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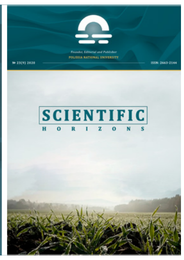

Analysis and assessment of water resources in the Kyrgyz Republic

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Abstract. The study aimed to analyse the factors of water use, environmental impacts and efficiency of water management to develop recommendations for their optimisation. The study determined that water consumption in agriculture decreased from 80% in 2020 to 76% in 2024, but water losses in irrigation systems remained high, decreasing only from 39% to 38%. In the Chui region, the largest water consumer, the share of water use decreased from 45% to 41%, and economic losses reduced from USD 40 million to USD 35 million. In water-scarce Osh region, water consumption dropped from 18% to 14%, but water availability in agriculture and the municipal sector remained limited. Wastewater treatment improved from 50% in 2020 to 55% in 2024, but this figure was far below international standards, where Switzerland and Canada had treatment rates of 95% and 90%, respectively. Comparative analysis demonstrated

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that developed countries are actively using digital leakage monitoring systems, smart irrigation technologies and multi-stage water treatment, which have reduced losses by up to 6-8%. In Kyrgyzstan, such technologies were introduced locally and only in some agricultural enterprises. Investments in water infrastructure amounted to USD 7 per capita, compared to USD 200 in Switzerland and USD 150 in Canada, which limited the modernisation of the water supply system. The problems identified confirmed the need to reform the water management system, including reducing water losses, modernising wastewater treatment facilities, introducing digital solutions for water management and adapting infrastructure to changing climate conditions

Keywords: hydrological changes; glacier degradation; climate risks; environmental and economic analysis; strategic planning

INTRODUCTION

The research relevance is determined by the growing pressure on water resources, increased water consumption and the effects of climate change. The Chui region has developed irrigation and hydropower, while the Osh region suffers from water shortages and low water use efficiency. Pollution of water bodies by industrial and agricultural wastewater degrades water quality, which requires modernisation of treatment technologies. Kyrgyzstan needs effective mechanisms for water management, balanced water uses and the study of international experience, including the practices of Switzerland and Canada. The problem is caused by ineffective management, significant water losses and glacier degradation, which reduces river flows and groundwater reserves. In the Chui region, outdated irrigation systems increase water losses, and in the Osh region, poor wastewater treatment exacerbates resource shortages. Insufficient oversight and investment are slowing down the modernisation of the water sector. A comprehensive study of these aspects is needed to develop sustainable water use strategies and prevent a water crisis.

The issue of the economic importance of water resources is considered in various studies. For example, S.S. Kozhokulov *et al.* (2021) considered the water resources of Kyrgyzstan as a strategic resource for economic development. The study emphasised that agriculture and hydropower were the main sectors dependent on water resources, but inefficient distribution and high-water losses reduced their economic potential. The study by A. Boronbaeva (2024) addressed the ecological state of the Ak-Bury River, identifying the problem of water pollution by industrial and agricultural waste. The study emphasised the need to modernise wastewater treatment facilities and develop comprehensive measures to prevent the degradation of water bodies. Consequently, aspects of transboundary regulation of water resources in Central Asia were studied by M. Djalilova (2024). The study highlighted the significant regional dependence on transboundary water resources, which required international cooperation and the development of coordinated water use mechanisms. For instance, N. Jafarzadeh *et al.* (2021) analysed the risk of groundwater pollution by heavy metals, determining the spatial distribution of pollutants and predicting their potential spread. This data was relevant for analysing the state of groundwater in Kyrgyzstan and assessing the risks of its degradation. Moreover, K. Makanda *et al.* (2022) reviewed water protection practices, emphasising the importance of sustainable management to ensure long-term water supply. The conclusions could be applied in the development of strategies for the protection of water bodies in Kyrgyzstan, especially in regions with high anthropogenic pressure.

Furthermore, K. Gunasekaran and S. Boopathi (2023) studied the application of artificial intelligence technologies in water treatment and management. The study examined water quality forecasting algorithms and automated water flow distribution systems. Such technologies could be adapted to optimise water supply in Kyrgyzstan, especially in urban areas. Furthermore, M. Faragò *et al.* (2022) analysed the life cycle and cost-effectiveness of water recycling methods, including the pyrolysis of sewage sludge. This approach could be useful in developing a strategy for water treatment and sludge utilisation in Kyrgyzstan. Notably, Q. Zuo *et al.* (2021) proposed a method for assessing water resources at the regional level based on multi-criteria analysis and scenario modelling. The methodology could be used to predict the pressure on water resources in the Chui and Osh regions. In addition, X. Liu *et al.* (2021) assessed the restoration of soil and water resources in China using the conjugation index and the integrated assessment tool. This approach assessed the effectiveness of measures to conserve water resources and adapt to climate change. In addition, M. Ben-Daoud *et al.* (2021) presented an indicator system for integrated water resources management that takes into account environmental, economic and social factors. These indicators could be adapted to assess water use in Kyrgyzstan and identify key water management issues. Furthermore, K.N. Musselman *et al.* (2021) studied trends in winter snowmelt and predicted a significant reduction in snow water resources. The approach was used to assess the long-term impact of climate change on the water balance, which could be useful for forecasting water supply in the Chui and Osh regions. In addition,

A. Hojjati-Najafabadi *et al.* (2022) investigated the possibility of using magnetic sensors to monitor pollutants in water resources. This method ensured accurate detection of hazardous pollutants and could be adapted to control water quality in Kyrgyzstan, which is especially relevant given the increasing level of pollution in rivers and groundwater.

Thus, the analysis of existing studies confirmed the relevance of the topic of water resources in Kyrgyzstan and identified the main areas for further research. The study aimed to analyse the water resources of Kyrgyzstan and their economic and environmental status. The study objectives were to analyse the dynamics of water resources and their use in Kyrgyzstan, assess environmental changes in Chui and Osh regions, and compare national and international water management practices.

MATERIALS AND METHODS

The main sources of information were official statistical data from the Ministry of Natural Resources, Ecology and Technical Supervision of the Kyrgyz Republic (n.d.), including information on water resource dynamics in Kyrgyzstan's rivers, water consumption in various sectors of the economy, and the level of water pollution in the Chui and Osh regions for 2020-2024. The Chui and Osh regions were selected due to their significant role in agricultural production and industry, which leads to increased pressure on water resources and requires detailed analysis for the development of effective water management strategies. In the Chui region, the following enterprises were considered: Joint Stock Company (JSC) "Chon-Kemin", Agricultural Production Cooperative (APC) "Kyzyl-Oktyabr" and Joint Venture (JV) "Altyn-Arashan", which actively use irrigation systems for growing grain and fodder crops. In the Osh region, the SPK "Zhayyl", the Farming Enterprise (FE) "Bayysh" and the Peasant Agricultural Enterprise (PAE) 'Komintern', specialising in horticulture and livestock farming, were studied. The assessment of water uses by these enterprises included an analysis of the efficiency of existing irrigation systems, water losses, the introduction of drip irrigation and digital water management technologies. The data covered indicators of average annual river flow, water reserves, water losses in irrigation, groundwater mineralisation and changes in water temperature. Additional information on the hydrological balance, evaporation rates from reservoirs, and glacier retreat was also addressed, enabling an assessment of the impact of climatic factors on the national water resources.

In addition, reports of international organisations such as the World Bank Group (2022), the United Nations Development Programme (UNDP) (2023), the Food and Agriculture Organization (FAO) (2021) and the International Water Management Institute (IWMI) (2025) were used. The data from international organisations allowed for a comparative analysis of water management policies and the identification of key differences in approaches to investment, water redistribution and treatment. An important aspect of the analysis was the study of the effectiveness of water conservation programmes, as well as an assessment of the impact of international environmental safety standards on the development of the water sector. To perform a statistical analysis of the dynamics of water resources in the rivers of Kyrgyzstan, the methods of calculating the average annual change in flow, linear trend of time series, correlation analysis and assessment of glacier degradation were used. The average rate of change in runoff was calculated using formula (1):

$$\Delta Q = \frac{Q_t - Q_{t-1}}{Q_{t-1}} \times 100\%, \quad (1)$$

where Q_t – volume of runoff in the current year, and Q_{t-1} – in previous year.

Linear regression identified trends in water resources change using equation (2):

$$Y = aX + b, \quad (2)$$

where a velocity change determinant, and b – initial value.

The correlation between temperature and water resources was determined by Pearson's coefficient $r = \frac{\sum(X_i-\bar{X})(Y_i-\bar{Y})}{\sqrt{\sum(X_i-\bar{X})^2\sum(Y_i-\bar{Y})^2}}$, which allowed to assess the influence of climatic factors, where X_i and Y_i-variable values $\bar{X}$ and $\bar{Y}$ – their average values. The average rate of glacier degradation was calculated using formula (3):

$$R = \frac{A_t - A_{t-1}}{T}, \quad (3)$$

where A_t and A_{t-1} – glacier areas in different years.

Changes in hydropower runoff were calculated as (4):

$$\Delta H = \frac{H_t - H_{t-1}}{H_{t-1}} \times 100\%, \quad (4)$$

where H_t and H_{t-1} – runoff volumes in different years.

These calculations made it possible to identify the dynamics of water use, assess the impact of climatic factors and determine the degree of degradation of water resources. The economic assessment of water use in Kyrgyzstan was based on the analysis of water consumption in agriculture, energy, industry and municipal sectors. The method of structural analysis was used to determine the share of water consumption by each sector, identify the main problems of water distribution and estimate economic losses from inefficient water use. Formula (5) was used to analyse water losses in water supply systems:

$$P = \frac{V_{in} - V_{out}}{V_{in}} \times 100\%, \quad (5)$$

where P – water losses level, V_{in} – supplied water level, and V_{out} – delivered to consumers.

To estimate the dependence of consumption on tariffs, the relationship was used (6):

$$W = k \times P^{-e}, \quad (6)$$

where W – water usage, k – demand elasticity coefficient, P – water price, e – price elasticity of demand.

The cost of water supply was calculated as (7):

$$C = \frac{T+O+M}{V}, \quad (7)$$

where C – cost per m^3, T – transport costs, O – operating costs, M – modernisation expenses, V – water volumes.

To analyse environmental changes in Chui and Osh regions, the method of comparative analysis of regional differences in the level of water pollution, changes in water temperature and glacier degradation was used. The data for the Chui region was compared with the Osh region to assess the impact of water supply infrastructure, climatic factors and the level of anthropogenic pressure on water resources. The analysis included calculation of the rate of change in water levels in lakes and rivers, the level of pollutants in water bodies and trends in groundwater salinity. The study assessed the factors that determine the level of pollution, including anthropogenic load, the efficiency of treatment facilities and changes in the flow of polluted water. SPSS and R statistical packages were used to process the data, which was used to conduct correlation and regression analysis of water resources dynamics and assess the impact of climate factors on the water balance. Spatial analysis of water pollution data was performed using GIS technologies, which ensured accurate visualisation of changes in the Chui and Osh regions.

A comparative analysis of water resource management was conducted based on a study of Swiss and Canadian practices in the areas of distribution, treatment and regulation of water use. Switzerland and Canada were selected due to their advanced water management methods, including highly efficient wastewater treatment, minimal water losses in distribution systems and significant investments in water infrastructure. The experience of these countries was assessed using MATLAB and STATA analytical tools, which made it possible to model the effectiveness of various water regulation strategies. Switzerland and Canada have introduced digital water monitoring systems that optimise water use in a changing climate. Data analysis using specialised software identified key mechanisms that can be adapted to improve water management in Kyrgyzstan. A method of comparing key indicators was used: wastewater treatment efficiency, water loss levels, government investment in water infrastructure, and water supply tariff policy. The integrated use of statistical, comparative and structural analysis identified key trends in the dynamics of water resources, assessed economic losses from inefficient water use and identified environmental threats to Chui and Osh regions. The identified differences in water management strategies identified promising areas for the development of the water sector and proposed mechanisms to improve the efficiency of water resource allocation.

RESULTS

Dynamics of water resources in the rivers of Kyrgyzstan. Between 2020 and 2024, Kyrgyzstan's water resources underwent significant changes. Glaciers continued to shrink, as evidenced by a decrease in their area by 1.0% in 2020, 1.2% in 2021, 0.8% in 2022, 0.5% in 2023 and 0.5% in 2024. Although the rate of glacier decline slowed, the overall trend remained negative, indicating a long-term decline in freshwater reserves. Average river flow also showed a steady decline. In 2020, it decreased by 0.5%, then by 0.6% in 2021, by 0.4% in 2022, and by 0.5% in both 2023 and 2024 (Ministry of Natural Resources, Ecology and Technical Supervision of the Kyrgyz Republic, n.d.). These indicators highlighted the gradual depletion of river sources, which affected agriculture, hydropower and domestic water supply. River pollution, expressed in increased concentrations of nitrates and ammonia, remained a problem throughout the period. In 2020, pollution levels rose by 1.2%, in 2021 by 1.5%, in 2022 by 1.8%, and in 2023 and 2024, the growth rate slowed to 1.1% and 1.0%, respectively. Despite the slowdown in pollution growth, river water quality continued to deteriorate, posing a threat to ecosystems and human health. Water losses in irrigation systems remained consistently high. In 2020, they amounted to 39%, in 2021 to 38.8%, in 2022 to 38.5%, in 2023 to 38.2%, and in 2024 to 38%. Despite a slight decrease, the problem of irrigation infrastructure wear and tear remained unresolved, leading to significant water losses and reduced agricultural production efficiency.

The mineralisation of groundwater also increased, indicating a deterioration in its quality. In 2020, the indicator increased by 1%, in 2021 by 1.3%, in 2022 by 1.2%, in 2023 by 0.8%, and in 2024 by 0.7%. These data indicated an intensification of groundwater pollution processes, especially in areas with intensive agricultural and industrial activities. Evaporation from reservoirs showed a steady increase. In 2020, water losses due to evaporation amounted to 4.8%, in 2021 to 5.0%, in 2022 to 5.2%, in 2023 to 5.3%, and in 2024 to 5.5%. The increase in water losses indicated the impact of climate change, such as rising air temperatures and decreasing precipitation, which made the water supply problem even more pressing. The water level in Lake Son-Kul has been declining gradually. In 2020 and 2021, it decreased by 0.5 cm annually, in 2022 by 0.4 cm, and in 2023 and 2024 by 0.3 cm. Although the rate of decline decreased, the overall decline in water reserves in the lake indicated a continuing shortage of incoming water. Water consumption in cities has been increasing. In

2020, it increased by 1.5%, in 2021 by 1.7%, in 2022 by 1.6%, in 2023 by 1.3%, and in 2024 by 1.2%. The growth in water consumption was driven by population growth and the expansion of urban infrastructure, but the growth rate was slowed by water conservation measures and improved water supply systems.

Water losses in water supply systems remained high but showed a slight decrease. In 2020, they amounted to 30%, in 2021 to 29.5%, in 2022 to 29%, in 2023 to 28.7%, and in 2024 to 28.5%. Despite the reduction in losses, the problem of pipeline wear and tear and inefficient resource management remained a concern. The decline in groundwater reserves was moderate. In 2020, they decreased by 0.8%, in 2021 by 0.7%, in 2022 by 0.6%, in 2023 by 0.5%, and in 2024 by 0.4%. Although the rate of depletion slowed, further decline in groundwater remained a concern, particularly in the southern regions of the country. The water quality in Issyk-Kul has been deteriorating. In 2020, the level of biogenic pollution increased by 0.5%, in 2021 by 0.7%, in 2022 by 0.8%, in 2023 by 0.6%, and in 2024 by 0.5%. The pollution of the lake affected its ecosystem and the region's tourist appeal. The water temperature in rivers showed an increase in summer. In 2020, it increased by 0.1°C, in 2021 by 0.1°C, in 2022 by 0.1°C, in 2023 by 0.1°C, and in 2024 by 0.1°C. The gradual increase in temperature indicated climate change and could lead to further deterioration of water ecosystems.

The volume of hydropower flow decreased. In 2020, it decreased by 0.3%, in 2021 by 0.4%, in 2022 by 0.3%, in 2023 by 0.5%, and in 2024 by 0.5%. The decline in water reserves affected electricity generation, increasing the risk of energy shortages. Water reserves in the Chu and Naryn rivers also declined. In the Chu River, the water level decreased by 0.5% in 2020, 0.6% in 2021, 0.4% in 2022, 0.3% in 2023, and 0.3% in 2024. In the Naryn, the decrease was 0.6% in 2020, 0.5% in 2021, 0.5% in 2022, 0.4% in 2023, and 0.2% in 2024. These indicators confirmed the general trend towards a decrease in water reserves (Table 1).

***Table 1**. Water resources dynamics in Kyrgyzstan's rivers (2020-2024)*

Parameter	2020	2021	2022	2023	2024
Glaciers	-1.0%	-1.2%	-0.8%	-0.5%	-0.5%
Average river flow	-0.5%	-0.6%	-0.4%	-0.5%	-0.5%
River pollution (nitrates, ammonia)	+1.2%	+1.5%	1.8%	1.1%	+1.0%
Water losses in irrigation	39%	38.8%	38.5%	38.2%	38%
Mineralisation of groundwater	+1%	+1.3%	+1.2%	+0.8%	+0.7%
Evaporation from reservoirs	4.8%	5.0%	5.2%	5.3%	5.5%
A decrease in the water level in Son-Kul	-0.5 cm	-0.5 cm	-0.4 cm	-0.3 cm	-0.3 cm
Growing water consumption in cities	+1.5%	1.7%	1.6 %	+1.3%	+1.2%
Water losses in water supply systems	30%	29.5%	29%	28.7%	28.5%
Reduction of groundwater reserves	-0.8%	-0.7%	-0.6%	-0.5%	-0.4%
Water quality in Issyk-Kul	0.5%	+0.7%	+0.8%	+0.6%	0.5%
Water temperature in rivers in summer	+0.1°C	+0.1°C	+0.1°C	+0.1°C	+0.1°C
Volume of hydropower runoff	-0.3%	-0.4%	-0.3%	-0.5%	-0.5%
Water reserves in Chu	-0.5%	-0.6%	-0.4%	-0.3%	-0.3%
Water reserves in Naryn	-0.6%	-0.5%	-0.5%	-0.4%	-0.2%

***Source:** compiled by the authors based on the International Futures (IFs) model (2025)*

Thus, Kyrgyzstan's water resources experienced negative changes in 2020-2024. The shrinking of glaciers, reduced river flows, deteriorating water quality, and increased water consumption require measures to rationally use water resources and modernise infrastructure.

Economic assessment of water uses in Kyrgyzstan. In the period from 2020 to 2024, there was a gradual decrease in water consumption in all major sectors of the Kyrgyz economy. In agriculture, the share of water use decreased from 80% in 2020 to 77% in 2024. This was due to the gradual modernisation of irrigation systems and water conservation measures. However, despite the improvements, water losses remained significant. Economic losses in agriculture decreased from USD 100 million in 2020 to USD 90 million in 2024, indicating a partial improvement in water use efficiency. In the energy sector, the share of water consumption decreased from 10% to 9.5% over five years. This was due to a reduction in hydropower runoff and the introduction of water efficiency measures at hydroelectric power plants (HPPs). Accordingly, economic losses in the energy sector decreased from USD 40 million to USD 35 million, but the sector's dependence on water resources remained high.

The industrial sector, which consumed 8% of water in 2020, reduced this figure to 7.7% by 2024. This was driven by the introduction of more efficient water treatment technologies and a decline in industrial production in certain industries. Economic losses during this period decreased from USD 25 million to USD 21 million, indicating a partial stabilisation of water costs. The utility sector also showed a decrease in water consumption.

In 2020, the share of water use was 7%, but by 2024 it had fallen to 6.8%. This was due to increased efficiency of water supply in cities and partial modernisation of networks. Nevertheless, water losses remained high, with economic losses amounting to USD 16 million in 2024 compared to USD 20 million in 2020 (Table 2).

***Table 2**. Economic assessment of water uses in Kyrgyzstan (2020-2024)*

Economic sector	Metric	2020	2021	2022	2023	2024
Agriculture	Share of water consumption (%)	80%	80%	79%	78%	77%
	Economic losses (USD million)	100	98	95	92	90
Energy	Share of water consumption (%)	10%	10%	9.8%	9.7%	9.5%
	Economic losses (USD million)	40	39	37	36	35
Industry	Share of water consumption (%)	8%	8%	7.9%	7.8%	7.7%
	Economic losses (USD million)	25	24	23	22	21
Utilities	Share of water consumption (%)	7%	7%	6.9%	6.8%	6.8%
	Economic losses (USD million)	20	19	18	17	16

***Source:** compiled by the authors based on the International Futures (IFs) model (2025)*

Between 2020 and 2024, a decrease in water consumption among the largest farms was observed in the Chui and Osh regions, indicating the gradual introduction of water-saving technologies. In the Chui region, agricultural enterprises such as Chon-Kemin JSC, Kyzyl-Oktyabr Agricultural Production Cooperative and Altyn-Arashan Agricultural Production Cooperative reduced their water consumption by an average of 1% per year. This was achieved through the modernisation of the irrigation system and the transition to drip irrigation, which reduced water losses and increased efficiency. Despite these positive changes, further investment in infrastructure improvements was still needed, as old canals in some areas still caused significant water losses.

In the Osh region, where water shortages were more pronounced, farms, including Jail, Komintern, and Bayysh farms, also reduced water consumption. The main measures were the reconstruction of irrigation networks and the introduction of water-saving irrigation methods, which reduced the pressure on water sources. Nevertheless, water shortages remained a serious problem, especially during dry periods when the water supply was unstable. Economic losses during the analysed period showed a steady downward trend. In the Chui region, they decreased from USD 40 million to USD 35 million, and in the Osh region, from USD 25 million to USD 21 million. This confirmed the partial effectiveness of the reforms and the introduction of modern water use technologies. However, despite this, a significant portion of water resources was still being lost due to the imperfect water distribution system and the lack of comprehensive control over its efficiency (Table 3).

***Table 3**. Dynamics of water consumption and economic losses in the Chui and Osh regions (2020-2024)*

Farms/Parameters	2020	2021	2022	2023	2024
Chui region					
Chon-Kemin JSC					
Share of water consumption (%)	12	11.8	11.5	11.2	11
Economic losses (USD million)	10	9.8	9.5	9.2	9.0
Kyzyl-October SPC					
Share of water consumption (%)	10	9.8	9.6	9.3	9.0
Economic losses (USD million)	8	7.8	7.5	7.2	7.0
Altyn-Arashan JV					
Share of water consumption (%)	9	8.8	8.5	8.2	8.0
Economic losses (USD million)	6.5	6.3	6.1	5.8	5.5
Osh region					
SPC Zhayil					
Share of water consumption (%)	8	7.8	7.5	7.2	7.0
Economic losses (USD million)	5.5	5.3	5.1	4.9	4.7
Komintern State Farm					
Share of water consumption (%)	6	5.8	5.6	5.4	5.2
Economic losses (USD million)	4.2	4.0	3.8	3.6	3.5
FH Bayysh					
Share of water consumption (%)	4	3.8	3.6	3.4	3.2
Economic losses (USD million)	2.8	2.6	2.5	2.3	2.2

***Source:** compiled by the authors based on Ministry of Natural Resources, Ecology and Technical Supervision of the Kyrgyz Republic (n.d.)*

The analysis demonstrated that the introduction of new irrigation technologies and the modernisation of irrigation systems had a positive impact on rational water use. However, insufficient funding and the high degree of infrastructure wear and tear limited the speed and scale of the necessary transformations. To further reduce water losses, more active support from the government and international organisations was needed, as well as incentives for farms to switch to more efficient water use methods. Thus, water consumption in Kyrgyzstan in the period 2020-2024 showed a downward trend in all major sectors of the economy. Despite the partial modernisation of irrigation systems, agriculture remained the largest consumer of water, and resource losses remained significant.

Environmental changes in the Chui and Osh regions In 2020, the level of water pollution in the Chui region was 10% and in the Osh region 15%. The main sources of pollution are untreated wastewater and agricultural runoff. The impact of climate change has led to a reduction in water reserves by 5% in the Chui region and 7% in the Osh region. Glacier degradation amounted to 3% and 4% respectively, which began to affect river flows. In 2021, pollution levels increased by 12% in the Chui region and by 17% in the Osh region, due to the insufficient efficiency of treatment facilities. Water shortages worsened, reaching 6% in the Chui region and 8% in the Osh region. Glacial losses accelerated, increasing to 4% in the Chui and 5% in the Osh regions, which began to affect water supply in agricultural areas. In 2022, water pollution in the Chui region reached 14% and 19% in the Osh region, reflecting an increase in anthropogenic pressure. Climatic factors led to a decrease in available water resources by 7% in Chui and 9% in the Osh region. Glacial degradation continued, reaching 5% and 6%, respectively, contributing to the instability of water flows.

In 2023, water pollution increased to 16% in the Chui region and 21% in the Osh region, indicating a critical burden on ecosystems. The impact of climate change has intensified, leading to a reduction in water resources by 8% in Chui and 10% in Osh. Glacial degradation has accelerated by 6% and 7%, increasing the risk of seasonal water shortages. In 2024, pollution reached 18% in Chui and 23% in Osh regions, confirming the growing degradation of water bodies. The decline in water reserves was 9% in Chui and 12% in Osh, which exacerbated water supply problems. Glacier degradation increased to 7% and 8%, respectively, indicating long-term threats to water supply and hydropower (Fig. 1).

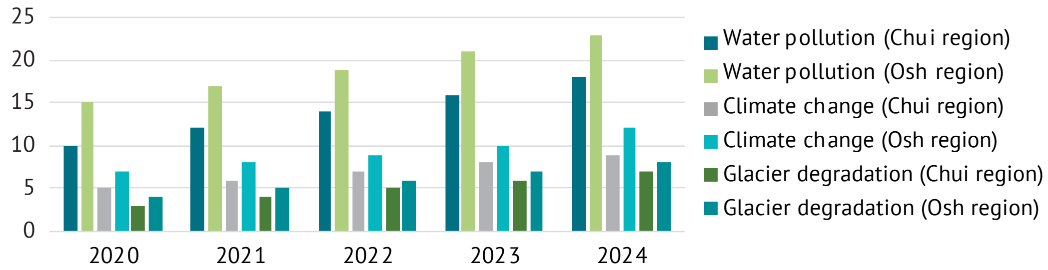

***Figure 1**. Environmental changes in the Chui and Osh regions (2020-2024)*
***Source:** compiled by the authors based on Ministry of Natural Resources, Ecology and Technical Supervision of the Kyrgyz Republic (n.d.)*

Thus, from 2020 to 2024, water pollution in the Chui and Osh regions increased, water reserves decreased, and glacier degradation increased the risk of water shortages. To stabilise water resources, comprehensive measures are needed to treat wastewater, adapt to climate change and modernise water infrastructure.

Comparative analysis of water management. In 2020, agriculture in Kyrgyzstan used 80% of water resources, with 45% in the Chui region and 18% in the Osh region. In Switzerland, agriculture consumed 3% of water, and in Canada, 10%. Water losses in Kyrgyzstan reached 34%, while in Switzerland they were 6% and in Canada 8%. These differences were due to the use of advanced technologies, including automated irrigation systems, soil moisture sensors and digital leakage control, which were actively used in Switzerland and Canada. The introduction of drip irrigation in Kyrgyzstan remained at an early stage, covering less than 5% of irrigated land, while in Switzerland and Canada, this figure reached 60% and 50%, respectively.

In 2021, water consumption in Kyrgyzstan's agriculture sector fell to 79%, and in the Chui and Osh regions to 44% and 17% respectively. Despite the reduction in consumption, wastewater treatment in the country remained inadequate, with only 50% of the total volume being treated, compared to 95% and 90% in Switzerland and Canada, respectively. Switzerland used multi-stage filtration systems, including mechanical, biological and chemical treatment of wastewater, followed by ultraviolet or ozone disinfection. This removes organic and chemical pollutants, ensuring high-quality treated water. In Canada, water reuse technologies were actively used, including closed water circulation systems in industry, water recycling in agriculture, and multi-stage wastewater treatment for reuse in municipal water supply. Intelligent irrigation systems used in developed countries include remote water supply control and automatic regulation of irrigation volumes depending on weather conditions. In Kyrgyzstan, such technologies remained uncommon, and only a few agricultural enterprises began to introduce automated systems.

In 2022, investments in Kyrgyzstan's water infrastructure amounted to just USD 7 per capita, compared to USD 200 in Switzerland and USD 150 in Canada. As a result, the national water supply systems remained worn out, with water losses in the Chui region reaching 38% and 45% in the Osh region. In Switzerland, government programmes were implemented to modernise pipelines and control water pressure, while in Canada, automated water supply systems were used to minimise leakage and increase the efficiency of water distribution. Digital technologies for water management, such as satellite monitoring and online water flow control systems, remained at the pilot project stage in Kyrgyzstan, while in Switzerland and Canada, they were applied at the state level, ensuring a rapid response to changes in the water balance.

In 2023, water consumption in Kyrgyzstan's agriculture decreased to 77%, but water losses in the systems remained at 30-32%. In the Chui region, losses dropped to 36%, and in the Osh region to 42%. In Switzerland, government subsidies for the introduction of water-saving technologies were in place, which reduced water consumption and cut operating costs. These measures included financial support for farmers to install drip irrigation and smart irrigation systems, soft loans for the modernisation of water supply networks and the introduction of water reuse systems, as well as subsidies to industrial enterprises for reducing water consumption and switching to closed water circulation technologies. Canada used water quota mechanisms that regulated the amount of permitted water consumption depending on the needs of the economy and available resources. The main methods included the division of quotas between sectors (agriculture, industry, utilities), seasonal regulation of consumption, when restrictions were imposed during periods of drought, and water quota trading, which redistributed resources between regions depending on priority needs. These mechanisms ensured the rational use of water and prevented water shortages during dry periods. The partial modernisation of irrigation allowed farmers, especially in the Chui region, to introduce automated irrigation systems regulated based on weather data, but their use remained localised. In Kyrgyzstan, there were no such mechanisms, which limited the introduction of modern water management technologies.

In 2024, water consumption in Kyrgyzstan's agriculture reached 76%, and water losses were reduced to 28-30% as a result of the partial modernisation of water supply. Wastewater treatment increased to 55%, but this figure remained significantly lower than in Switzerland and Canada. Switzerland had strict legislative standards for water quality control and a multi-level water management system. Canada used adaptive water regulation mechanisms, including dynamic quotas, where water consumption volumes were adjusted according to water availability and weather conditions. Flexible tariff systems encouraged water conservation through differentiated pricing, increasing the cost of consumption during periods of shortage. The water rights market allowed resources to be redistributed between sectors of the economy through the sale or lease of water use quotas. Regional agreements between regions ensured the redistribution of water resources according to the needs of industry, agriculture and municipal water supply, preventing shortages during dry periods. In Kyrgyzstan, legal regulation of water use remained weak, leading to the irrational use of water resources. The experience of developed countries has shown that adapting digital and intelligent water management systems to local climatic and economic conditions could significantly improve water use efficiency in Kyrgyzstan. The introduction of smart irrigation systems and the use of Big Data to forecast water demand would ensure more efficient resource allocation, especially in arid regions (Fig. 2).

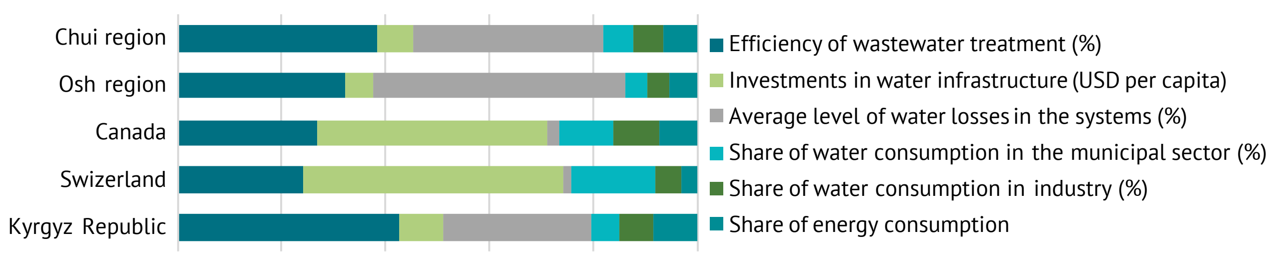

***Figure 2**. Comparative analysis of water management (2020-2024)*

***Source:** compiled by the authors based on National Statistical Committee of the Kyrgyz Republic (2021), Ministry of Natural Resources, Ecology and Technical Supervision of the Kyrgyz Republic (n.d.)*

The successful practices of Switzerland and Canada can be applied in Kyrgyzstan through the modernisation of irrigation systems, automation of water supply control and the introduction of water reuse systems. Government subsidies and tax breaks, similar to the Swiss and Canadian mechanisms, can help reduce water losses and increase the efficiency of water distribution. The introduction of advanced wastewater treatment technologies and investments in infrastructure are key to the sustainable management of the national water resources.

DISCUSSION

The study results demonstrated that Kyrgyzstan's water resources are significantly affected by climate and human factors. In the Chui region, water consumption was high, but significant water losses in irrigation reduced its efficiency. The Osh region experienced water shortages due to limited sources and poor wastewater treatment. Water pollution continued to increase, especially in areas with developed agriculture and industry. A comparison with Switzerland and Canada showed insufficient investment in water infrastructure and low efficiency of treatment systems. The development of water-saving technologies and the modernisation of resource management are necessary for sustainable water use. Research on water resource management demonstrates a wide range of approaches, but their results do not always take into account regional characteristics and the economic consequences of inefficient water use. For instance, S.K. Jain and V.P. Singh (2023) examined integrated water resources planning and management, emphasising mathematical modelling and strategic forecasting of water distribution. The study demonstrated that integrated management systems, including consumption forecasting and risk management, can minimise water losses and improve water supply efficiency. These findings confirm the problems of the Kyrgyz water sector related to insufficient investment and inefficient water resource allocation. However, this study is unique in that it includes a regional analysis of water use in the Chui and Osh regions, making it more applicable to the national conditions. In addition, a comparative analysis with international practices has allowed specific measures to be proposed for optimising water supply.

The issue of water pollution is considered in many modern studies. For instance, X. Yuan and Z. Jun (2021) assessed the risks associated with diffuse water pollution using quantitative forecasting models and found that the main sources of pollution are agricultural and industrial runoff, which correlates with the findings of this study on the growth of water pollution in Kyrgyzstan. However, the study emphasised the mathematical modelling of pollution, while this study considers not only its sources, but also the impact on the availability of water resources and the country's economy. The advantage of this study is its comprehensive approach, which includes not only environmental, but also economic and managerial assessments, proposing solutions to minimise water losses and improve water supply.

In the context of the issue of water security, T. Peng *et al.* (2020) analysed the impact of environmental change on water resources. The study identified three key challenges: a decline in freshwater reserves, deterioration in the quality of water bodies, and inefficient water allocation. These conclusions largely correlate with the results of this study, which also recorded trends in glacier degradation, water pollution and increased pressure on water resources. However, T. Peng *et al.* did not sufficiently address regional differences in the distribution of water resources, while this study examined in detail the specifics of water use in the Chui and Osh regions. This made it possible to propose specific measures to improve the efficiency of water management, taking into account territorial differences. Some studies examine the impact of seasonal changes on water quality. In particular, D. Hammoumi *et al.* (2024) analysed seasonal fluctuations in surface water quality using the Water Quality Index (WQI) and Principal Component Analysis (PCA). The study determined that climatic factors, including precipitation and air temperature, have a significant impact on water quality dynamics. These results are partly consistent with the present study, which also examined the impact of climate change on water resources in Kyrgyzstan. However, the study by D. Hammoumi *et al.* conducted a statistical analysis, whereas this study examined not only environmental but also economic and management aspects of water use. This provides a more comprehensive picture of the state of the national water resources and suggests ways to improve water use efficiency.

Various studies are devoted to assessing the sustainability of water resources and their distribution in the context of climate and anthropogenic changes. G. Wang *et al.* (2020) analysed water load trends using a system dynamic model and an improved fuzzy integrated assessment method. The results showed that the change in the water balance depends on the pace of urbanisation, industrial growth, and climatic factors. This partially coincides with this study, which also identified the impact of climate change and growing urban water consumption on Kyrgyzstan's water reserves. However, the study by G. Wang *et al.* was dedicated to forecasting changes, whereas this study examined the current situation and assessed the economic impacts of water use. In addition, this study sufficiently addressed the differences between the regions of the country, which provided more detailed recommendations for water management.

Other studies emphasise the cost-effectiveness and reuse of water resources. For instance, M. Faragò *et al.* (2021) studied the transition from wastewater treatment to integrated water resource recovery, analysing the environmental and economic impacts of the full implementation of such technologies. The findings confirmed that integrated wastewater management not only reduces the burden on water bodies but also increases the economic efficiency of water supply. These results are reflected in the present study, which also emphasises the need to modernise wastewater treatment facilities in Kyrgyzstan. However, the study by M. Faragò *et al.* analysed technological solutions and economic evaluation of processes, while this study considers systemic problems, including environmental and management aspects. Thus, the proposed integrated approach not only identified the need for technological changes but also ways to integrate them into the existing water use system.

Water quality and the degree of pollution of water bodies are important areas of water resource analysis. The study by H. Aydin *et al.* (2020) assessed water quality in rivers in northeastern Turkey using the Water Quality Index (WQI) and multiple statistical methods. The study determined that agricultural activities and industrial pollution are the main factors of water quality deterioration. These results are consistent with the data of this study, which also recorded an increase in water pollution in Kyrgyzstan, especially in the Chui and Osh regions. However, the study by H. Aydin *et al.* conducted a statistical analysis of water metrics, while this study considers not only the environmental but also the economic impact of pollution. This integrated approach not only assessed the degree of pollution but also proposed measures to reduce it, including the modernisation of water treatment facilities and the improvement of the water quality control system.

Spatial and seasonal analysis of water quality is also an important aspect of research. J.B. De Melo Carvalho Passos *et al.* (2021) conducted a multivariate statistical analysis of water quality in the Doce River basin in southeastern Brazil. The study demonstrated that water quality varies depending on the season and sources of pollution, which confirms the need for adaptive water management strategies. These results partially coincide with the present study, which also noted the dependence of the state of water bodies on climatic factors and seasonal changes. However, the study by J.B. De Melo Carvalho Passos *et al.* did not analyse the economic impact of water quality deterioration, while this study assessed the impact of pollution on water supply, agriculture and the municipal sector in Kyrgyzstan. Approaches to water management were considered from different perspectives, including the assessment of water availability, pollution and wastewater treatment efficiency. The study by M. Naderi (2021) analysed the level of water management based on the concepts of water supply and water availability. The study determined that the effectiveness of water management is determined by the balance between water demand and availability, as well as the quality of water supply infrastructure. These results confirm the conclusions of this study on the need to modernise water supply systems in Kyrgyzstan, especially in regions with high levels of water losses. However, the study by M. Naderi analysed a macro-level assessment of water management, while this study analyses in detail the regional differences affecting water use in the Chui and Osh regions. This approach identified specific water allocation problems and proposed targeted strategies to address them.

Other studies addressed the economic and environmental aspects of water use. Z. Shi *et al.* (2020) conducted a comprehensive assessment of the economic efficiency of water use, pollution levels, and wastewater treatment efficiency in China. The study determined that insufficient investment in wastewater treatment plants and weak control over industrial discharges lead to an increase in water pollution, reducing the availability of clean water for agriculture and the population. These findings are consistent with this study, which also noted the deterioration of water quality in Kyrgyzstan due to pollution from industrial and agricultural wastewater. However, the study by Z. Shi *et al.* conducted an economic assessment of production processes and their impact on the water environment, while this study covers not only industrial but also municipal and agricultural aspects of water use. This broader coverage included a comprehensive assessment of the water situation and the proposal of solutions to minimise water losses.

Changes in the hydrological cycle under the influence of climatic factors are an important area of research. D. Yang *et al.* (2021) reviewed the impact of global climate change on water resources, emphasising the role of rising temperatures, changing precipitation patterns and glacial melt in shaping the water balance. The conclusions coincide with the findings of this study, which recorded a decrease in water levels in Kyrgyzstan's rivers and lakes, as well as a reduction in ice cover, which poses a threat to the long-term water supply. However, the study by D. Yang *et al.* is more general in nature, considering hydrological processes at the global level, while this study emphasised specific regional changes and their impact on water use. This focus makes the results more relevant for the development of practical recommendations for adapting Kyrgyzstan's water systems to changing climate conditions. Thus, the reviewed studies confirm the problems identified in this study, including water scarcity, water pollution and insufficient efficiency of wastewater treatment plants.

A.C. Kharake and V.S. Raut (2021) and S. Hajji *et al.* (2022) investigated water resources from different perspectives. S. Hajji *et al.* assessed the decline in water reserves in the Amu Darya basin due to climate change and increased water consumption, which partially coincides with this study, which also identified a decrease in glaciers and an increase in water consumption in Kyrgyzstan. A.C. Kharake and V.S. Raut conducted the chemical analysis of pollution, while this study additionally considers economic impacts, such as losses in the utility sector and the need to modernise wastewater treatment plants. In contrast to the transboundary approach of S. Hajji *et al.*, this study analysed regional differences, especially in the Chui and Osh regions. K. Leonard *et al.* (2024) and M.D. Molekoa *et al.* (2022) studied climate change and water management. K. Leonard *et al.* analysed the impact of rising temperatures, decreasing snow cover and changing precipitation on water resources in New York State, which confirms the findings of this study on glacier degradation and lower river levels in Kyrgyzstan. However, K. Leonard *et al.* conducted forecasting, whereas this study provides a detailed look at current changes and their impact on water supply. M.D. Molekoa *et al.* studied spatial pollution of water bodies, but without an economic assessment of the consequences, which distinguishes their work from the present study, which also proposes measures to modernise the infrastructure.

Notably, A. Lohrmann *et al.* (2021) and K. Cheng *et al.* (2022) analysed water management from different angles. A. Lohrmann *et al.* assessed the water footprint of the European energy sector during the transition to renewable energy sources, which echoed the findings of this study on the impact of water consumption on hydropower in Kyrgyzstan. However, the study forecasted the long-term impact of energy transformation, while this study analysed current water use issues in detail. At the same time, K. Cheng *et al.* studied the coordination of water and soil resources, taking into account ecological and economic factors, and proposed a methodology for optimal resource allocation. Their study touched upon issues of sustainable management but did not include a detailed economic assessment, which distinguishes it from the present study, where water losses were analysed and measures for modernising water infrastructure were proposed. The analysis showed that Kyrgyzstan continues to face significant water management challenges related to high water losses, dilapidated infrastructure, and insufficient adoption of modern technologies.

CONCLUSIONS

The study conducted a comprehensive assessment of the state of Kyrgyzstan's water resources for the period 2020-2024, including an analysis of the dynamics of water use, economic losses, environmental changes and the impact of climate factors. The study covered key aspects of the water balance, such as river flows, glacier degradation, water quality, losses in irrigation systems and growth in water consumption in various sectors of the economy. The analysis of water consumption showed that agriculture remained the largest consumer of water, despite significant losses in irrigation, which reached 38-40%. The Chui region, which has a well-developed irrigation infrastructure, experienced high volumes of water losses, while the Osh region experienced an acute shortage of water resources due to insufficient water supply and inefficient wastewater treatment. The energy sector saw a decline in hydropower flows, which increased the vulnerability of the energy system to changes in precipitation and glacier degradation. The environmental change assessment revealed a deterioration in water quality due to increased pollution of rivers by industrial and agricultural runoff.

During the study period, the level of pollution in Chui and Osh regions increased by 3-5%, indicating that the efficiency of treatment facilities was insufficient. The water and environmental situation were further complicated by the progressive degradation of glaciers, which lost 0.5% to 1.2% of their volume per year, affecting the availability of water resources in the long term. The economic analysis of water use showed that inefficient water allocation led to significant financial losses. The largest losses were recorded in agriculture due to water losses in irrigation, as well as in the municipal sector, where up to 28-30% of water was lost in water supply systems. In the energy sector, the lack of water reduced the productivity of hydroelectric power plants, increasing the national dependence on seasonal fluctuations in water resources. A comparative analysis of water management in Kyrgyzstan and developed countries (Switzerland and Canada) demonstrated that Kyrgyzstan has insufficient investment in water infrastructure, low efficiency of treatment technologies and a high share of water losses. In countries with developed water policies, modern technologies for water treatment and redistribution are used to minimise the negative impact of pollution and shortages. Based on the data obtained, conclusions were drawn about the need for a comprehensive reform of the water sector in Kyrgyzstan. The key areas should include modernisation of water infrastructure, introduction of water-saving technologies, improvement of wastewater treatment and development of adaptive water management strategies to address climate change.

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Анотація. Дослідження мало на меті проаналізувати фактори водокористування, вплив на навколишнє середовище та ефективність управління водними ресурсами для розробки рекомендацій щодо їх оптимізації. Дослідження визначило, що споживання води в сільському господарстві зменшилося з 80 % у 2020 році до 76 % у 2024 році, але втрати води в іригаційних системах залишалися високими, зменшившись лише з 39 % до 38 %. У Чуйській області, найбільшому споживачеві води, частка водокористування зменшилася з 45 % до 41 %, а економічні втрати скоротилися з 40 мільйонів доларів США до 35 мільйонів доларів США. У Ошській області, яка має дефіцит води, споживання води скоротилося з 18 % до 14 %, але доступність води в сільському господарстві та комунальному секторі залишалася обмеженою. Очищення стічних вод покращилося з 50 % у 2020 році до 55 % у 2024 році, але цей показник був значно нижчим за міжнародні стандарти, де Швейцарія та Канада мали рівень очищення 95 % та 90 % відповідно. Порівняльний аналіз показав, що розвинені країни активно використовують цифрові системи моніторингу витоків, інтелектуальні технології зрошення та багатоступеневу очистку води, що дозволило знизити втрати до 6-8 %. У Киргизстані такі технології були впроваджені локально та лише в деяких сільськогосподарських підприємствах. Інвестиції у водну інфраструктуру становили 7 доларів США на душу населення порівняно з 200 доларами США у Швейцарії та 150 доларами США в Канаді, що обмежувало модернізацію системи водопостачання. Виявлені проблеми підтвердили необхідність реформування системи управління водними ресурсами, включаючи зменшення втрат води, модернізацію очисних споруд, впровадження цифрових рішень для управління водними ресурсами та адаптацію інфраструктури до змін кліматичних умов

Ключові слова: гідрологічні зміни; деградація льодовиків; кліматичні ризики; еколого-економічний аналіз; стратегічне планування