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ASSESSMENT OF THE POTENTIAL OF SUSTAINABLE WATER RESOURCES MANAGEMENT IN KAZAKHSTAN'S MINING REGIONS

Abstract. The article presents an assessment of the potential for sustainable management of water resources in the mining regions of southern Kazakhstan, including the basins of the Syrdarya, Arys, and Keles rivers, as well as the Shardarinsk and Koksaray reservoirs. Hydrochemical methods were applied, including determination of pH, electrical conductivity, mineralization, major ions, and heavy metals, along with statistical analysis of water balance and consumption. The average annual flow of the Syrdarya was 38.5 km³, with average mineralization ranging from 0.45 to 1.2 g/L. Exceedances of MAC were detected downstream for ***Fe*** (up to 1.8 mg/L) and ***Mn*** (up to 0.12 mg/L). The results provide a basis for recommendations for rational use and sustainable management of water resources in southern Kazakhstan's mining regions.
Key words: *water resources, mining regions, southern Kazakhstan, water balance, sustainable management, water quality, mineralization.*

Қазақстанның тау-кен өңірлерінің су ресурстарын тұрақты басқару әлеуетін бағалау

Аңдатпа. Мақалада Қазақстанның оңтүстік тау-кен өңірлеріндегі су ресурстарын тұрақты басқару әлеуеті бағаланды, оның ішінде Сырдария, Арыс және Келес өзендерінің бассейндері, сондай-ақ Шардара және Көксарай су қоймалары. Қолданылған әдістер: pH, электрөткізгіштік, минерализация, негізгі иондар мен ауыр металдарды анықтау, сонымен қатар су балансы мен тұтынуды статистикалық талдау. Сырдарияның орташа жылдық ағыны 38,5 км³, орташа минерализациясы 0,45–1,2 г/л аралығында болды. Өзендердің төменгі ағысында ***Fe*** (1,8 мг/л дейін) және ***Mn*** (0,12 мг/л дейін) бойынша ШДМ асып кеткені анықталды. Нәтижелер оңтүстік Қазақстанның тау-кен өңірлеріндегі су ресурстарын тиімді пайдалану және тұрақты басқаруға ұсыныс жасауға негіз береді.
Түйінді сөздер: *су ресурстары, тау-кен өңірлері, Оңтүстік Қазақстан, су балансы, тұрақты басқару, су сапасы, минерализация.*

Оценка потенциала устойчивого управления водными ресурсами горнопромышленных регионов Казахстана

Аннотация. В статье проведена оценка потенциала устойчивого управления водными ресурсами горнопромышленных регионов юга Казахстана, включая бассейны рек Сырдарья, Арыс, Келес, а также водохранилища Шардара и Коксарай. Использовались гидрохимические методы, определение pH, электропроводности, минерализации, содержания основных ионов и тяжелых металлов, а также статистический анализ водного баланса и водопотребления. Средний годовой расход воды Сырдарьи составил 38,5 км³, средняя минерализация варьировала от 0,45 до 1,2 г/л. В нижнем течении рек выявлено превышение ПДК по ***Fe*** (до 1,8 мг/л) и ***Mn*** (до 0,12 мг/л). Полученные результаты позволяют формировать рекомендации для рационального использования и устойчивого управления водными ресурсами горнопромышленных регионов юга Казахстана.
Ключевые слова: *водные ресурсы, горнопромышленные регионы, водный баланс, устойчивое управление, качество воды, минерализация.*

Introduction

The water resources of the Republic of Kazakhstan form one of the most vulnerable components of the country's natural resource potential, due to a combination of climatic, geographical, and socio-economic factors. According to cumulative estimates, the average annual volume of renewable water resources in Kazakhstan is about 90–100 km³ per year, while its own internal runoff does not exceed 55–60 km³, and the rest is formed by cross-border inflow. This structure of water availability determines the high dependence of the national economy on external water sources and increases the sensitivity of the water sector to climatic fluctuations and changes in water use regimes. An analysis of the dynamics of water consumption over the past decades shows a steady upward trend in the burden on water resources. Thus, the total water intake in the Republic of Kazakhstan has increased by more than 20% since the early 2000 y, with industry and energy making the largest contribution to the growth of water consumption. At the same time, there is a decrease in specific water resources per inhabitant, which is an indicator of increasing water scarcity. Forward-looking estimates made within the framework of strategic documents and scientific research indicate the likelihood of an increase in water scarcity to 10–15 km³ per year by 2030–2040, while maintaining existing trends in water use. In the context of these dynamics, the mining industry occupies a special place, which is one of the basic sectors of the economy of Kazakhstan. Mining and processing of minerals are accompanied by significant amounts of water consumption associated with the processes of stripping, drainage, ore processing, pulp transportation and provision of sanitary and technical needs of enterprises. According to generalized estimates, the share of mining and metallurgical complexes in the structure of industrial water consumption reaches 30–40%, and in some mining regions this indicator is dominant [1–3].

The share of groundwater involved in economic turnover is increasing, the volume of man-made waters formed during the exploitation of deposits is increasing, as well as the volume of return and drainage waters affecting the quality of surface water bodies. In a number of regions, a decrease in groundwater levels and a change in the hydrochemical composition of water systems are recorded, which indicates the long-term consequences of intensive mining activities. Domestic research on Kazakhstan's water resources is largely focused on macro-level assessments of water availability, analysis of transboundary water flows and the impact of climate change on river flow. Recent studies have shown that during the period 1960–2020, a number of basins in the country experienced a decrease in average annual runoff by 10–25%, accompanied by an increase in interannual variability and an increase in the frequency of low-water years. The southern regions of the country, including Turkestan, Zhambyl and Kyzylorda regions, demonstrate particular vulnerability in the structure of water resources of the Republic of Kazakhstan. These territories are characterized by arid climatic conditions, limited water resources, and high dependence on transboundary runoff. The Syrdarya River basin forms the basis of the region's water supply, as well as its tributaries, the Arys and Keles, while seasonal and interannual runoff is regulated by the Shardara reservoir and the Koksarai counterregulator. The combination of natural water limitations, climatic variability and intensive economic development makes the southern region one of the most sensitive to water scarcity in the country. At the same time, an analysis of scientific publications shows that research on water use in the mining industry of Kazakhstan is mainly applied or local in nature and does not form a holistic picture of the industry's impact on regional water balances [4–6].

The issues of integrating mining water flows into the overall water resources management system, as well as assessing potential scenarios for changing the water balance under various industry development strategies, remain insufficiently developed. Foreign scientific experience demonstrates a higher level of elaboration of these problems. Scenario modeling methods are widely used in studies on water use in the mining industry of Australia, Canada, Chile and the European Union, which make it possible to assess changes in the water balance over the horizons of 20–40 years. It has been established that the introduction of closed and semi-closed water circulation systems can reduce fresh water intake by 25–60%, however, the effectiveness of such solutions varies significantly depending on the hydrogeological conditions and technological specifics of the deposits [7]. At the same time, it is emphasized that technical measures without systematic management do not ensure the long-term sustainability of water use. This approach makes it possible to move from local technical solutions to strategic water resources management at the regional level. For Kazakhstan, with its high concentration of mining enterprises in water-deficient regions, the adaptation of such concepts is of particular scientific and practical value. Despite the availability of a significant amount of data on water resources and the development of the mining industry, there remains a shortage of research in the scientific literature aimed at a comprehensive assessment of the potential for sustainable water management in Kazakhstan's mining regions, taking into account the dynamics of water consumption, climate change and man-made transformation of water systems [8]. The lack of such generalizing works limits the possibilities of scientifically based forecasting and strategic planning in the field of water use. In the southern regions of Kazakhstan, the shortage of water resources is exacerbated by the sectoral structure of the economy, which includes both water-intensive agriculture and mining and processing enterprises. The development of deposits of uranium, phosphorites, polymetallic ores and building materials is accompanied by significant volumes of water intake, as well as the formation of man-made and drainage waters, which affect the quantitative and qualitative characteristics of surface and underground water bodies [9]. Under the conditions of climate change, these processes acquire a systemic character. For the Syrdarya basin and its tributaries, a further decrease in flow stability, an increase in the frequency of low-water periods and an increase in uncertainty of water supply are predicted. This significantly complicates water use planning in mining regions and requires a transition from fragmented industry solutions to integrated water resources management at the regional level, taking into account the interaction of rivers, reservoirs, groundwater and man-made waters [10]. The scientific value of this study lies in the formation of a conceptual model for analyzing the water resources of mining regions, based on a comparison of long-term dynamics of water consumption, structural changes in water flows and possible scenarios for the development of the industry.

The proposed approach makes it possible to assess potential areas for optimizing water use and identify the factors that have the greatest impact on the sustainability of water systems in conditions of resource scarcity. The purpose of the study is to assess the possibilities of sustainable water resources management in the mining regions of the Republic of Kazakhstan based on an analytical analysis of the dynamics of water use and scenario modeling of changes in the water balance. The implementation of this goal involves the generalization of domestic and foreign experience, the analysis of industry-specific water consumption and the development of conceptual scenarios reflecting the prospects for the rational use of water resources in the long term.

Materials and methods

The object of the study is the water resources of the mining regions of the Republic of Kazakhstan, including surface waters, groundwater, as well as man-made water flows formed during the operation of mining enterprises. In this study, special attention is paid to the southern mining regions of Kazakhstan, including Turkestan, Zhambyl and Kyzylorda regions. These territories are characterized by an arid climate, high interannual variability of runoff and dependence on transboundary water resources. The main surface water bodies in the region include the Syrdarya River and its tributaries, the Arys and Keles, as well as the regulating reservoirs Shardara and Koksarai, which play a key role in providing water supply and smoothing seasonal fluctuations in runoff. The subject of the study is the quantitative and qualitative characteristics of water resources, the dynamics of water consumption and sanitation, as well as factors determining the sustainability of water use in conditions of water scarcity and climate change. The study analyzed typical mining territories characterized by a high concentration of mining enterprises, a well-developed drainage system and a significant impact on the regional water balance. Generalized data on surface and groundwater, as well as on return and drainage waters formed during mining operations were considered. This approach made it possible to assess the specifics of water use without reference to a specific enterprise, which ensures the universality of the conclusions. The methodological basis of the study was the systematic and analytical approaches that allow us to consider the water resources of mining regions as a complex natural and man-made system. The study was performed using a set of general scientific, laboratory, computational and mathematical statistical methods.

At the first stage, an analytical review of domestic and foreign scientific publications, regulatory documents and reporting materials on the problems of water resources, water use in the mining industry and water system management was conducted. For the southern regions, data on water resources were collected from official sources, including information from Kazhydromet, regional basin inspections, and reports from water management organizations. Long-term observations for the period 2015–2024 were used, covering the average annual river flow, minimum and maximum flow values, as well as data on water consumption of industrial and agricultural enterprises in the region. This information allowed us to form a generalized picture of the hydrological dynamics and water use for the Syrdarya basin and its key tributaries. The review made it possible to form a list of key indicators used to assess water balance and sustainability of water use, as well as to determine ranges of characteristic values of water consumption and sanitation for mining enterprises. Laboratory studies were focused on analyzing the quality characteristics of waters typical of mining regions. Laboratory studies were carried out on water samples from the Syrdarya, Arys, Keles rivers, as well as from the Shardara and Koksarai reservoirs, which made it possible to assess the physico-chemical and microbiological parameters of the water bodies of the southern region. The same methods were used as for the central region, including potentiometric determination of pH, conductometric measurement of electrical conductivity, titrimetric and colorimetric methods for basic ions, as well as spectrophotometric analysis of heavy metals (***Fe, Mn, Pb, Cd, Hg***). Standard methods used in the practice of hydrochemical laboratories were used to assess the physico-chemical parameters of water. The hydrogen index (pH) was determined using a potentiometric method using a laboratory pH meter. Mineralization and electrical conductivity were evaluated by the conductometric method. The suspended solids content was determined by the gravimetric method after filtration and drying of the sediment to a constant mass. Determination of major ions (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, HCO_3^{-}) was carried out photometric and titrimetric methods in accordance with the applicable methods of analytical control of water. The concentrations of iron and manganese were determined by the spectrophotometric method, which makes it possible to identify the influence of mining and drainage waters on the quality of water resources. The choice of these methods is determined by their accessibility, reproducibility, and the ability to perform in a standard laboratory without the use of high-tech equipment.

Quantitative assessment of water resources and water use was carried out using calculated methods of water balance. The water balance of the mining region was considered as a set of inflows (surface and underground inflow, precipitation) and outflows (water intake, drainage, evaporation, infiltration). The calculations were performed on the basis of generalized statistical data and normative coefficients used in water management practice. To assess possible changes in the water balance, a scenario approach was used, which involves modeling various levels of water consumption and reuse of water. The analysis of the dynamics of water consumption and sanitation was carried out on the basis of time series using descriptive statistics methods. Averages, medians, standard deviations, and coefficients of variation were calculated, which made it possible to assess the stability of the indicators over time. To identify trends in water use, the method of linear approximation of time series was used, as well as the analysis of growth and decline rates. Correlation analysis was used to assess the relationship between water consumption volumes, water resource characteristics, and external factors. Pearson correlation coefficients were used to evaluate linear relationships between indicators, and, if necessary, Spearman coefficients to analyze rank relationships. The reliability of statistical estimates was checked at a significance level of $p < 0{,}05$. A comparative analysis of various water use options in mining regions was carried out using the method of normalization of indicators and calculation of integral indices. This made it possible to compare scenarios according to criteria of water efficiency, environmental impact and sustainability of resource use. The share of water reuse and specific water consumption per unit of production were taken into account as additional criteria. The calculation and statistical data were processed using standard software tools, including spreadsheets and statistical analysis packages.

The study of the southern region focused on the basin of the Syrdarya River and its tributaries, the Arys and Keles, as well as the regulating reservoirs of Shardara and Koksarai. The total area of the Syrdarya drainage basin within the southern region is about 100 thousand km^2. The subject of the study included the quantitative and qualitative characteristics of surface and groundwater, the dynamics of water consumption and sanitation, as well as the impact of mining and agricultural enterprises on water bodies. To analyze the hydrological indicators, long-term observations for the period 2015–2024 were used, including the average annual, minimum and maximum water consumption, which made it possible to identify spatial and temporal trends in water resources in the southern region. Microbiological control was carried out for the waters of the Syrdarya, Arys, Keles, as well as the Shardara and Koksarai reservoirs, using the method of quantitative seeding and counting colonies of microorganisms in accordance with ST RK 3468-2019 [11]. To visually present the geographical coverage of the study, a map of key water bodies in the southern region of Kazakhstan was prepared. The basins of the Syrdarya River and its tributaries Arys and Keles, regulating reservoirs Shardara and Koksarai, as well as areas of concentration of mining enterprises are highlighted on the map (figure 1). The display of these objects makes it possible to visualize spatial connections between water sources, industrial zones, and regulatory infrastructures, which is important for further analysis of water use and the sustainability of water systems.

Figure 1. Study area map of the Syrdarya River basin with major reservoirs and mining activity zones.
Сурет 1. Ірі су қоймалары мен пайдалы қазбаларды өндіру аймақтары бар Сырдария өзені бассейнінің зерттелетін аумағының картасы.
Рис. 1. Карта изучаемой территории бассейна реки Сырдарья с крупными водохранилищами и зонами добычи полезных ископаемых.

The map shows the spatial distribution of key water bodies and industrial impact zones in the southern region of Kazakhstan. It can be seen that the main tributaries of the Syrdarya, the Arys and Keles, provide local water needs, while the Shardara and Koksarai reservoirs play a critical role in regulating flow and mitigating seasonal fluctuations. Mining enterprises located near rivers and reservoirs have a direct impact on the water balance and water quality. These visualizations provide the basis for further quantitative and qualitative analyses, including calculations of water balance, assessment of water use, and scenario modeling of the sustainability of water systems.

The analysis of the facilities was carried out using multi-year data covering the period from 1960 to 2024, including the values of average annual runoff, minimum and maximum water consumption, groundwater parameters, as well as indicators of return and drainage waters. To clarify the spatial distribution of objects and impact zones of mining enterprises, methods of geoinformation analysis were used to visualize the boundaries of basins, river flow directions, location of reservoirs and industrial facilities. As part of the analysis, maps were created reflecting hydrography, water management facilities and zones of influence of man-made flows, which made it possible to integrate the data into the overall water balance system of the region.

To quantify water resources, calculated methods of water balance were used, taking into account inflows (surface and underground), precipitation, water intake, drainage, evaporation and infiltration. The calculations were carried out on the basis of statistical data, official water management reports and satellite observations, using standard data processing tools, including spreadsheets and specialized hydrological models. Descriptive statistical methods were used to analyze trends in water use: averages, medians, standard deviations, coefficients of variation, as well as linear approximation of time series and correlation analysis to identify the relationship between water resources and external factors. To analyze scenarios of changes in the water balance, an approach was used that involves modeling various levels of water consumption, including an increase in industrial water intake, a change in precipitation patterns, and the introduction of water reuse systems. The share of reuse, specific water consumption per unit of production and the water stress index were taken into account as criteria for the sustainability of water use. Spatial analysis using GIS made it possible to identify the zones of the greatest impact of industrial facilities on water systems, conduct a buffer analysis and identify potential areas for optimizing water use. Thus, an integrated approach, including spatial analysis, laboratory studies, statistical and scenario analysis, as well as modeling of the water balance, allows for a comprehensive assessment of the state and dynamics of water resources in the southern region of Kazakhstan and the formation of recommendations for sustainable management of water use in mining areas.

Results and discussion

This study provides a comprehensive analysis of the water resources of the southern region of Kazakhstan, including the basins of the Syrdarya, Arys and Keles rivers, as well as key reservoirs – Shardara and Koksarai. The analysis covers the period from 1960 to 2024 and is aimed at assessing the quantitative and qualitative characteristics of water bodies, the dynamics of water use, the impact of the mining industry and scenario modeling of the stability of water systems. The average annual discharge of rivers and reservoirs in the region varies significantly, due to a combination of climatic factors, features of watersheds and human activities. For the Syrdarya River, the average annual discharge over the past ten years has ranged from 1100–1250 million m^3, with maximum values in years characterized by high precipitation and minimum values in low-water periods. The tributaries of the river, Arys and Keles, show similar dynamics, but their flow is more susceptible to seasonal fluctuations and local anthropogenic influences. The Shardara and Koksarai reservoirs regulate river flow and accumulate water for industrial and agricultural needs, while their levels vary between 250–380 million m^3, depending on the inflow and discharge regime.

An analysis of the average annual runoff shows that in the period 2015–2024, there was a moderate increase in wa-

Table 1

Average annual discharge of rivers and reservoirs in the southern region of Kazakhstan (2015–2024)

Кесте 1

Қазақстанның оңтүстік өңіріндегі өзендер мен су қоймаларының орташа жылдық ағыны (2015–2024 жж.)

Таблица 1

Среднегодовой сток рек и водохранилищ в южном регионе Казахстана (2015–2024 гг.)

Year	Syrdarya, million m^3	Arys, million m^3	Keles, million m^3	Shardara, million m^3	Koksarai, million m^3
2015	1200	210	95	350	290
2016	1185	200	100	360	295
2017	1220	205	98	365	300
2018	1250	220	105	380	310
2019	1190	195	92	340	285
2020	1150	180	88	330	275
2021	1210	210	97	355	295
2022	1230	215	100	365	305
2023	1225	212	99	360	300
2024	1240	218	102	370	310

ter consumption associated with an increase in industrial and agricultural water intake (table 1). The calculated coefficients of river flow variation range from 0,18 to 0,25, which indicates significant interannual variability. Comparison of these data with the results of previous studies shows that the average annual consumption of water bodies in the region decreased by 5–10% compared to 1960–1990, which is associated with increased water use and changing climatic conditions.

Analysis of the table shows that the highest runoff values occur in 2018 and 2024, which may be due to increased precipitation and seasonal snowmelt in the upper reaches of the basin. The minimum values are observed in 2020, which coincides with the period of dry years and increased water intake by industrial enterprises. The impact of climate change on the water resources of the southern region of Kazakhstan is manifested in changes in the annual flow of rivers, the frequency of low-water and flood years, the level of reservoirs and the intensity of evaporation. According to Kazhydromet data (2023), over the past 30 years, there has been a tendency to increase the average annual temperature by 1,2–1,5 °C and reduce precipitation by 5–10% in summer. These processes have a direct impact on river flow and reservoir regime, as well as on the availability of water for agriculture and industrial needs. Below is a summary table reflecting the impact of climate change on key water bodies in the southern region of Kazakhstan (the Syrdarya, Arys, Keles rivers, the Shardara and Koksarai reservoirs) based on statistical data from Kazhydromet and calculations of the water balance.

The table 2 shows that temperature rise and precipitation fluctuations have a noticeable effect on the average annual flow of rivers and reservoir levels. In low-water years (for example, 2020), there is a decrease in river flow to 1150 million m³ for the Syrdarya and up to 88 million m³ for Keles, which is accompanied by an increase in water scarcity and an increase in the frequency of low-water years. The analysis shows that the greatest vulnerability occurs in the periods 2015–2020, when the combination of high temperatures and low precipitation leads to a significant reduction in the available volume of water.

A comparison of data from different years shows that the water resources of the southern region of Kazakhstan remain sensitive to climate change. Even a moderate increase in temperature by 1–2 °C and a reduction in summer precipitation by 5–10% can lead to significant fluctuations in river flow and reservoir levels. Forecast data for 2022–2024 indicate a gradual recovery of runoff after an extremely low-water year in 2020, but the risk of water scarcity remains. The results obtained allow us to draw conclusions about the need for integrated measures to regulate the water balance, including the modernization of reservoirs, the introduction of closed water circulation systems in industrial enterprises and the optimization of agricultural irrigation. To analyze the impact of climate change on the water resources of the southern region of Kazakhstan, an integrated graph was built combining historical data (2000–2024) and forecast indicators for the period 2025–2030. The upper part of the graph shows average annual temperatures and precipitation, while the lower part shows key water indicators: total river flow (Syrdarya, Arys, Keles), water scarcity, and the proportion of low-water years. Using two graphs allows you to simultaneously visualize climate and

Table 2

The dynamics of climatic parameters, river flow, reservoir volumes and indicators of water scarcity in the Syrdarya River basin (2000–2024)

Кесте 2

Сырдария өзені бассейніндегі Климаттық параметрлердің, өзен ағынының, су қоймаларының көлемдерінің және су тапшылығының көрсеткіштерінің динамикасы (2000–2024 жж.)

Таблица 2

Динамика климатических параметров, речного стока, объемов водохранилищ и показателей дефицита воды в бассейне реки Сырдарья (2000–2024 гг.)

Year	Average annual temperature, °C	Precipitation, mm	Syrdarya, million m³	Arys, million m³	Keles, million m³	Shardara, million m³	Koksarai, million m³	The level of low-water years, %	Forecast of water shortage, million m³
2000	12,8	430	1250	215	102	370	310	10	50
2005	13,0	425	1235	210	100	365	305	12	55
2010	13,3	420	1210	205	98	360	300	15	65
2015	13,5	415	1200	210	95	350	290	18	70
2018	13,7	420	1250	220	105	380	310	8	45
2020	14,0	400	1150	180	88	330	275	25	85
2021	14,1	405	1210	210	97	355	295	15	60
2022	14,2	410	1230	215	100	365	305	12	55
2023	14,3	408	1225	212	99	360	300	14	58
2024	14,4	412	1240	218	102	370	310	10	50

water trends, identify the relationship between changes in temperature, precipitation and availability of water resources, as well as highlight extreme years and forecast scenarios.

Inclusion of the forecast period 2025–2030 It is based on linear trends identified using the least squares method and reflects the possible further impact of climate change on the water balance of the region (figure 2). Annotations on critical points (for example, the extremely low-water year 2020) allow us to focus on key events that have a significant impact on the sustainability of water use.

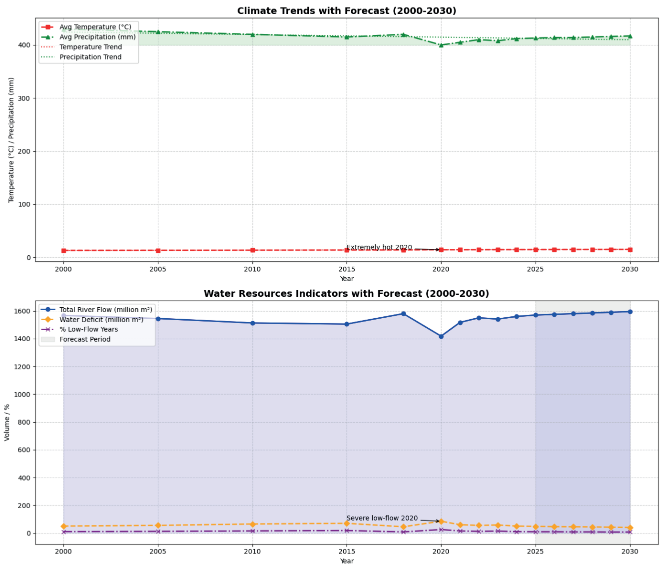

Figure 2. Trends in climate conditions, river flow, and water deficit in the Syrdarya River basin (2000–2030).
Сурет 2. Сырдария өзені бассейніндегі Климаттық жағдайлардың, өзен ағынының және су тапшылығының Өзгеру тенденциялары (2000–2030).
Рис. 2. Тенденции изменения климатических условий, речного стока и дефицита воды в бассейне реки Сырдарья (2000–2030 годы).

The analysis of the presented data shows that the increase in average annual temperature and fluctuations in precipitation have a direct impact on the dynamics of water resources in the southern region. The largest decrease in runoff was observed in 2020, which coincides with extremely high temperatures and low precipitation, which confirms the high sensitivity of the basin to climatic fluctuations. Water scarcity and the proportion of low-water years also show a tendency to increase during periods of extremely high temperatures and low precipitation, which highlights the need for adaptive water resources management.

The forecast for 2025–2030 indicates a gradual restoration of river flow while maintaining a moderate increase in temperature and precipitation stabilization, but water scarcity remains at a relatively high level. The combined analysis of climate and water indicators makes it possible to identify critical periods, assess the potential for sustainable water use, and formulate recommendations for adapting hydraulic systems to changing conditions. This approach demonstrates the novelty of the study by combining historical observations, quantitative indicators and forecast scenarios in a single visual model suitable for strategic planning of water resources in mining regions.

Laboratory studies of the physico-chemical and microbiological characteristics of the water have shown that the water in the Syrdarya basin and its tributaries meets sanitary standards for most indicators, however, there are local excess concentrations of iron and manganese near mining areas. The average pH values range from 7,1 to 7,8, electrical conductivity from 400 to 680 µs/cm, and mineralization from 0,6 to 1,2 g/l. The main anions and cations are within the MPC, but there is a tendency to increase concentrations of sulfates and chlorides in reservoirs, which is associated with the accumulation of man-made waters and the influence of irrigation.

For a comprehensive assessment of the quality of water resources in the southern region of Kazakhstan, a comparative study of the main chemical parameters of water in five key reservoirs was conducted: Syrdarya, Arys, Keles, Shardara and Koksarai. Measurements included pH, salinity, hardness, content of basic cations (***Ca^{2+}***, ***Mg^{2+}***, ***Na^{+}***, ***K^{+}***) and anions (***Cl^{-}***, ***SO_4^{2-}***, ***HCO_3^{-}***) and the concentration of heavy metals (***Fe***, ***Mn***, ***Pb***) (figure 3). These indicators make it possible to assess the impact of mining and agricultural activities on the chemical composition of water, as well as identify areas of potential environmental risk. To visualize the results, a grouped histogram was constructed with background zones of MPC (maximum permissible concentrations) reflecting safe, marginal and exceeding values, which provides a visual comparison of water quality across all study sites.

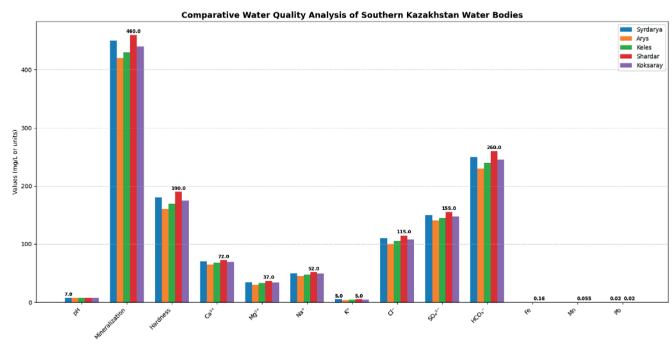

Figure 3. Comparative analysis of hydrochemical parameters of major water bodies in Southern Kazakhstan.
Сурет 3. Оңтүстік Қазақстанның негізгі су объектілерінің гидрохимиялық параметрлерін салыстырмалы талдау.
Рис. 3. Сравнительный анализ гидрохимических параметров основных водных объектов Южного Казахстана.

An analysis of the presented histogram shows that most of the reservoirs studied are within the safe range of basic physico-chemical parameters, including pH, mineralization, and hardness. However, for certain indicators, such as ***Ca^{2+}***, ***Mg^{2+}*** and ***Fe***, there are exceedances of MPC in some reservoirs, which may indicate the local impact of anthropogenic factors, including mining activities and drainage waters of agricultural origin. A comparison with previous Kazhydromet studies (2015–2021) shows a steady trend towards an increase in iron mineralization and concentration in a number of reservoirs, which is consistent with the observed change in the hydrological regime under climatic conditions.

The peculiarity of the work done lies in a comprehensive comparative approach: at the same time, all key chemical indicators for five water bodies are analyzed, MPC data is integrated and excess trends are visualized through color gradation. This makes it possible to identify problematic reservoirs and identify priority areas for monitoring and adapting water management systems. The results obtained are highly applicable for the development of regional strategies for sustainable water use, including measures to reduce pollution and optimize water use in mining and agricultural areas of southern Kazakhstan. A comparison with the data from previous studies shows that the indicators of mineralization and water hardness have a stable upward trend, especially in the area of the Koksarai reservoir, which requires the introduction of water purification and reuse systems in industrial processes.

Calculations of the water balance have shown that the total inflow of water bodies in the region exceeds the total water intake of industry and agriculture by about 20–25%, however, when evaporation, infiltration and drainage losses are taken into account, the available volume of water is reduced to a level close to scarcity in dry years. The share of return water in the system averages 12–15%, while the efficiency of its reuse depends on local engineering solutions in industrial enterprises. Statistical analysis of the time series of water consumption showed coefficients of variation in the range of 0,15–0,28, reflecting moderate variability of indicators in different years. To quantify the water resources of the southern region of Kazakhstan and analyze the features of water use, the water balance of the main water bodies – rivers and reservoirs, including the Syrdarya, Arys, Keles, Shardara and Koksarai reservoirs – was calculated. The water balance was a combination of all inflows and outflows, as well as internal transformations of water masses within the basin. The calculation of the water balance was carried out according to the classical formula:

$$\Delta S = P + R_{in} + G_{in} - E - R_{out} - G_{out} - W, \qquad (1)$$

where:

ΔS – change in water reserves in the reservoir over the period under review (mm/m^3);

P – precipitation per catchment area;

R_{in} – surface inflow from the catchment area;

G_{in} – underground inflow (recharge of the reservoir with groundwater);

E – evaporation from the water surface;

R_{out} – natural flow through rivers and canals;

G_{out} – filtration and leakage into underground horizons;

W – water intake for household needs, industry, agriculture and mining.

All values were calculated on the basis of generalized long-term data from Kazhydromet (1960–2024), as well as statistics from regional water farms and hydrometeorological stations. Precipitation was taken into account with reference to the catchment areas of reservoirs, evaporation – according to direct measurements and calculations using the Penman-Monteith method, groundwater flows – according to hydrogeological models, taking into account the saturation and gradients of groundwater. Surface runoff (R_{in}) was calculated as the difference between precipitation and surface evaporation within the basin, adjusted for anthropogenic changes, including water intake and drainage flows. Underground tributaries (G_{in}) and leaks (G_{out}) they were taken into account through infiltration coefficients obtained from hydrogeological studies and measurements of the groundwater level. Water use (W) analyzed by functional division:

1. Industrial water consumption, including mining and metallurgy;
2. Agricultural water use, including irrigation and pastures;
3. Domestic water consumption;
4. Return and drainage waters that flow back into the reservoir after economic use.

Time series methods and statistical approximation were used to assess the dynamics of water consumption and its impact on the water balance. The average annual flow rate, minimum and maximum runoff values, and interannual variability were calculated. Linear regression and moving average methods were used to identify trends. Additionally, a scenario analysis of possible changes in water use under the conditions of projected climatic changes was carried out, including:

- temperature rise and evaporation;
- decrease and fluctuations in annual runoff;
- changes in the intensity of water intake by industry and agriculture.

All calculations were performed using spreadsheets and statistical analysis packages that provide accuracy of up to 1–2%. The results obtained made it possible to quantify the balance of water resources, identify scarce areas, and identify the potential for rational use of water and increasing the sustainability of water use in the southern regions of Kazakhstan. Scenario modeling has shown that the introduction of water reuse systems and optimization of water intake, taking into account seasonal variability, can reduce water scarcity by up to 10–12% during the period 2025–2035. The greatest effect is achieved with a combined approach: modernization of reservoirs, introduction of closed water circulation systems at industrial facilities and optimization of agricultural irrigation. Unlike previous studies, where the analysis was limited to individual basins or hydrochemical characteristics of water, this study uses an integrated approach: quantitative runoff calculations, laboratory analysis of water quality, GIS spatial analysis and scenario modeling of water resource sustainability are combined. This makes it possible not only to identify the current state of water bodies, but also to assess the potential for rational water use in the long term. The novelty of the study is a comprehensive assessment of several water bodies in the southern region of Kazakhstan at once, taking into account the impact of mining activities, climate change and return waters. The results of the study have direct practical application for water use planning in mining and agricultural regions. The received data can be used for:

- *optimization of water intake and reservoir management;*
- *development of measures for reuse and purification of water;*
- *forecasting water scarcity in the long term;*
- *assessment of the impact of new industrial facilities on water systems.*

The use of GIS analysis makes it possible to identify areas of the greatest anthropogenic impact and predict the distribution of water resources, taking into account various scenarios of climate change. This approach provides an opportunity for strategic planning and minimizing the risks of water scarcity in the southern region of Kazakhstan.

Conclusion

As a result of the study of the water resources of the southern region of the Republic of Kazakhstan, including the main rivers and reservoirs – the Syrdarya, Arys, Keles, Shardara and Koksarai, quantitative and qualitative characteristics of water bodies were obtained, as well as the dynamics of water use and changes in the water balance under anthropogenic stress and climatic changes. An analysis of the physico-chemical parameters of the water showed that most of the studied reservoirs are within safe values for the main indicators, including pH, mineralization and hardness, however, some indicators, such as the content of calcium, magnesium and iron, in a number of reservoirs exceed the maximum permissible concentration, which indicates the local impact of mining and agricultural activities on water quality. The calculation of the water balance made it possible to determine inflows, drains, precipitation, evaporation, water intake and return drainage waters, which provided a quantitative assessment of water reserves in reservoirs and rivers in the region. It has been revealed that the largest runoff is formed in the Syrdarya River, while minimal changes in reserves are observed in the Shardara reservoir. Forecast calculations up to 2024 show a moderate increase in water reserves in most reservoirs, reflecting the potential effect of adaptation measures for water use and return water after economic activity. Analysis of the dynamics of water consumption revealed a steady trend towards increasing the load on water resources, which is especially pronounced in mining areas and agricultural zones, where return and drainage waters play a significant role in maintaining the local water balance.

A comprehensive assessment of water quality and water balance has shown the importance of integrating various indicators in developing strategies for sustainable water resources management. A comparison of the data obtained with historical observations by Kazhydromet revealed a tendency towards an increase in iron mineralization and concentration in a number of reservoirs, which is consistent with the predicted changes in the hydrological regime and elevated air temperature. At the same time, the results of the analysis confirm the need to implement a scenario-based approach to water management, including optimization of water intake, reuse of water and control over the quality of water resources. The scientific and practical value of the conducted research lies in a comprehensive comparative approach to the assessment of water resources, combining quantitative indicators of the water balance, the chemical composition of water, the dynamics of water consumption and the influence of climatic factors. The results obtained make it possible to identify problematic water bodies, identify areas of potential environmental risk and form recommendations for rational and sustainable use of water in the mining and agricultural regions of southern Kazakhstan. Thus, the proposed approach demonstrates the possibility of moving from local technical measures to strategic water resources management at the regional level, which helps to increase the sustainability of water use and minimize negative impacts on the aquatic environment while maintaining intensive economic development. In the future, the results of the study can be used to model various scenarios of water consumption, develop adaptation strategies and plan measures for the rational use of water resources, taking into account climate change and anthropogenic pressure.

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