lands. This region relies heavily on water from trans-boundary rivers like the Syr Darya and Ili. Turkestan alone has 458.8 thousand hectares of irrigated land, making up 25.8% of the nation's total. The WEF Nexus framework emphasizes modernizing irrigation to increase efficiency and reduce energy consumption. Drip and sprinkler irrigation systems reduce evaporation and ensure optimal hydration. Using solar-powered pumps can cut fossil fuel dependence, reducing energy use and costs.

Coordination between sectors is crucial to balance agricultural irrigation needs, energy demands, and environmental sustainability. Joint infrastructure investments and accurate monitoring with neighboring countries like China and Uzbekistan are essential for equitable water distribution. Upgrading irrigation infrastructure in Turkestan to reduce water loss is necessary for sustainable water use. Automated irrigation controls can optimize water distribution based on crop schedules.

The western economic district (Aktobe, Atyrau, West Kazakhstan, and Mangystau regions) makes up only 2.8% of the nation's irrigated land due to arid conditions and water scarcity. The region relies on the Ural River and Caspian Sea Basin for inconsistent surface water. Diversifying the water supply with groundwater extraction, desalination, and rainwater harvesting is essential but energy-intensive. Energy-efficient irrigation systems powered by renewable sources like solar and wind can support these processes. Financial incentives for adopting efficient irrigation techniques and alternative energy will encourage uptake among farmers.

Infrastructure upgrades will help minimize water wastage, while diversifying crop selection to include drought-resistant varieties will align agriculture with available resources. Automated monitoring tools and carefully timed irrigation schedules are necessary for sustainable resource management.

In the northern economic district (Akmola, Kostanay, Pavlodar, and North Kazakhstan regions), grain farming dominates, contributing 9.6% of Kazakhstan's irrigated lands. Pavlodar alone has 130,000 hectares under irrigation, mainly sourced from local rivers and reservoirs. Modernizing irrigation infrastructure is crucial for reducing water loss and the energy burden of irrigation pumping. Soil moisture monitoring and climate data analysis will help farmers establish optimal irrigation schedules. Using renewable energy sources like wind and solar power will ensure sustainable irrigation.

Cross-sector collaboration will improve coordination between agriculture and industry, ensuring irrigation practices align with industrial energy demands. Subsidies and incentives for efficient irrigation practices will help farmers adopt them without prohibitive costs. Remote sensing and GIS technologies will monitor water flows, optimize crop management, and implement adaptive strategies.

The central economic district, comprising Karaganda and Ulytau regions, faces limited water availability and fragile ecosystems, contributing only 3.8% of the nation's irrigated lands. Groundwater extraction and wastewater reuse are essential for sustaining irrigation. Solar-powered pumps for groundwater extraction can minimize energy costs, while wastewater treatment systems can provide irrigation water. Training water managers and empowering Water User Associations (WUAs) will ensure equitable resource distribution. Automated monitoring can identify optimal extraction rates for sustainable resource allocation. Farmers should adopt drought-resistant crops and modern irrigation technologies that align with the district's environmental conditions.

In the eastern economic district, including Abai and East Kazakhstan regions, securing equitable access to the Irtysh and Ile rivers is vital due to their importance for irrigation. Cross-border agreements with China are necessary, as these rivers provide 45% of the water in the Balkhash-Alakol Basin. Expanding the region's reservoir capacity will stabilize water supplies during dry periods. Efficient irrigation techniques like automated controls and precision farming will ensure effective water use.

The Water-Energy-Food (WEF) Nexus framework reveals the intricate connections between water, energy, and food production across Kazakhstan's economic districts. Focusing on region-specific challenges and promoting efficient irrigation technologies, renewable energy, and accurate monitoring systems will help Kazakhstan balance agricultural needs with sustainable water and energy consumption.

The Participatory Water Management framework emphasizes the involvement of local communities in decision-making, ensuring their voices are considered in policy development, planning, and implementation. This framework can guide strategies for optimizing irrigated land use across different economic districts, ensuring diverse regional needs are met through inclusive water governance.

In the southern economic district (Almaty, Zhambyl, Zhetysu, Kyzylorda, and Turkestan regions), irrigation plays a critical role in sustaining agricultural productivity, with nearly 75% of Kazakhstan's irrigated lands located here. The region relies heavily on water from transboundary rivers like the Syr Darya and Ili for high-value crops. Turkestan holds 458.8 thousand hectares of irrigated land, 25.8% of the national total. Local farmers and WUAs are directly impacted by water shortages and need involvement in decision-making for equitable water distribution and sustainable management.

The participatory framework advocates empowering WUAs with resources and technical support to manage local irrigation networks effectively. This involvement will help shape irrigation schedules that align with crop needs and minimize waste. Farmers should be encouraged to switch to water-efficient irrigation methods like drip and sprinkler systems, with financial incentives and training programs to support these technologies.

In Kyzylorda, socio-economic vulnerabilities make it crucial that marginalized communities have access to clean water. Engaging them through consultations and educational programs will help policymakers understand their needs and challenges. Cross-border negotiations with China and Uzbekistan must include local stakeholder input to secure equitable access to shared water resources. Collaborative conservation programs can maintain the ecological balance of transboundary rivers while ensuring farmers maximize agricultural productivity.

In the western economic district (Aktobe, Atyrau, West Kazakhstan, and Mangystau regions), arid conditions and scarce water resources limit irrigation to 2.8% of the nation's irrigated lands. Despite this, many local farmers rely on irrigation for livestock grazing and crop cultivation, particularly in the Ural River and Caspian Sea Basin. Groundwater extraction, desalination, and rainwater harvesting can supplement surface water, though these methods are energy-intensive and require technical expertise.

The participatory framework ensures local stakeholders receive training on efficient irrigation practices. Financial support should help them adopt energy-efficient irrigation technologies like solar-powered pumps. Local WUAs should collaborate with agricultural research institutions to develop drought-resistant crops. Collaborative management between local water managers and government officials will minimize water use conflicts and establish equitable distribution.

In the northern economic district (Akmola, Kostanay, Pavlodar, and North Kazakhstan regions), grain farming dominates, contributing 9.6% of Kazakhstan's irrigated lands. Pavlodar alone holds 130,000 hectares under irrigation, primarily from local rivers and reservoirs. Grain farming relies heavily on irrigation, which must be balanced with industry and livestock production.

Empowering local WUAs to participate in water governance ensures equitable access between agriculture and other sectors. Training on precision irrigation practices that monitor soil moisture and optimize schedules will minimize water waste and align irrigation with crop requirements. Automated irrigation controls should be encouraged through government subsidies.

Cross-sector collaboration between agriculture and industry will improve data sharing and help develop coordinated water allocation policies. Farmers should receive incentives to grow water-efficient crops and adopt renewable energy sources like wind and solar power to reduce irrigation costs.

The central economic district, including Karaganda and Ulytau regions, faces fragile ecosystems and limited water availability, with only 3.8% of the country's irrigated lands. Groundwater extraction and wastewater reuse are critical to sustaining irrigation. Solar-powered groundwater pumps and wastewater treatment systems can supply irrigation water while minimizing energy consumption.

The participatory framework encourages collaboration between water managers, local WUAs, and government agencies. Local water managers need technical training on managing groundwater resources, while WUAs should receive funding to implement modern irrigation techniques and educate farmers on water-efficient practices. Aligning irrigation practices with available water resources will reduce water use while maintaining agricultural productivity.

Farmers should receive training and incentives to switch to drought-resistant crops, minimizing water consumption. This will align agricultural practices with environmental conditions, sustaining irrigation and reducing ecological stress.

In the eastern economic district (Abai and East Kazakhstan regions), securing equitable access to the Irtysh and Ile rivers is vital for irrigation. Cross-border agreements with China are necessary to ensure equitable water distribution. Expanding reservoir capacity will help stabilize water supplies during dry seasons and periods of reduced river flow.

Local WUAs should be involved in cross-border negotiations to ensure agricultural water needs are considered. Collaborative programs between local water managers and neighboring countries can enhance monitoring and conservation efforts. Automated irrigation systems and precision farming practices will help farmers maximize water use and reduce waste.

The Participatory Water Management framework ensures diverse local stakeholder needs are included in decision-making processes, helping advocate for equitable water access and sustainable irrigation practices. This inclusive approach balances sectoral trade-offs, improves irrigation efficiency, and develops coordinated policies across Kazakhstan's economic districts.

Conclusion

The primary goal of this study was to identify ways in which Kazakhstan could improve the efficiency and sustainability of its water resource management in the context of irrigated agriculture. This involved assessing the current state of water usage, understanding reliance on external sources, and evaluating the aging infrastructure. The methods included a comprehensive review of literature, quantitative data analysis, stakeholder interviews, and comparative analysis of water management practices in neighboring regions. There are several key findings and conclusions:

1. Heavy reliance on external water sources: Kazakhstan relies heavily on water originating from neighboring countries, especially from the Irtysh and Ili rivers in China, the Syr Darya, Talas, and Shu rivers from Central Asia, and the Volga and Ural rivers in Russia. This reliance on transboundary rivers poses significant challenges for water security. Approximately 46% of Kazakhstan's water supply comes from external sources, highlighting its vulnerability in ensuring equitable and consistent access to water.

2. Disparity in regional water availability: regional water availability varies significantly across Kazakhstan's economic districts. The southern district, with regions such as Turkestan, Almaty, and Zhambyl, accounts for 74.8% of irrigated lands. In contrast, the western and central districts collectively account for only about 6.6% due to arid conditions and limited surface water resources. This disparity necessitates region-specific management strategies that cater to local geographical and climatic conditions.

3. Inefficiencies in water transport and usage: about 40% of water sourced from transboundary rivers is lost due to inefficient infrastructure and management practices. The lack of modernized water management systems means substantial amounts of water are wasted before reaching agricultural or industrial areas. This inefficiency affects agricultural productivity, especially given that agriculture consumes approximately 60% of Kazakhstan's water resources.

4. Decline in irrigated arable land: From 1991 to 2023, Kazakhstan experienced a significant decline in irrigated arable land, reducing by 529.5 thousand hectares (or 22.9%). This decline is attributed to a combination of factors, including outdated irrigation infrastructure, changing agricultural practices, and challenges in water availability. Turkestan remains the region with the largest irrigated land (25.8% of the national total).

5. Potential for technology adoption: Implementing efficient irrigation techniques such as drip and sprinkler systems, alongside the adoption of precision farming, can improve water management.

However, high upfront costs and a lack of technical expertise have hindered widespread adoption, particularly among smallholder farmers.

6. By applying economic region-specific solutions informed by various frameworks, Kazakhstan can modernize irrigation, reduce water loss, and achieve sustainable agricultural development. IWRM focuses on policy coordination and international collaboration, SES balances socio-ecological dynamics, the WEF Nexus ensures balanced sectoral trade-offs, and Participatory Water Management enables local governance.

In the southern economic district (Almaty, Zhambyl, Zhetysu, Kyzylorda, and Turkestan regions), agriculture is central to the economy, with nearly 75% of Kazakhstan's irrigated land. This area relies on transboundary rivers like the Syr Darya and Ili for high-value crops. Integrated Water Resources Management (IWRM) emphasizes international collaboration with China and neighboring Central Asian countries to secure fair water-sharing agreements and invest in cross-border infrastructure. Modernizing outdated canal systems in Turkestan and adopting efficient irrigation techniques like drip and sprinkler systems can reduce water loss. Automated controls help optimize irrigation schedules and improve yields. The Socio-Ecological Systems (SES) framework highlights the impact of irrigation on groundwater, soil health, and ecosystems. Empowering Water User Associations (WUAs) ensures equitable water distribution, especially in socio-economically vulnerable regions like Kyzylorda. Adaptive management strategies should consider regional disparities and ensure sustainable irrigation access for marginalized communities. The Water-Energy-Food (WEF) Nexus underscores the interconnectedness of water, energy, and food production, advocating for renewable energy sources like solar-powered pumps to minimize energy consumption. Precision farming and soil moisture monitoring align irrigation schedules with crop needs. Participatory Water Management involves farmers and WUAs in decision-making, advocating for cross-border water sharing and water-efficient practices.

In the western economic district (Aktobe, Atyrau, West Kazakhstan, and Mangystau regions), arid conditions and scarce water resources cover only 2.8% of Kazakhstan's irrigated lands. IWRM emphasizes diversifying water supplies through groundwater extraction, desalination of Caspian Sea water, and rainwater harvesting. Groundwater extraction requires careful management to avoid over-extraction. Upgrading aging irrigation systems will reduce water losses and improve storage. The SES framework calls for resilience to climatic extremes, promoting adaptive irrigation practices like drought-resistant crops and efficient techniques. Capacity-building for local water managers will help monitor resources and develop region-specific strategies. The WEF Nexus encourages energy-efficient irrigation technologies like solar-powered pumps to minimize fossil fuel reliance. Switching to less water-intensive crops and using renewable energy sources aligns irrigation practices with ecological conditions. The participatory framework ensures farmers receive training and financial incentives for efficient irrigation systems. Collaboration between WUAs and research institutions promotes region-specific solutions.

In the northern economic district (Akmola, Kostanay, Pavlodar, and North Kazakhstan regions), grain farming dominates, contributing 9.6% of Kazakhstan's irrigated land. Pavlodar has 130,000 hectares under irrigation, mainly from local rivers and reservoirs. IWRM recommends modernizing infrastructure to reduce water loss and energy consumption. Automated irrigation controls and systems like sprinklers and micro-irrigation optimize practices. Cross-sector data sharing ensures irrigation schedules align with industrial energy needs. The SES framework emphasizes efficient management of surface and groundwater resources to maintain soil quality and groundwater levels. Remote sensing tools monitor irrigation practices and their impact on river flows. The WEF Nexus advocates for renewable energy sources like wind and solar power for irrigation. The participatory framework empowers local WUAs to ensure equitable schedules and provides precision farming training to minimize water waste.

In the central economic district (Karaganda and Ulytau regions), water availability is limited by fragile ecosystems. Groundwater extraction and desalination can supplement surface water but must be managed sustainably. IWRM recommends training local water managers and empowering WUAs to improve water distribution. SES emphasizes precision irrigation for efficient groundwater extraction to minimize ecological impact. Switching to drought-resistant crops aligns irrigation with available resources. The WEF Nexus recommends using solar-powered pumps to minimize energy costs, while wastewater treatment systems can supply irrigation water. The participatory framework promotes collaboration between WUAs and government agencies, ensuring irrigation schedules align with groundwater availability and providing technical training to farmers.

The eastern economic district (Abai and East Kazakhstan regions) relies heavily on the Irtysh and Ile rivers for irrigation. IWRM emphasizes cross-border agreements with China to secure equitable river access. Expanding reservoir capacity stabilizes water supplies during dry periods, while SES highlights monitoring river flows and groundwater levels for adaptive management. The WEF Nexus recommends efficient irrigation technologies to align agricultural output with water availability, using solar-powered systems to optimize energy use. Participatory Water Management involves WUAs in cross-border negotiations to ensure local irrigation needs are met. Collaborative conservation efforts between local water managers and neighbouring countries balance agriculture with ecological requirements.

In conclusion, this study not only contributes to the academic understanding of water resource management in arid regions like Kazakhstan but also offers practical strategies that can be implemented to improve water efficiency in agriculture. The multi-faceted approach recommended by this study–encompassing technology implementation, farmer engagement, policy refinement, and international cooperation–provides a comprehensive roadmap for addressing the water challenges faced by Kazakhstan, ensuring the long-term sustainability of its water resources and agricultural sector.

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