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Analysis of the State of Water Resources, Water Use, and Water Security in the Agricultural Sector of Kazakhstan and Ways to Address Them

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ABSTRACT

The effective management of water resources is one of the key challenges of modern society, as increasing climate variability and growing water demand intensify pressure on limited and spatially uneven water availability. The concept of sustainable water use, aimed at balancing resource availability with long-term environmental, economic, and social stability, plays a crucial role in ensuring water security. High dependence on transboundary inflow, climatic vulnerability, and sectoral competition for water in Kazakhstan highlight the need for comprehensive and integrated approaches to water resource assessment and management. An analysis of international experience in the field of water security and water resource management made it possible to identify six groups of criteria for sustainable and efficient water use applicable to the conditions of Kazakhstan. It has been determined that in the Republic of Kazakhstan, more than 70% of abstracted water is used in agriculture, which, under existing climatic conditions, increases the pressure on water resources. Water availability in the agricultural sector accounts for only one-third of the required volume, indicating a shortage of water resources and posing a significant risk to the country's food security. The purpose of this study is to develop an integrated analytical approach for assessing water resources, water use, and water security in Kazakhstan under climate change conditions. The object of the research includes water resources as a natural component, sectoral water use systems, and territorial water supply mechanisms. A systemic and interdisciplinary approach was applied, combining structural analysis, logical generalization, and comparative assessment of climatic, hydrological, and socio-economic factors. Results show that climate change increases spatial and temporal variability of water resources, destabilizes water supply, and raises the sensitivity of key sectors to hydrological fluctuations. Improving water security requires the transition to integrated water resource management, incorporating climate factors into strategic planning and strengthening adaptive governance mechanisms.

1. INTRODUCTION

Contemporary global transformations are strengthening the role of water resources as a system-forming factor determining the sustainability of socio-economic development, the spatial organization of economic activity, and the level of environmental security. Their significance is determined not only by the volume of available water resources but also by the conditions of their formation, distribution, and use within the economic system. As global climate change, demographic pressure, and the transformation of the world economic structure intensify, the role of water resources increases substantially, acquiring a strategic and system-forming character [1-3].

In countries with limited natural water potential, the water factor largely determines the limits of economic growth, the sustainability of key sectors, and the possibilities for long-term development [4].

Kazakhstan is among the states for which the issue of water resources has a pronounced systemic and long-term character [5]. A significant part of the country's territory is located in arid and semi-arid climatic zones, which predetermines the

natural limitation of water resources and their high spatial heterogeneity [6]. Water resources are distributed extremely unevenly both territorially and temporally, creating substantial differences in the level of regional water availability. These differences, in turn, cause persistent socio-economic and environmental disproportions, influencing the development of agriculture, industry, and infrastructure [7].

The relevance of water resources for Kazakhstan is reinforced by the specific features of their formation and use. A significant share of the country's surface runoff is transboundary in nature, which increases the dependence of the national water supply system on external natural and institutional factors [8]. Such dependence creates additional constraints for water policy and requires consideration of the regional and international context in managerial decision-making. Under conditions of climate variability, the transboundary nature of water resources increases the uncertainty of water management planning and necessitates the alignment of domestic water use priorities with international obligations and cooperation mechanisms [9].

Climate variability under the conditions of Kazakhstan acts as a driver of profound changes in the water balance, affecting runoff seasonality, territorial distribution of resources, and the sustainability of water supply. An increase in average air temperature, changes in precipitation patterns, and the growing frequency of extreme hydrometeorological events lead to changes in the volume, seasonality, and stability of water resources [10]. These processes have a complex impact on both surface water and groundwater, reducing the reliability of traditional water supply sources and the resilience of water management systems as a whole [11].

Climate variability intensifies interannual and intraseasonal instability of river runoff, which significantly complicates water resource management processes and increases the risks of water scarcity [12]. Under conditions of growing uncertainty, the importance of adaptive approaches increases, aimed at enhancing the flexibility of water management systems, developing forecasting mechanisms, and incorporating long-term climate risks into strategic planning [13].

Table 1. Criteria for assessing sustainable and efficient water use (Kazakhstan)

Criterion Group	Content	Interpretation for Kazakhstan
Resource-related	Compliance of water consumption volumes with renewable resources	Consideration of runoff limitations and interannual variability
Economic	Water intensity of production, efficiency of water use	Reduction of losses, implementation of water-saving technologies
Environmental	Preservation of environmental flow and water quality	Prevention of ecosystem degradation
Social	Accessibility of water for the population and rural areas	Ensuring water security
Institutional	Efficiency of management and coordination	Basin-based principle, consideration of climate factors
Adaptive	Capacity to respond to climate risks	Flexibility and scenario planning

Water use as a set of forms and mechanisms for utilizing water resources in economic activity plays a particularly important role in the socio-economic development of Kazakhstan. Water use covers key sectors of the economy, including agriculture, industry, and the municipal sector, and directly affects economic stability, food security, and the standard of living of the population [14]. At the same time, the high water intensity of certain sectors increases pressure on water resources and heightens the sensitivity of the economy to climatic and hydrological changes, which requires improving the efficiency and rationality of water use [15].

Based on the analysis, as well as the generalization of international concepts of water security and integrated water resources management, the following groups of criteria for sustainable and efficient water use relevant to the conditions of Kazakhstan can be identified (Table 1).

The efficiency of water use in Kazakhstan is largely determined by the mismatch between actual water consumption and the potentially sustainable level of resource use, especially in the agricultural sector. Under conditions of climate instability, the criteria of adaptability and environmental sustainability acquire priority significance compared with short-term economic efficiency.

Water use determines not only the economic but also the environmental parameters of territorial development. It has a direct impact on the condition of aquatic ecosystems and the level of anthropogenic pressure on water bodies. Imbalanced use of water resources under climate change conditions may lead to degradation of aquatic ecosystems, deterioration of water quality, and a decline in their environmental sustainability [16]. In this regard, the integration of environmental constraints and sustainable development principles into the water resource management system becomes particularly important [13].

Table 2. Comparative assessment of water use and water resource management: Kazakhstan and international cases

Criterion	Republic of Kazakhstan	International Cases (EU, Central Asia, Arid Regions)
Climatic conditions	Arid and semi-arid zones, high runoff variability	Similar conditions in the countries of Central Asia and the middle east
Water use structure	Dominance of agriculture (> 70%)	Agriculture is the key water consumer
Dependence on transboundary waters	High (> 40% of surface runoff)	High in countries with transboundary basins
Environmental constraints	Increasing, ecosystem approach limited	Active implementation of the ecosystem approach
Integration of climate factors into management	Partial, emerging	Scenario planning is widely applied
Institutional model	Basin-based principle, institutional reform	IWRM as the basic management model
System adaptability	Moderate, limited by infrastructure and data	Higher due to monitoring and digitalization
Strategic orientation	Transition toward water security	Sustainable development and climate adaptation

The development of digital monitoring platforms, forecasting systems, and information-analytical tools is considered one of the key elements for improving water resource management efficiency. Modern monitoring systems make it possible to promptly track the condition of water bodies, identify risks, and adjust managerial decisions in real time (Table 2).

Investments in reservoirs, irrigation infrastructure, and the digitalization of the water sector serve as important adaptive instruments under conditions of climate uncertainty [7, 8].

Taken together, institutional reforms and the development of management instruments create the prerequisites for a transition to a comprehensive and adaptive water resource management system aimed at ensuring water security, sustainable development, and the long-term environmental sustainability of Kazakhstan.

Despite certain progress in the field of water management, a number of systemic problems and contradictions remain in this area. One of the key issues is the mismatch between the growing needs of the economy and the objective limitation of water resources, as well as the fragmented nature of managerial decisions based predominantly on a sectoral approach [17]. Insufficient integration of the climate factor into strategic and territorial planning reduces the adaptive potential of water management systems and increases long-term risks of water scarcity.

The scientific development of the problem of water resources and water use is characterized by significant diversity of theoretical and applied approaches. Scientific literature widely presents studies devoted to hydrological processes, water resource management, and adaptation to climate change [18]. At the same time, most works are focused on analyzing individual components of the water management system, which limits the possibilities for a comprehensive assessment of interrelationships between water resources, water use, and water security.

Under the conditions of Kazakhstan, the need for integrated analysis is reinforced by the specific natural, institutional, and territorial conditions, as well as by the transboundary nature of water resources. This creates a need for developing a comprehensive analytical approach aimed at coordinating natural, economic, and managerial factors under conditions of climate variability and long-term uncertainty.

Thus, the analysis of the state of water resources and water availability in the republic revealed significant shortcomings in water consumption, namely the inefficient use of water resources due to water losses, outdated methods, and the lack of water-saving technologies and practices, leading to water scarcity. The scientific novelty of the research lies in the development of proposals aimed at improving the water resource management system through encouraging water users to adopt efficient water use practices, implementing modern water-saving technologies, introducing water metering tariff systems, and applying geographic information system (GIS) technologies.

Based on the above, the purpose of this study is a comprehensive analysis and scientific substantiation of approaches to assessing water resources, water use, and water security in Kazakhstan under climate change conditions.

To achieve the stated objective, the following tasks are to be addressed:

– to substantiate the relevance of water resources as a strategic factor in the development of Kazakhstan;

– to analyze the impact of climate change on the water balance and the sustainability of water security;

– to reveal the role of water use in the country's socio-economic development;

– to identify key problems and contradictions in the water resource management system;

– to assess the degree of scientific elaboration of the problem and substantiate the need for a comprehensive analytical approach.

2. METHODOLOGY

The methodological framework of the study is based on a systems approach, which makes it possible to consider water resources, water use, and water security as interconnected components of a unified natural-technogenic and socio-economic system. The application of the systems approach is determined by the multi-level nature of the problem under study, which includes natural, climatic, economic, and institutional components whose interaction shapes the resilience of the water management complex under climate change conditions.

Within the systems approach, water resources are considered not in isolation, but in the context of the processes of their formation, distribution, and use, as well as taking into account feedback links between water use, the condition of aquatic ecosystems, and the socio-economic development of territories. This approach makes it possible to identify structural interrelationships, contradictions, and constraints arising within the water resource management system, and to assess the impact of climate variability on the sustainability of water supply.

The methodological concept of the study is based on a comprehensive and interdisciplinary approach that combines elements of environmental, economic, and managerial analysis. This makes it possible to take into account both the natural characteristics of water resources and the socio-economic conditions of their use, as well as institutional mechanisms for regulating water use. Particular attention is paid to balancing water protection and economic priorities under conditions of limited water resources and increasing climate risks.

The study applies methods of analysis and synthesis aimed at examining individual elements of the water management system and their subsequent generalization within a unified analytical model. The method of logical generalization is used to identify patterns and trends in the field of water use and water security, as well as to formulate conceptual conclusions. The comparative method is applied to compare different approaches to assessing water resources and managing them under climate variability conditions. Structural analysis makes it possible to determine the role and significance of individual elements of the water management system and the nature of their interaction.

A special place in the research methodology is occupied by qualitative analytical analysis focused on interpreting processes and trends without reference to specific quantitative indicators. The choice of this approach is determined by the purpose of the study, aimed at forming a holistic understanding of the problems and prospects of water resource management under climate uncertainty, rather than calculating individual parameters of the water balance.

Multispectral satellite imagery from the Landsat program (Level-2 Surface Reflectance) was used to assess vegetation

moisture conditions. Images for June 2016 and June 2025 with a spatial resolution of 30 m were selected to ensure temporal comparability. The data provide consistent spectral bands suitable for moisture index calculations, particularly in the near-infrared (NIR) and shortwave infrared (SWIR) ranges. Standard preprocessing, including atmospheric correction and cloud masking, was applied prior to analysis.

As the information base of the study, generalized scientific concepts of water resources, water use, and climate change presented in the works of domestic and foreign researchers are used, as well as analytical and regulatory materials characterizing the water management sector of Kazakhstan. In addition, materials from international and regional organizations reflecting modern concepts of sustainable and adaptive water resource management are taken into account.

Regulatory and legal sources are used to analyze institutional aspects of water resource management and to assess the degree of integration of the climate factor into water policy. Analytical materials are applied to identify key directions for the development of the water supply system and existing managerial constraints. At the same time, the study is not oriented toward statistical modeling or forecasting, but focuses on identifying qualitative patterns and structural problems.

The study has an analytical-review and conceptual character, which implies the synthesis of existing scientific approaches and their adaptation to the specific conditions of Kazakhstan. This format makes it possible to ensure a high degree of generalization and theoretical substantiation of the obtained conclusions, as well as their applicability in the development of strategies and concepts for water resource management under climate change conditions.

The methodological limitations of the study are associated with the rejection of detailed quantitative calculations in favor of comprehensive qualitative analysis. At the same time, the chosen methodology ensures the identification of key interrelationships and trends determining the sustainability of water use and water security, and forms a basis for further applied and empirical research.

3. RESULTS AND DISCUSSION

3.1 Analysis of the state of water resources under climate change conditions

The water resources of Kazakhstan are formed under conditions of pronounced natural and climatic heterogeneity, determined by the country's vast territorial extent, landscape diversity, and the arid character of the climate across most of its territory. A significant feature of the national water balance is the high dependence on external runoff sources. According to national and international analytical reviews, more than 44% of Kazakhstan's surface water resources are of transboundary origin, entering from neighboring states of Central Asia and China [19]. This circumstance determines the increased vulnerability of the national water supply system to both climatic and institutional factors.

The country's total renewable water resources are characterized by high interannual variability, which complicates long-term planning of water use and water security. The spatial distribution of water resources is sharply disproportionate: the southern and southeastern regions experience chronic water scarcity, whereas the northern and eastern territories possess a relatively more stable water balance [6]. Such asymmetry creates unequal conditions for socio-economic development and increases regional water security risks (Figure 1).

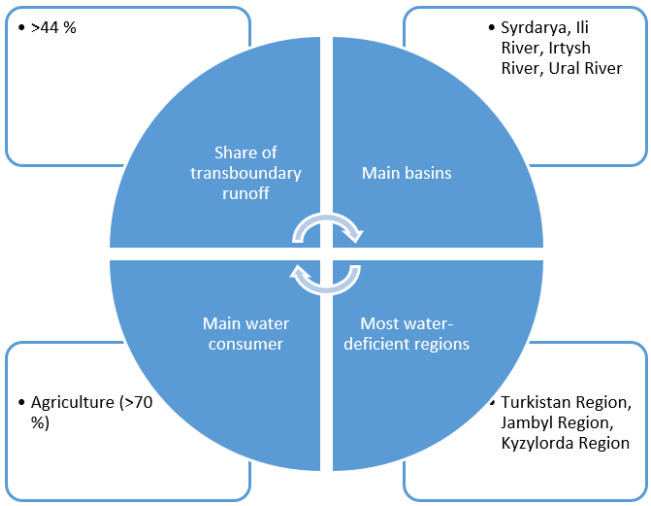

Figure 1. Generalized characteristics of water resources of the Republic of Kazakhstan
Note: Compiled by the authors based on this study [8]

The severity of the water supply problem in Kazakhstan is determined by a set of interrelated factors, among which the key ones are the limitation of available water potential, pronounced territorial heterogeneity of its distribution, high interannual variability, and increasing anthropogenic pollution of water bodies. Conceptual studies by domestic authors emphasize that these structural features create persistent vulnerability in the water supply system, which intensifies under conditions of climate change and growing transboundary water management risks.

At the same time, the following climatic trends are recorded:

- increase in average annual air temperature;
- shift in the timing of the growing season;
- increase in the frequency of droughts and extreme hydrometeorological events.

The combined impact of these factors leads to greater instability of seasonal and interannual runoff, reducing the reliability of traditional water management planning and forecasting schemes [18]. Under climate uncertainty, the need to transition to adaptive water resource management models increases.

Spatial analysis shows that water scarcity in Kazakhstan has not only a quantitative but also a qualitative character. In a number of basins, water quality deterioration is associated with high anthropogenic pressure, irrigation return flow, pollution of water bodies, and wear of water management infrastructure [12].

Particular concern is caused by the Balkhash-Ili Basin and the lower reaches of the Syr Darya, where climatic, environmental, and transboundary risks are combined. In these regions, simultaneous reduction of water resources, deterioration of water quality, and increasing conflict in water use are observed, making them critically vulnerable from the perspective of sustainable development [20].

Thus, according to conceptual assessments of water resources in Kazakhstan, the key feature of their condition is not so much the absolute volume as the high interannual and

territorial variability of water potential. It is noted that it is precisely the spatial asymmetry of water resources and the limited possibilities for their redistribution that form the basis of water scarcity in a number of regions, regardless of short-term runoff fluctuations [1]. Under climate change conditions, these structural features intensify, confirming the need for a comprehensive assessment of water resources taking into account long-term trends.

The conducted analysis shows that climate variability manifests itself as a complex factor transforming the water balance of Kazakhstan, affecting its spatial, seasonal, and functional characteristics. One of the key factors is the accelerated melting of glaciers in the Tian Shan and Altai Mountains, which form up to 90% of river runoff in the southern regions of the country. This process is accompanied by a short-term increase in water availability; however, in the long term it carries the risk of a sharp reduction in water resources and intensified water scarcity [10, 21].

In the long term, a further aggravation of the water supply situation is expected, caused by the reduction of river runoff formed in the territories of neighboring states, as well as by climatically determined decreases in local runoff resources. Potential changes in the water balance are considered a factor of direct threat to the sustainable socio-economic development and environmental security of the country, which requires a transition to forecast-oriented and adaptive approaches to water resource management.

3.2 Analysis of water use and water security in the Republic of Kazakhstan

The structure of water use in Kazakhstan has a distinctly agrarian character. According to data from the Ministry of Water Resources and Irrigation of the Republic of Kazakhstan [22], more than 70–72% of abstracted water is used in agriculture, primarily for irrigation. This structure reflects a historically established model of economic development; however, under climate change conditions, it increases pressure on water resources (Figure 2).

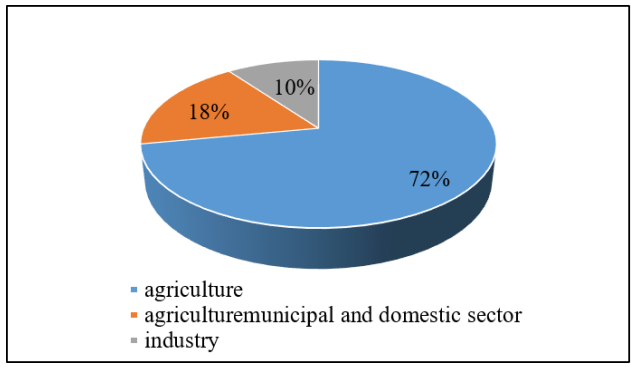

Figure 2. Structure of water use in the Republic of Kazakhstan
Note: Compiled by the authors based on source [22]

Conceptual studies emphasize that the historically established orientation of water use toward extensive irrigated agriculture has resulted in high water intensity of the economy and limited the adaptive capacity of the water management system. It is noted that without structural changes in the water use system and improved efficiency of water use at the sectoral level, the sustainability of water security remains limited even in the presence of significant water resources.

The territory of Kazakhstan belongs to a zone of insufficient moisture. The share of irrigated land ranges from 2% to more than 20%, with the largest proportion of irrigated land concentrated in the southern region, where cultivation of agricultural crops without irrigation is impossible.

According to statistical data from the Committee for Land Resources Management of the Ministry of Agriculture of the Republic of Kazakhstan [23], the area of irrigated land in the republic amounts to 2.3 million hectares, of which 1.9 million hectares belong to the category of agricultural land (Figure 3).

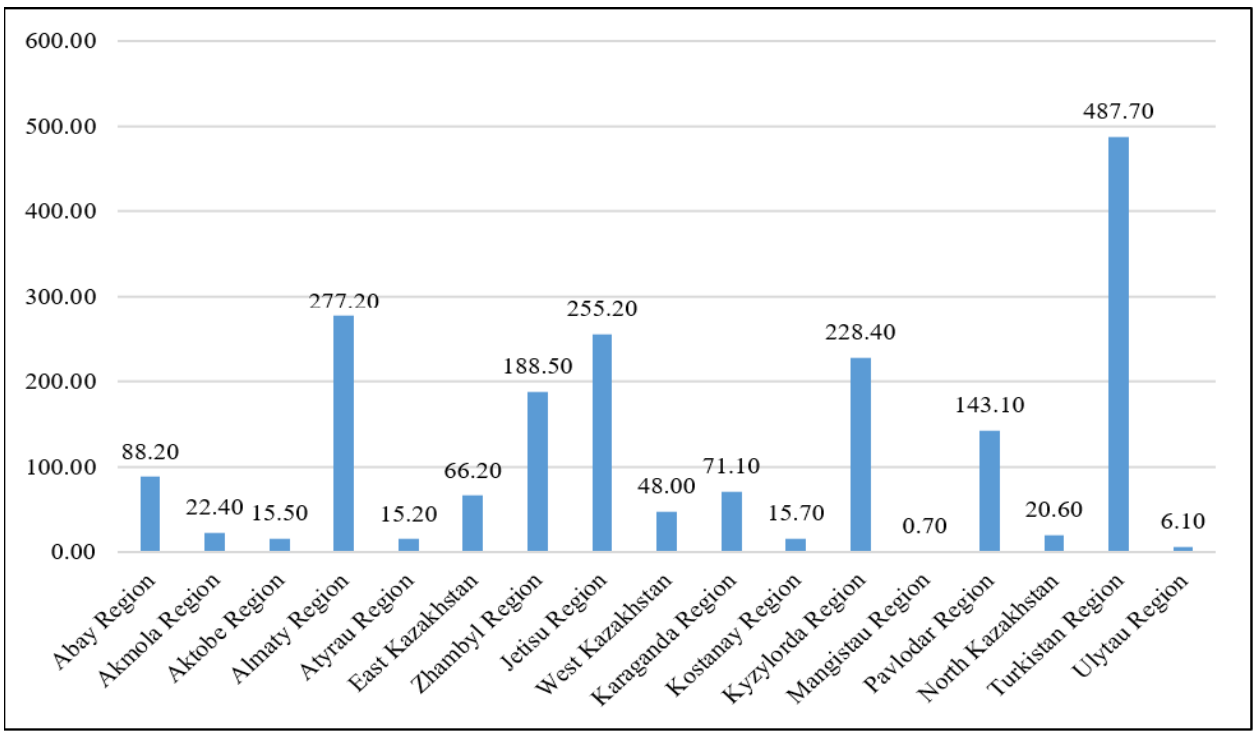

Figure 3. Distribution of irrigated agricultural land in the Republic of Kazakhstan as of 01.01.2024
Note: Compiled by the authors based on data from this study [23]

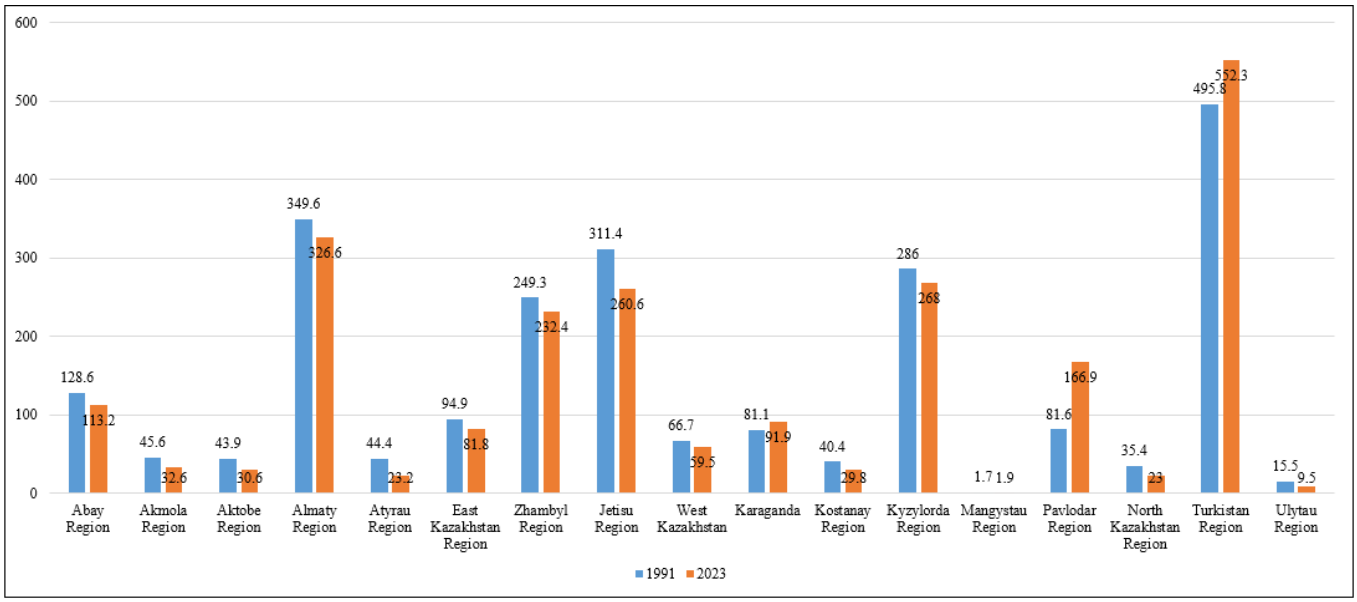

Figure 4. Dynamics of irrigated land area in the Republic of Kazakhstan for 1991–2023
Note: Compiled by the authors based on data from this study [23]

As can be seen from Figure 3, the largest area of irrigated land is concentrated in the Turkistan Region, Almaty Region, and Kyzylorda Region. At the same time, analysis for the period from 1991 to 2023 showed that irrigated land in most cases tended to decline and increased only in Karaganda Region, Pavlodar Region, and Turkistan Region (Figure 4).

As for the total water-covered area in the republic, 7.6 million hectares are occupied by water, which constitutes 2.8% of the territory (Figure 5).

As can be seen from the figure, during the period from 1991 to 2023, the area of land occupied by artificial reservoirs, rivers, and streams increased, while the area occupied by lakes decreased. This is confirmed by the actual situation in recent years, when the republic has experienced water shortages in the agricultural sector. Thus, analysis for 1992–2022 showed that since 1999, per capita water availability in the republic has decreased by 21%.

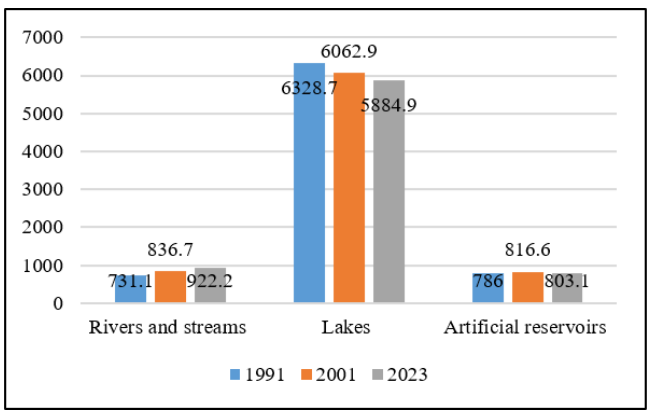

Figure 5. Dynamics of water-covered land areas
Note: Compiled by the authors based on this study [23]

One of the reasons for the reduction in water resource volume is identified as the deterioration of irrigation systems, the cultivation of crops requiring large volumes of water, and the lack of innovative technologies and irrigation systems [24]. Of the total volume of consumed water, the largest share falls on the agricultural sector.

The analysis showed that in the agricultural sector this indicator has a downward trend: in 1994 it amounted to 80%, while in 2021 it was 63%. At the same time, only 50% of the consumed water volume reaches the fields. Therefore, the main objective of the Concept for the Development of the Water Resource Management System of Kazakhstan for 2023–2029 [25] is to reduce water losses from 20% to 15%.

At present, there are a number of problems in the use of water resources by agricultural producers: the absence of water-use metering devices, uneven delivery of irrigation water from the main canal to land plots, and others. Land plots located near the canal receive water in excess, while more distant agricultural users experience difficulties in obtaining irrigation water. The situation is aggravated by the water-use payment system: payment is charged per 1 hectare of irrigated land rather than for the volume of water consumed. A change in the water-use payment system could motivate agricultural producers to install metering devices and apply water-saving technologies in order to reduce water losses.

In 2025, 4.8 billion m³ of water were allocated for irrigation, while the total demand of the agricultural sector is estimated at 12 billion m³, indicating a persistent structural deficit of water resources. Under conditions of climate instability, this gap represents a serious risk to food security.

Water supply processes, accompanied by water withdrawal from natural sources, regulation of river runoff, and territorial redistribution of water resources, are inevitably associated with transformation of the natural hydrological regime of water bodies and adjacent territories. Conceptual studies emphasize that such interventions create complex, often adverse environmental impacts affecting both quantitative and qualitative characteristics of water resources.

In this regard, the water supply problem should be considered not as a task of satisfying sectoral water demands, but as an issue of sustainable functioning of natural-economic systems within functionally integrated basin hydrological cycles.

The key risks of water use and water security include:

- increasing dependence on external water sources;
- intensification of competition between economic sectors;

- increased probability of socio-economic conflicts in water-deficient regions.

These risks are systemic in nature and intensify under the influence of climate change, which requires reconsideration of existing water allocation models.

Analysis of water security under modern conditions goes beyond engineering-technical and sectoral tasks and requires taking into account the interaction of natural, economic, and social factors within integrated basin systems, which corresponds to the conceptual approaches of domestic water resource studies.

Thus, the functioning of the water supply system is complicated by a number of structural problems, among which the key ones are:

- high deterioration of irrigation canals;
- significant water losses during transportation;
- limited implementation of water-saving technologies;
- absence of water consumption metering devices;
- inefficient payment system for the use of water resources.

Considering water security within the logic of functioning of natural-economic systems makes it possible to move from analyzing structural and institutional constraints to assessing their socio-economic and environmental consequences manifested at the level of regions and individual water basins.

3.3 Socio-economic and environmental aspects of water use

Water resources exert both direct and indirect influence on the socio-economic development of Kazakhstan, forming the basic conditions for the functioning of the agricultural sector, industry, and the population settlement system. Water availability determines the level of food security, rural employment, and the sustainability of regional economies, especially under conditions of arid climate and high territorial differentiation of water resources. Water scarcity or instability of water supply reduces the sustainability of agricultural production, limits economic activity, and intensifies socio-economic differentiation of regions, primarily in the southern and southeastern parts of the country [2].

The environmental aspects of water use are associated with the impact of economic activity on the condition of aquatic ecosystems and natural landscapes. Intensive water use without considering environmental constraints leads to ecosystem degradation, reduced environmental flow, deterioration of water quality, and disruption of natural biogeochemical processes [16]. Under the conditions of Kazakhstan, these problems are aggravated by the arid climate and the high sensitivity of aquatic ecosystems to anthropogenic pressure.

Particularly high environmental vulnerability is demonstrated by major water bodies of significant regional and transboundary importance, including the Caspian Sea and Lake Balkhash. Reduction of water inflow, deterioration of water quality, and changes in the hydrological regime have a negative impact on biodiversity, fisheries, and ecosystem services, which in the long term creates additional socio-economic risks [3]. In this regard, the environmental component of water use acquires strategic significance and should be considered an integral element of water policy.

The connection between water use and sustainable development goals is manifested in the need to coordinate economic interests with environmental constraints and social priorities. Water policy oriented toward sustainable development should ensure a balance between the needs of economic development, preservation of aquatic ecosystems, and adaptation to climate change. Thus, the socio-economic and environmental aspects of water use form a unified framework of problems and challenges requiring a comprehensive and interdisciplinary approach.

The socio-economic consequences of water resource scarcity are manifested in reduced crop yields, increased production costs, reduced employment in agriculture, and intensified migration processes from water-deficient territories. Under climate change conditions, these processes may acquire a cumulative character, since increasing climate risks intensify uncertainty in economic activity and reduce the adaptive potential of rural communities. Thus, water resources act not only as a factor of economic development but also as an element of social stability and territorial balance.

3.4 Institutional and managerial aspects

Institutional and managerial aspects play a key role in forming a sustainable system of water use and water security in Kazakhstan. The establishment of the Ministry of Water Resources and Irrigation of the Republic of Kazakhstan and the transition to the basin-based management principle reflect an effort to modernize the water resource management system and align it with international approaches to integrated water resources management. These institutional changes create the basis for more coordinated and systematic regulation of water use, taking into account natural and socio-economic factors.

Domestic conceptual studies substantiate that effective water resource management should be based on understanding water security as a process of functioning of natural-economic systems that include elements of the natural environment, population, and economic activity. The complexity of such systems is determined by the presence of direct, feedback, and transformed links between natural and socio-economic components, which makes the basin approach a methodologically justified management instrument.

The basin-based management principle makes it possible to consider water resources within the boundaries of natural hydrological systems, which contributes to more accurate consideration of the spatial differentiation of water resources and the interests of different water users. Under climate change conditions, this approach acquires special importance because climatic impacts manifest unevenly across territories and require adaptive managerial decisions. Ignoring climate scenarios in strategic planning significantly limits the possibilities for forming a long-term sustainable water security system.

Within the basin approach, a limited number of key natural-economic systems are distinguished within the territory of Kazakhstan, each characterized by specific hydrological, environmental, and water management conditions. These systems include the basins of the Syr Darya, Ili-Balkhash Basin, Irtysh River, Ishim River, Ural-Caspian Basin, Nura-Sarysu Basin, Tobol-Torgai Basin, and Chu-Talas Basin. These basins differ in degree of transboundary character, runoff type, environmental status, and dominant water management specialization, which determines the need for differentiated managerial decisions.

Practice shows that water security problems within these basins have a distinctly individual character, which excludes universal management solutions and requires the development of adapted planning and monitoring instruments.

Domestic conceptual works emphasize that fragmentation of water resource management and the predominance of a sectoral approach have long been key factors of inefficient water use. The need is substantiated for transitioning to an integrated management system based on forecasting, intersectoral coordination, and consideration of natural limitations of water potential. These provisions conceptually coincide with modern international approaches to adaptive water resource management.

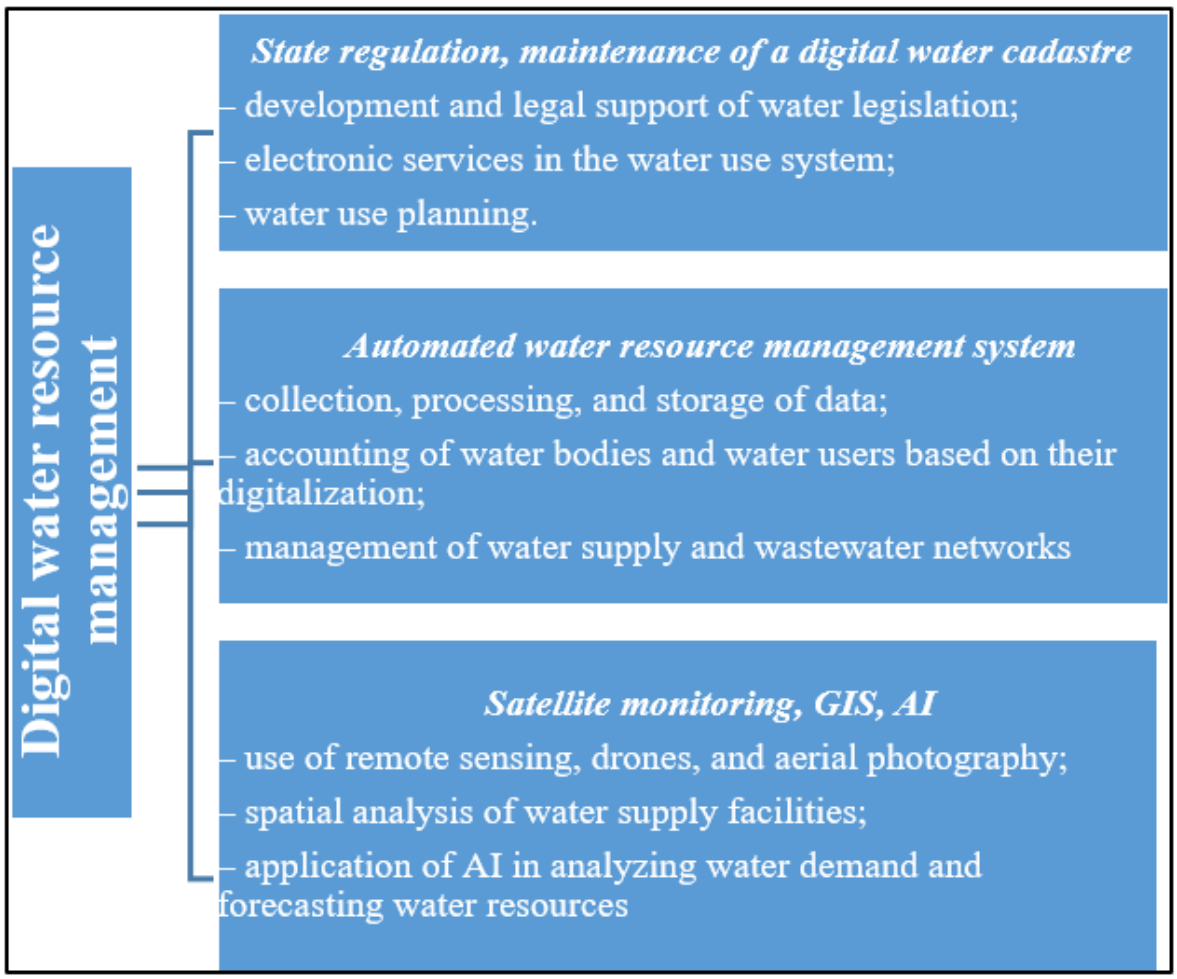

Figure 6. Digital water resource management model
Note: Compiled by the authors

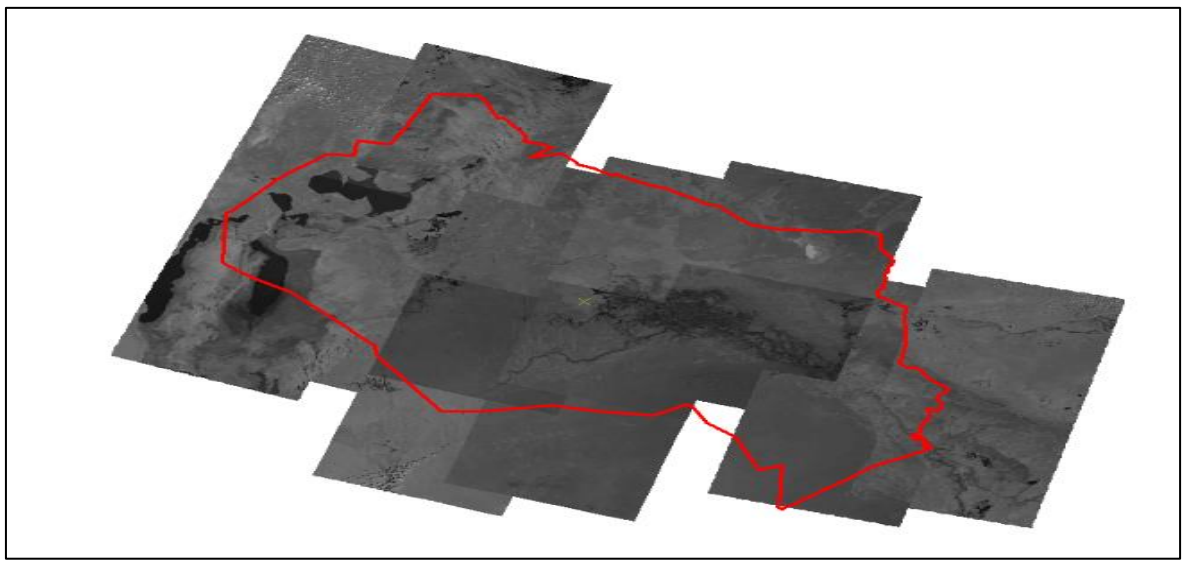

Figure 7. Scheme of Syrdarya District, Kyzylorda Region
Note: Compiled by the authors based on satellite imagery from Landsat 8/9

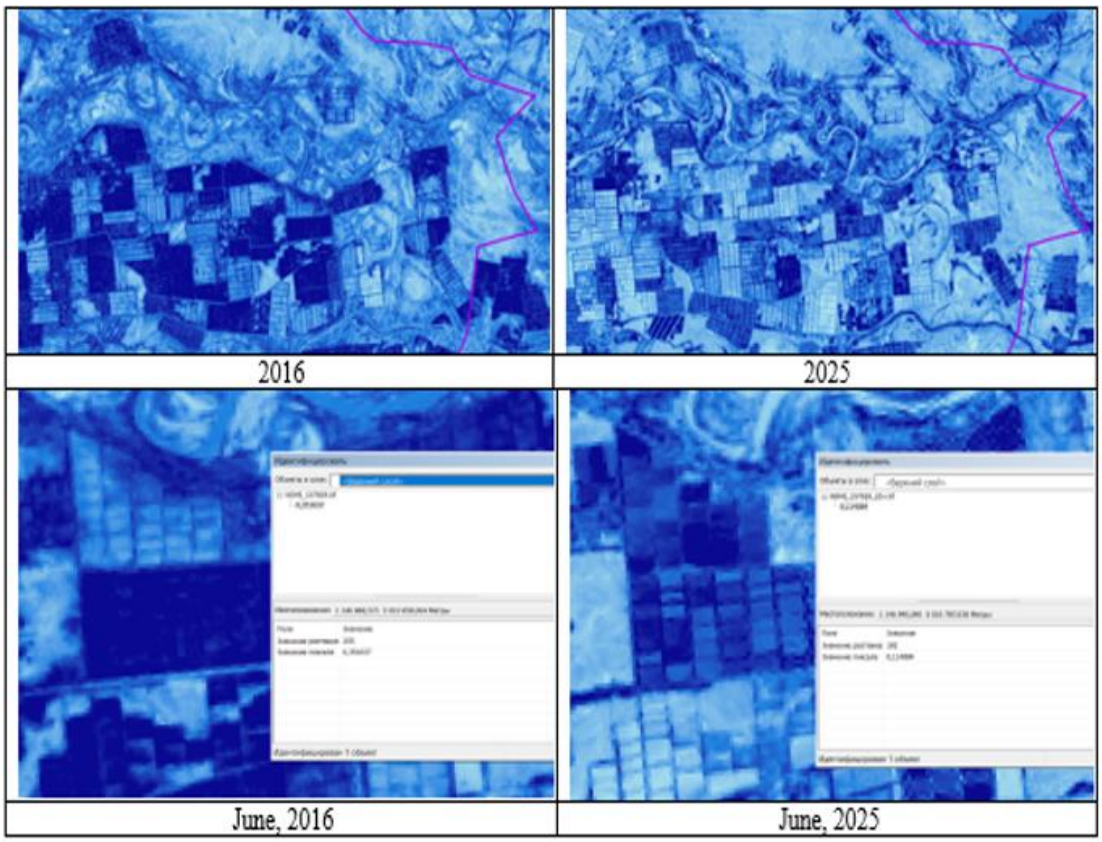

Figure 8. Satellite images of the territory of Kyzylorda Region
Note: Compiled by the authors

An important direction for improving water resource management is the development of strategic planning and monitoring instruments. Integration of the climate factor into strategic documents and water development programs makes it possible to improve the validity of managerial decisions and reduce risks associated with climate uncertainty. At the same time, special importance is attached to moving from reactive response measures to proactive and adaptive management.

One such direction is the digitalization of water resource management, including satellite monitoring, implementation of geographic information systems, installation of soil moisture sensors, introduction of automatic water distribution systems, and others. The model of digital water resource management is presented in Figure 6.

The basis for maintaining a digital cadastre is the creation of an information database on water bodies, water users, and water supply systems. This is achievable through satellite monitoring. Space monitoring is carried out on the basis of satellite imagery and makes it possible to create a database using information obtained through remote sensing from Landsat multispectral imagery (Level-2 Surface Reflectance) with a spatial resolution of 30 m for June 2016 and June 2025, which are used to analyze the condition of agricultural land, determine water levels in reservoirs, and assess territorial moisture availability. The object of study is Syrdarya District in Kyzylorda Region (Figure 7).

To determine soil moisture, satellite images of areas in Kyzylorda Region were obtained from Landsat 7 and 8/9 for the period from 2016 to 2025 (Figure 8).

For this purpose, the Normalized Difference Moisture Index (NDMI) index characterizing soil moisture and vegetation condition is calculated using Eq. (1):

$$NDMI = \frac{NIR - SWIR}{NIR + SWIR} \quad (1)$$

where,

NIR - reflection in the near-infrared range;

SWIR - reflection in the short-wave infrared range.

Table 3. Normalized Difference Moisture Index (NDMI) index values

Index Values	Description	Color on the Scheme
-1 – -0.8	Absence of moisture and vegetation cover	Dark brown
-0.8 – -0.6	Absence of moisture and sparse vegetation cover	Brown
-0.6 – 0.4	Drought and very low vegetation density	Light brown
-0.4 – -0.2	Drought and insignificant vegetation cover	Yellow
-0.2 – 0	High level of moisture deficit and insignificant vegetation cover	Light yellow/white
0 – 0.2	Moderate level of moisture deficit and medium vegetation density	Light blue
0.2 – 0.4	Insufficient moisture and above-average vegetation density	Blue
0.4 – 0.6	Sufficient moisture and high vegetation density	Dark blue
0.6 – 0.8	Optimal moisture and very high vegetation density	Deep blue
0.8 – 1	Excessive moisture and territory fully covered with dense vegetation	Purple

Note: Compiled based on this study [26]

Further, based on the classification of NDMI index values, the degree of moisture of the studied territory is determined (Table 3).

According to this classification, early June 2016 was characterized by insufficient moisture, while the same period in 2025 showed a moderate level of moisture deficit [27]. Thus, by applying remote sensing methods, it is possible to monitor territorial moisture levels and make operational decisions in water resource management.

As can be seen from Figure 8, in 2016 the average NDMI index value was 0.35, while in 2025 it was 0.11. The NDMI index varies within the range from –1 to +1. If the index is closer to –1, this indicates a moisture deficit; conversely, if the index value is closer to +1, it indicates waterlogging.

Thus, in order to form a sustainable system of water use and water supply, a transition to a digital management model is proposed through the use of information technologies, satellite monitoring, and artificial intelligence. This approach will make it possible to address the key tasks of monitoring, efficiency, and forecasting of water resource use in Kazakhstan.

3.5 Criteria for sustainable and efficient water use: National and international context

Under climate change conditions, sustainable and efficient water use is considered not only a technological or economic task, but a multi-level system of criteria reflecting the balance between resource capacities, socio-economic needs, and environmental constraints. In international practice, sustainable water use is interpreted as the ability of a water management system to ensure long-term satisfaction of societal needs without undermining the ecological sustainability of aquatic ecosystems and the adaptive potential of future generations.

For Kazakhstan, the relevance of developing and applying such criteria is determined by the combination of arid natural conditions, high water intensity of the economy, and significant dependence on transboundary water resources. In this regard, criteria for sustainable water use must take into account both national specificity and international approaches used in countries with similar climatic and water management conditions.

International practice demonstrates that countries with limited water resources and arid climate focus on integrated water-efficiency criteria combining economic, environmental, and managerial indicators. In particular, in EU countries the key reference point is the concept of Integrated Water Resources Management, which implies consideration of climate risks, ecosystem constraints, and intersectoral interaction.

In states with high dependence on transboundary water resources (countries of Central Asia and the Middle East), special attention is paid to:

- sustainability of water security under climate uncertainty;
- reduction of agricultural water intensity;
- development of interstate coordination mechanisms [9].

For Central Asia, including Kazakhstan, international studies emphasize the need to transition from extensive water use to adaptive and water-saving models based on scenario analysis and long-term planning [20, 21].

The comparative analysis shows that Kazakhstan generally follows global trends in water policy development; however, a number of structural constraints remain:

- high share of water-intensive agriculture;
- insufficient integration of climate scenarios into water management planning;
- limited implementation of the ecosystem approach.

At the same time, institutional reforms aimed at developing basin management and strengthening monitoring create prerequisites for bringing the national system of water-use criteria closer to international sustainability standards.

Integration of criteria for sustainable and efficient water use into the water resource management system makes it possible to:

- improve the sustainability of water security;
- reduce climatic and socio-economic risks;
- ensure alignment of water policy with sustainable development goals.

Under the conditions of Kazakhstan, these criteria may be considered a strategic assessment tool ensuring the transition from reactive measures to proactive water resource management under climate change conditions.

4. CONCLUSIONS

The generalization of the research results allows the conclusion that under climate change conditions, the water resources of Kazakhstan constitute one of the key limiting factors of sustainable socio-economic and territorial development. Unlike regions with a relatively stable water balance, Kazakhstan is characterized by a combination of arid natural-climatic conditions, high interannual runoff variability, and significant dependence on transboundary water resources, which increases the vulnerability of the national water security system.

Comparative analysis with international cases shows that the water use and water security problems identified in Kazakhstan largely correspond to global trends characteristic of countries with limited water resources and highwater intensity of the economy. As in a number of states in Central Asia, the Middle East, and North Africa, the dominant role of agriculture in the water consumption structure increases pressure on water resources and heightens the sensitivity of the economy to climate change. At the same time, a specific feature of Kazakhstan is the combination of internal water scarcity with high dependence on external runoff, which intensifies institutional and geopolitical water security risks.

The results of the study show that climate change acts not as an isolated factor, but as a catalyst for already existing structural imbalances in the water use system. In the long term, climate change intensifies spatial differentiation of water resources, aggravates contradictions between economic sectors, and increases the significance of environmental constraints. Similar processes have been recorded in international practice, where the transition to adaptive and integrated water resource management models is regarded as the key response to climate challenges.

Comparison of institutional and managerial aspects shows that the reforms implemented in Kazakhstan generally correspond to international approaches to Integrated Water Resources Management, including the basin principle and the development of monitoring systems. However, compared with leading international cases, insufficient integration of climate scenarios into strategic planning, limited application of the

ecosystem approach, and weak linkage between water policy and socio-economic adaptation mechanisms remain.

The key result of the study is the substantiation of the need to transition from a predominantly reactive water resource management model to a proactive and adaptive system based on the criteria of sustainable and efficient water use. International experience shows that it is precisely the combination of resource, economic, environmental, social, and institutional criteria that makes it possible to ensure long-term water security under climate uncertainty. For Kazakhstan, the application of these criteria acquires special importance due to natural-climatic specificity and the transboundary nature of water resources.

Comparison of the obtained results with conceptual provisions formed within the national scientific school indicates the continuity of the key problems of water resources and water use in Kazakhstan. Limited water potential, spatial asymmetry of resources, and high water intensity of the economy were identified as systemic challenges already at early stages of research. Under modern conditions, these problems have not lost relevance but are intensified under the influence of climate change, which requires a transition from a predominantly resource-oriented approach to a predictive and adaptive model of water resource management.

Overall, the research results confirm that further alignment of the national water policy of Kazakhstan with international standards of sustainable water resource management, while simultaneously taking national characteristics into account, is a key condition for improving water security, reducing climate risks, and achieving sustainable development goals.

Comparison of the obtained results with provisions formulated within national conceptual studies of water resources demonstrates a pronounced continuity of the key problems of water security in Kazakhstan. Limited water potential, spatial asymmetry of resources, high anthropogenic pressure, and vulnerability of river runoff were identified as systemic challenges already at early stages of research. Under modern conditions, these problems remain relevant but are intensified under the influence of climate change, which objectively requires a transition to a predictive and adaptive model of water resource management.

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