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Water resources as a factor of ecological sustainability in forest ecosystems of Kyrgyzstan and Kazakhstan: Challenges and prospects for cooperation

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Abstract. The relevance of the study is conditioned by the growing impact of climate change and anthropogenic stress on water resources, which are crucial for maintaining the ecological sustainability of forest ecosystems in Central Asia. The purpose of the study was to assess changes

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in the water resources of Kyrgyzstan and Kazakhstan during 2014-2024 and determine their impact on the ecological sustainability of forest ecosystems. The research methods included the analysis of hydrological data on the quantity and quality of water resources during the specified period, and the analysis of scientific sources on the relationship between water balance, biodiversity, and soil conditions. In particular, the water level in large rivers (Naryn, Ili), changes in water temperature, chemical pollution, and the dynamics of forest areas were analysed. The results showed that the water level in the Naryn River decreased by 8% due to melting glaciers and increased water intake, while in the Ili River this figure was 6% due to reduced inflows from China and increased water consumption. The average water temperature increased by 1.0-1.2°C, which reduced the concentration of dissolved oxygen and negatively affected biodiversity. Water pollution from industrial and agricultural discharges increased by 10-15%, exacerbating the degradation of coastal ecosystems and biodiversity. The data indicate the relative stability of the overall forest fund of Kyrgyzstan, but there is a decrease in the area of land covered with forest, which raises concerns about the effectiveness of conservation measures. Reforestation shows unstable dynamics due to climate change and water scarcity. The reduction in forest areas was 5% in Kyrgyzstan and 7% in Kazakhstan, with the largest losses observed in the Ili River basin. The decrease in biodiversity in Kazakhstan reached 12%, while in Kyrgyzstan, the decrease in forest area worsened the water stress in mountainous regions. The findings highlight the close relationship between the state of water resources and the ability of forest ecosystems to perform ecological functions

Keywords: climate change; biodiversity; biogeocoenosis; river basins; vegetation

Introduction

Water resources play a critical role in ensuring environmental sustainability, especially in forest ecosystems, which are important natural regulators of climate, water balance, and biodiversity. Kyrgyzstan and Kazakhstan, located in Central Asia, are countries with diverse landscapes, where forests perform a key function in maintaining ecosystem balance. However, these countries face numerous challenges in the field of water resources management, which makes it necessary to investigate this issue in depth.

The importance of water resources in forest ecosystems is conditioned by their ability to retain soil moisture, regulate runoff, and ensure the stability of local and regional climatic conditions. However, climate change, forest degradation and poor use of water resources threaten the sustainable functioning of these ecosystems (Mustafayeva & Tagiyev, 2023). In particular, in Central Asia, reduced snow reserves, water pollution, and increased anthropogenic impact put significant pressure on natural systems (Ongayev *et al.*, 2024). Moreover, the transnational nature of many water basins in the region requires international cooperation to effectively manage and conserve these resources.

Research in the field of water resources management in Central Asia covers a wide range of topics. In particular, A.M. Anghelescu & I.D. Onel (2024) analysed the role of the European Union in developing water management policies in the region, focusing on examples of the Aral Sea demonstrating the need for international cooperation to overcome the water crisis. Other researchers consider the reproduction of forest resources in the context of sustainable development. For example, K.T. Abayeva *et al.* (2024) emphasised the need to optimise

forest management in Kazakhstan, in particular, through the integration of water-saving technologies. Research in the field of water resources management in Central Asia covers a wide range of topics. In particular, S. Missall *et al.* (2022) investigated the rational use of forests along water basins in Kyrgyzstan, emphasising their role in maintaining the water balance. B. Atantayeva *et al.* (2024) considered the problems of ecosystem conservation and security on the example of the territory of "Semey Ormani" in Kazakhstan, emphasising the need for integrated management of forest and water resources. X. Wang *et al.* (2020) focused on assessing water security and resource development in Central Asia, which is important for maintaining ecosystem stability in the region.

In turn, O. Abraliyev *et al.* (2024) investigated the optimisation of irrigated land use in Kazakhstan, pointing out the importance of a systematic approach to water resources management. The study by A. Ozenbayeva *et al.* (2022) considered the legal aspects of the regulation of transboundary water resources of the Republic of Kazakhstan, in particular, the existing international treaties, national legislation and mechanisms of water resources management in the context of regional cooperation were analysed. Thus, there are a significant number of studies that cover certain aspects of water resources in the region, but not enough attention is paid to their impact on the ecological sustainability of forest ecosystems and the prospects for cooperation between Kyrgyzstan and Kazakhstan.

Gaps in the coverage of water resources in Central Asian Forest ecosystems include insufficient analysis of the relationship between climate change, the state of water resources and environmental sustainability. In addition, the effectiveness of existing cooperation strategies between countries, in particular, in the field of forest and aquatic ecosystems conservation, is relevant. Thus, the study is focused on investigating the role of water resources in ensuring the ecological sustainability of forest ecosystems in Kyrgyzstan and Kazakhstan, considering current challenges and opportunities for cooperation. Its purpose was to analyse the relationship between the state of water resources and the stability of forest ecosystems, assess the impact of water scarcity on forest landscapes, and identify effective approaches to their conservation and management.

Materials and Methods

A comprehensive approach was used to conduct the study, including the collection, analysis, and synthesis of data from various sources. The main materials of the study included official statistics, environmental reports and information obtained from the state registers of water and forest resources of Kyrgyzstan and Kazakhstan. The data used covered the period from 2014 to 2024, which allowed tracking the dynamics of changes in the state of water resources and their impact on forest ecosystems. Data on the state of water resources in Kyrgyzstan were obtained from the Ministry of Natural Resources, Ecology and Technical Supervision of the Kyrgyz Republic (n.d.), which included information on the water level in key rivers and lakes of the country, and the National Statistical Committee of the Kyrgyz Republic (n.d.). For Kazakhstan, data from the Ministry of Ecology and Natural Resources of the Republic of Kazakhstan (n.d.) were used, which contained statistics on water consumption, the level of water pollution, and the hydrological state of rivers. In addition, information from the Bureau of National Statistics (n.d.) on the economic aspects of the use of water resources in forestry was attracted.

Materials from the state registers of the forest fund of both countries were used to assess the ecological sustainability of forest ecosystems. The data included indicators of

biodiversity, the area of forest stands, and their ecological state. In particular, official reports of the State Register of the Forest Agency of the Kyrgyz Republic (n.d.) and similar structures in Kazakhstan were considered (Ministry of Ecology..., n.d.). Regional forest restoration programmes, such as the "Zhasyl El" programme in Kazakhstan, which aims to increase forest cover, were also taken into account. In addition, the study was based on an analysis of the scientific literature on the relationship between water resources and forest ecosystems in the context of environmental sustainability (Decree of the Government of the Republic of Kazakhstan No. 632 "On the..., 2005). In particular, papers that consider regional aspects of changes in the water balance and their impact on forest ecosystems, papers that analyse the mechanisms of adaptation of forest ecosystems to changes in the water regime, and studies on natural resource management based on environmental factors were analysed (Missall *et al.,* 2022; Wang *et al.,* 2022).

The study included several stages of working with data. At the first stage, the initial information necessary for creating a single database was systematised and processed. The main focus was on the development of structured data on quantitative indicators of water resources, forest cover area, biodiversity level, and economic aspects of the use of natural resources in Kazakhstan and Kyrgyzstan. Python and Microsoft Excel software tools were used to process large amounts of data. Python was used to automate data collection, processing, and pre-analysis processes, while Microsoft Excel provided additional verification of the received data and its visual structuring.

The second stage of the study included a qualitative analysis of scientific literature and statistical reports related to water resources management, the state of forest cover, and the impact of anthropogenic and climatic factors on environmental sustainability in the region. The main focus was on materials that highlight local features of the relationship between water resources and forest ecosystems. The collected data helped to identify key impact factors and assess their significance for ensuring ecosystem sustainability.

At the final stage, the results obtained were synthesised, which allowed formulating conclusions about the impact of water resources on forest ecosystems. The results of the analysis contributed to a better understanding of the main dependencies and helped to identify recommendations for water management to maintain environmental sustainability. The integrated approach provided a deep study of the problem and allowed to formulate conclusions that are relevant both for the scientific community and for practical use. Overall, the study was based on the integration of statistical and analytical data to gain a comprehensive understanding of the relationship between water resources and the ecological sustainability of forests in the region.

Results

General state of water resources of the regions under study. Analysis of data on water resources of Kyrgyzstan and Kazakhstan for the period 2014-2024 indicates significant changes in the level of water supply, water quality, and hydrological state of key reservoirs in the region (Table 1).

Table 1. General state of water resources of Kazakhstan and Kyrgyzstan for the period 2014-2023

Indicator	Unit of measurement	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Kazakhstan											
Renewable fresh water resources (annual runoff)	mln. m³	108,100	115,600	160,000	122,100	110,700	107,600	87,300	76,800	82,700	103,900
Fresh water intake	mln. m³	23,078	21,661	21,634	22,454	23,542	23,516	24,585	24,518	24,967	24,366
Fresh water intake per capita	m³	1,334.9	1,234.8	1,215.8	1,244.8	1,288.1	1,270.2	1,310.8	1,290.4	1,271.5	1,224.4
Water resource exploitation index	%	21.35	18.74	13.52	18.39	21.27	21.86	28.16	31.92	30.19	23.45
Level of load on water resources	%	32.01	30.04	30.01	31.14	32.65	32.62	34.10	34.01	34.63	33.79
Kyrgyzstan											
Water intake from natural sources	mln. m³	-	-	-	-	-	8,068.7	8,017.9	7,999.5	8,741.9	8,872.5
Water intake from underground horizons	mln. m³	-	-	-	-	-	254.8	249.8	252.9	258.4	271.0
Water consumption	mln. m³	-	-	-	-	-	5,211.1	5,237.5	5,310.0	5,844.0	6,028.0
For production needs	mln. m³	-	-	-	-	-	84.3	82.5	80.2	79.1	67.6
For irrigation and agricultural water supply	mln. m³	-	-	-	-	-	4,920.7	4,942.0	4,986.9	5,515.6	5,697.0
Wastewater volume	mln. m³	-	-	-	-	-	99.3	123.4	133.1	132.2	132.2

Note: data for Kyrgyzstan are provided according to the information of the water resources service under the Ministry of Water Resources, Agriculture and Processing Industry of the Kyrgyz Republic for the period 2019-2023. Despite the fact that the analysis covers the period 2014-2024, data for 2024 are not included in the table, since at the time of the study they have not yet been published on official statistical resources

Source: compiled by the authors based on National Statistical Committee of the Kyrgyz Republic (n.d.), Ministry of Ecology and Natural Resources of the Republic of Kazakhstan (n.d.), Bureau of National Statistics (n.d.)

Table 1 shows the instability of the water balance in Kazakhstan, where the annual runoff varies from 87.3 to 160 mln. m^3, which indicates the impact of climate change. Although fresh water intake remains stable (21.6-24.9 mln. m^3), the load on water resources reaches a critical 34%, and a decrease in the per capita intake indicates an increase in demographic pressure. In Kyrgyzstan, there is a stable intake of water from natural sources (8,017.9-8,872.5 mln. m^3) and a gradual increase in water consumption, which in 2023 reached 6,028 mln. m^3, mainly for agriculture. Compared to Kazakhstan, Kyrgyzstan has a lower level of load on water resources, but its dependence on groundwater and irrigation increases. In Kazakhstan, the high level of resource exploitation and instability of the water balance require the introduction of effective water resources management.

In Kyrgyzstan, the average water level in the main rivers, in particular in the Naryn River, decreased by 8% compared to the initial period of the study. The main reason for this is the intense melting of glaciers caused by an increase in average annual temperatures, which leads to a decrease in the total ice cover and, accordingly, long-term water reserves in rivers. In addition, climate change is accompanied by an increase in the frequency of droughts and a shift in snowmelt regimes, which leads to additional stressful conditions for water resources. Anthropogenic impact, in particular, water intake for irrigation agriculture and hydropower, further exacerbates the situation (Ushkarenko *et al.*, 2024). An increase in the average summer water temperature by 1.2°C leads to a decrease in the concentration of dissolved oxygen, which negatively affects the chemical composition of water and the biodiversity of aquatic ecosystems. In addition, according to research, river water pollution caused by discharges from industrial and agricultural enterprises has increased by 15% over the past decade (Wang *et al.,* 2022).

In Kazakhstan, there is a similar trend of decreasing water resources, in particular in the Ili River basin During the analysed period, the water level in the basin decreased by 6%. The main factors are an increase in domestic water consumption, in particular in agriculture, where the area of irrigated land is actively expanding, and a reduction in the inflow of water from China, which is conditioned by the intensive use of water resources for the economic development of Xinjiang. Lower water levels in Lake Balkhash, which is heavily dependent on the Ili River, have led to degradation of coastal forest ecosystems, reduced biodiversity, and soil salinisation. An increase in the water temperature in the lake by 1.0°C, together with an increase in the level of pollution by 10%, leads to an increase in negative environmental consequences, since pollution is usually caused by the flow of chemicals from agricultural wastewater and industrial enterprises (Kusmambetov & Suleimenova, 2022) (Table 2).

Table 2. Changes in the state of water resources in Kyrgyzstan and Kazakhstan for the period 2014-2024

Indicator	Kyrgyzstan	Kazakhstan
Average water level drop	-8%	-6%
Increased seasonal fluctuations in water levels	+10% variation	+8% variation
Water temperature rise	+1.2°C	+1.0°C
Pollution increase (water quality index)	+15% (increase in the concentration of harmful substances)	+10% (growth in industrial and agricultural wastewater)

Table 2 , Continued

Indicator	Kyrgyzstan	Kazakhstan
Reduced dissolved oxygen concentration	-0.5 mg/L (average reduction of 8%)	-0.3 mg/L (average 5% reduction)
Increased water consumption (agriculture)	+12% compared to 2014	+18% compared to 2014

Source: compiled by the authors based on K.D Kusmambetov & S.Z. Suleimenova (2022), W. Liu *et al.* (2023), G.N. Yusupova *et al.* (2024)

The results of the study indicate the need to introduce adaptive measures in the field of water resources management. In particular, it is recommended to optimise water consumption, modernise irrigation systems, and reduce the anthropogenic load on river basins. This will not only preserve water quality, but also improve the ecological state of water bodies, which is important for ensuring long-term environmental sustainability of the region. In addition, the study highlights the importance of modernising water infrastructure, considering conflicts of interest between different water users, which is crucial for developing effective water management strategies (Yusupova *et al.,* 2024). In addition, economic approaches demonstrate that the introduction of economic incentives can become an effective means of optimising water use, which, in turn, will help to reduce the negative impact on water resources.

Generalisation of findings and analysis of data for 2014-2024 indicate that in order to ensure the sustainability of water resources in Kyrgyzstan and Kazakhstan, it is necessary to implement integrated measures aimed at preserving water quality, modernising infrastructure and optimising water consumption. These measures should consider both natural and anthropogenic factors affecting water resources, which will reduce environmental stress and contribute to the long-term stability of the region.

State of forest ecosystems in Kazakhstan and Kyrgyzstan. The ecological sustainability of forest ecosystems in the region has undergone significant changes under the influence of water resources, which is directly reflected in the area of plantings, forest structure and biodiversity level (Table 3).

Table 3. State of forest ecosystems of Kazakhstan and Kyrgyzstan for the period 2014-2023

Year	Kazakhstan: Forest area, mln. ha	Kazakhstan: Forest-covered land, mln. ha	Kazakhstan: Forested area, %	Kyrgyzstan: Total Forest area, thous. ha	Kyrgyzstan: Forest area, thous. ha	Kyrgyzstan: Reforestation, thous. ha	Kyrgyzstan: Harvested wood, thous. m^3
2014	29.3	12.6	4.6	1,171.8	706.3	1.5	25.0
2015	29.3	12.7	4.6	1,172.0	704.2	2.2	18.1
2016	29.4	12.7	4.7	1,172.0	704.1	3.7	33.2
2017	29.8	12.9	4.7	1,172.0	704.1	2.4	13.7
2018	30.1	12.9	4.7	1,172.0	704.1	2.4	10.3
2019	30.0	13.1	4.8	1,172.0	704.1	2.9	5.3

Table 3, Continued

Year	Kazakhstan: Forest area, mln. ha	Kazakhstan: Forest-covered land, mln. ha	Kazakhstan: Forested area, %.	Kyrgyzstan: Total Forest area, thous. ha	Kyrgyzstan: Forest area, thous. ha	Kyrgyzstan: Reforestation, thous. ha	Kyrgyzstan: Harvested wood, thous. m^3
2020	30.0	13.3	4.9	1,172.0	704.1	1.8	9.0
2021	30.6	13.6	5.0	1,171.9	704.0	0.7	6.5
2022	30.9	13.7	5.0	1,171.8	703.9	1.6	11.1
2023	30.9	13.7	5.0	1,171.7	703.9	1.6	12.5

Source: compiled by the authors based on National Statistical Committee of the Kyrgyz Republic (n.d.), Ministry of Ecology and Natural Resources of the Republic of Kazakhstan (n.d.), Bureau of National Statistics (n.d.)

Official data indicate the stability of the total forest fund of Kyrgyzstan, which during 2014-2023 remained at the level of about 1,172 thous. ha. At the same time, the area of land covered with forest decreased from 706.3 thous. ha in 2014 to 703.9 thous. ha in 2023, which raises concerns about the effectiveness of measures to preserve existing forests. Reforestation shows uneven dynamics: if in 2016 this indicator reached a peak (3.7 thous. ha), then in subsequent years the area of new plantings significantly decreased, reaching only 1.6 thous. ha in 2023.

However, independent studies indicate a more alarming state of forest resources. In Kyrgyzstan, water scarcity, which is aggravated by a decrease in the volume of ice cover and unfavourable climatic conditions, led to a reduction in the area of forest stands by 5% over the analysed period. This is especially acute in mountainous areas, where lack of humidity limits the natural processes of forest regeneration. Insufficient water resources lead to a decrease in the density of plantings, slowing down the growth of trees and increasing their vulnerability to pests and diseases, which together leads to a decrease in the number of key tree species by about 10% (Missall *et al.,* 2022). This, in turn, negatively affects the ecosystem functionality of forests, reducing their ability to perform important environmental services such as carbon uptake and biodiversity maintenance. The decrease in the area of forest-covered land may be underestimated due to insufficient monitoring and limited assessment methods. In addition, there is a deterioration in the quality of forests due to damage to stands, which is confirmed by significant fluctuations in wood harvesting. For example, in 2019, this figure was only 5.3 thous. m^3, while in 2023 it increased to 12.5 thous. m^3, which is partly conditioned by sanitary logging. To prevent further degradation of forest ecosystems in Kyrgyzstan, it is necessary to strengthen monitoring, develop comprehensive forest restoration measures, and improve forest resource management.

Official data show that in Kazakhstan, the total area of land covered with forest increased from 12.6 mln. ha in 2014 to 13.7 mln. ha in 2023, and forest cover remains stable at 5% (Ministry of Ecology..., n.d.). However, these data do not fully reflect the actual state of forest ecosystems, especially in regions suffering from water scarcity, soil degradation and erosion processes, in particular, in the Ili River basin. There is a decrease in the area of forest cover by 7%, which is associated with a complex of factors, including a decrease in the water level, which affects soil moisture, increased erosion processes, and degradation of soil resources. Insufficient moisture caused by a decrease in water reserves leads to a loss of soil fertility,

which limits the ability of forests to self-heal. Soil degradation in the Ili River basin leads to a decrease in biodiversity: the number of both endemic and economically important tree species has decreased by 12% (Abayeva *et al.,* 2024; Atantayeva *et al.,* 2024). These changes place an additional burden on the ecological system, as reduced diversity weakens the ability of forest ecosystems to adapt to stressful impacts such as droughts and climate change.

Forest restoration programmes, among which the "Zhasyl El" initiative in Kazakhstan occupies a leading place, demonstrate a certain local efficiency, which explains the increase in total areas covered by forest (Forest Agency of…, n.d.). This programme aims to increase forest cover by planting new plantings and restoring degraded areas. However, at the regional level, the impact of such measures is insufficient to fully compensate for losses caused by water scarcity and erosion processes. In addition, in many regions, there is a need for integrated measures that combine the modernisation of irrigation systems, the use of the latest technologies for monitoring the state of forests and optimisation of water consumption, which would allow for more efficient restoration of forest resources.

Another significant problem is the change in the structure of forest stands. A decrease in water volumes leads to a transition from dense, multi-species forests to sparse forest-steppe formations that are less resistant to external influences. This negatively affects the ability of forest ecosystems to provide important environmental services, such as carbon uptake, biodiversity maintenance, and microclimate management. Changes in the composition of the species fund caused by water scarcity have long-term consequences for regional environmental sustainability, which is enhanced by an increase in anthropogenic load. However, there are positive examples in some areas. According to the latest data, some regions of Kyrgyzstan show gradual restoration of woodlands due to local ecosystem restoration programmes. These programmes include improving irrigation systems, using state-of-the-art monitoring technologies, and specialised forest management, which contributes to the stabilisation or even small growth of forest cover in individual areas. For example, in the Naryn region, the government has introduced a programme for the restoration of forests, which provides for the use of local seedlings and the use of modern technologies for monitoring the state of woodlands (Missall *et al.,* 2022). These measures help not only to restore the area of forest cover, but also improve its quality by optimising irrigation systems and maintaining the water regime, which is critical for biodiversity conservation. However, even these successful local examples cannot compensate for the overall downward trend in forest cover, which requires the development of integrated strategies at the regional level.

Thus, the overall state of forest ecosystems in Kyrgyzstan and Kazakhstan indicates a significant reduction in the area of forest stands and a decrease in the level of biodiversity due to water scarcity and related environmental problems. To ensure the long-term environmental sustainability of the region, it is necessary to implement integrated measures aimed at modernising water infrastructure, optimising irrigation systems, and developing regional forest restoration programmes. Such measures will contribute not only to the restoration of woodlands, but also to the preservation of their ecological functionality, which is critical for maintaining the sustainability of natural systems in the region.

Water resources as a key factor of ecological sustainability of forest ecosystems in Kyrgyzstan and Kazakhstan. Water resources are one of the most important factors determining the ecological sustainability of forest

ecosystems. In Central Asian regions such as Kyrgyzstan and Kazakhstan, where water availability is limited by geographical and climatic conditions, the role of water balance in maintaining forest life is becoming critical. Forest ecosystems, in turn, provide a range of ecosystem services, including climate regulation, biodiversity conservation, water intake, and soil stabilisation. Thus, there is a close relationship between the state of water resources and the ability of forests to function as environmentally sustainable systems.

In Kyrgyzstan, water resources play a crucial role in maintaining mountain forests, which are a source of ecosystem services for both local communities and the region as a whole (Kaldybaev *et al.*, 2024). Rivers such as the Naryn form the backbone of the country's water balance, providing the soil moisture needed for trees and other plants to grow. However, due to a decrease in the average water level due to climate changes, there is a gradual reduction in the area of forest cover. Lack of water affects the growth rate of trees, reduces their viability and ability to renew naturally (Yanitskyi, 2024). Combined with the increasing frequency of extreme weather events, such as droughts, this puts additional pressure on forest ecosystems.

In Kazakhstan, the situation is even more critical due to the relatively low water supply and high level of anthropogenic load on water resources. Irrigation systems designed primarily for agricultural needs consume significant amounts of water, reducing its availability to natural ecosystems. For example, in the Ili River basin, a decrease in the water level directly affects the degradation of forests in its floodplain, which are an important component of the region's ecosystem balance (Abraliyev *et al.,* 2024). Such changes lead to an increase in the vulnerability of forests to soil erosion, a decrease in biodiversity, and a decrease in their ability to absorb carbon dioxide.

An important factor that worsens the situation is climate change. An increase in the average annual temperature, a decrease in precipitation, and an increase in its uneven distribution lead to a gradual depletion of water resources (Belmega *et al.*, 2024). This creates a negative feedback loop, where a decrease in the area of forests that serve as natural regulators of the hydrological cycle contributes to an even greater water shortage in ecosystems. This dynamic is particularly noticeable in the semi-desert and steppe zones of Kazakhstan, where woodlands have a limited adaptive capacity for droughts.

Forward-looking estimates show that without effective water management, both countries may face further degradation of forest ecosystems. In Kyrgyzstan, the area of forests is expected to decrease by 5-7% over the next 10 years if the water level drops by 10% (Missall *et al.,* 2022). In Kazakhstan, similar losses can reach 8-10%, especially in regions with a high density of irrigation systems (Abraliyev *et al.,* 2024). Such trends will not only affect environmental sustainability, but will also have serious socio-economic consequences associated with reduced availability of resources for the local population.

To ensure the sustainability of forest ecosystems, it is necessary to implement integrated measures that include effective water management, modernisation of irrigation systems and the creation of water protection zones. In particular, strategic restoration of catchments in the mountainous regions of Kyrgyzstan can help stabilise the water level in rivers. In Kazakhstan, measures to improve the efficiency of water use in agriculture are important, which will increase the availability of water resources for natural ecosystems. In addition, it is necessary to encourage forest restoration through the introduction of adaptive vegetation species that can survive in harsher climates.

Consequently, water resources play a key role in ensuring the ecological sustainability of forests in Kyrgyzstan and Kazakhstan. Their scarcity has a direct negative impact on the functioning of forest ecosystems, creating a threat to their existence in the long term. Considering current trends, immediate measures for the conservation and rational use of water resources are critical to maintaining the viability of forests and preserving their ecological role in the region.

International cooperation water and forest resources management. The management of transboundary water resources is critical for the ecological sustainability of forest ecosystems in Kyrgyzstan and Kazakhstan. Common river basins, such as the Naryn and Ili, require coordination of efforts by both countries to ensure the rational use of water resources and the conservation of biodiversity.

President of Kazakhstan Kassym-Jomart Tokayev announced the creation of the Ministry of Water Resources and Irrigation of the Republic of Kazakhstan (n.d.), a specialised agency that will deal with solving water problems both within the country and in cooperation with neighbouring states. The move underscores Kazakhstan's commitment to sustainable water management and the introduction of green technologies.

Kyrgyzstan and Kazakhstan actively cooperate in the field of water resources management, especially in relation to transboundary rivers. One of the key initiatives is the Law of the Kyrgyz Republic No. 47 "On Ratification of the Agreement between the Government of the Kyrgyz Republic and the Government of the Republic of Kazakhstan on the Use of Interstate Water Management Structures on the Chu and Talas Rivers" (2001). This agreement provides a legal basis for joint management and maintenance of water bodies, ensuring the rational use of water resources and maintaining ecological balance in the basins of these rivers. Within the framework of this agreement, a joint commission has been established that coordinates the actions of both countries in the operation and maintenance of water management facilities. This includes joint monitoring of water resources, exchange of information on hydrological indicators, and coordination of water use plans. Such cooperation contributes to the effective management of water resources and prevents possible conflicts related to their use.

Regarding forest resources, there is currently no information on specific joint programmes between Kyrgyzstan and Kazakhstan. However, both countries are aware of the importance of preserving forest ecosystems and may consider developing joint initiatives in this area. This may include sharing experiences in reforestation, joint research, and developing strategies to adapt forests to climate change. Expanding cooperation in the field of forest resources can be an important step to ensure the ecological sustainability of the region and the conservation of biodiversity. Joint efforts to manage both water and forest resources will contribute to sustainable development and environmental security in both countries.

Investment in infrastructure is also a key element of cooperation. Co-financing projects aimed at improving irrigation systems, water conservation and restoring degraded forest areas will contribute to the sustainable development of both countries. An example of successful international cooperation is the Ukrainian-Romanian partnership in the field of water management, which is implemented within the framework of the Agreement between the Government of Ukraine and the Government of Romania "On Cooperation in the Field of Water Management in Border Waters" (1997), where joint efforts are aimed at rational and environmentally sound use of water and other natural

resources of the Danube, Tisa, Prut, and Sirey river basins. The implementation of such initiatives between Kyrgyzstan and Kazakhstan will contribute to strengthening the ecological sustainability of forest ecosystems and ensuring the sustainable development of the region.

Discussion

The results obtained confirm the general trends of changes in the water resources of Kyrgyzstan and Kazakhstan described in the literature. In particular, an analysis of Kyrgyzstan's water resources revealed an 8% decrease in the water level in the Naryn River due to melting glaciers and anthropogenic impact. This is consistent with the conclusions obtained by N.M. Nuralieva (2022), who noted that Kyrgyzstan's glaciers are significantly reduced by climate change, which in the long run reduces the availability of water resources for economic and environmental needs. In Kazakhstan, a 6% decrease in the water level in the Ili River basin and the degradation of coastal ecosystems are consistent with the findings of Y. Yu *et al.* (2021), which indicated a significant impact of human activity, in particular, the intensification of agricultural water consumption and changes in water management at the interstate level. Similarly, K. Orazaliev *et al.* (2024) emphasised that reducing the flow of water from China to the Ili basin, associated with the economic development of Xinjiang, is becoming a key problem for Kazakhstan, creating tension in the use of transboundary waters. The problems of water pollution were also confirmed by A. Tursunova *et al.* (2022). The researchers noted that the increase in industrial and agricultural discharges into water bodies of Kazakhstan and Kyrgyzstan by 10-15% is a consequence of inefficient water resources management and insufficient environmental control.

L. Andersson & E. Ardfors (2021) focused on assessing the possibilities of forest restoration in Kazakhstan, which partially coincides with the results obtained on the ecological sustainability of forest ecosystems. However, unlike the current approach, which considers the impact of water resources on the state of forest ecosystems, this study focuses more on reforestation strategies without a detailed analysis of water supply as a key environmental factor.

The results confirm the importance of integrating water management and environmental policy, as indicated in the literature. B. Sulaimanova *et al.* (2023) considered the role of investment and innovation in the sustainable management of agricultural resources in Kyrgyzstan, in particular, in the context of the green economy. The study focused on the need to invest in the modernisation of irrigation systems and the use of innovative technologies for water conservation. The results support these conclusions, as the degradation of aquatic ecosystems in Kyrgyzstan is largely caused by outdated water management methods that need to be reformed through the introduction of new technologies. The study by S. Giritlioglu & N. Tsoy (2024) emphasised the importance of water security for regional stability by analysing the relationship between Uzbekistan and Afghanistan. It was pointed out that water management in Central Asia is often accompanied by geopolitical tensions that increase the risks of environmental degradation. While the findings focus on Kyrgyzstan and Kazakhstan, they also highlight the impact of transboundary water use on ecosystem degradation. In particular, the reduced flow of water from China to the Ili basin is an example of similar problems that threaten regional stability.

B. Janusz-Pawletta *et al.* (2024) examined the role of stakeholder dialogue in improving water management in Central Asia. The researchers emphasised that effective cooperation between the countries of the region is key to ensuring sustainable water use. The results

obtained support this thesis, since the measures proposed in the paper, such as the modernisation of irrigation systems and the creation of water protection zones, require interstate coordination to achieve success. The study by N. Osmonova (2020) was devoted to the analysis of sustainable cooperation in the use of transboundary waters on the example of the Chu and Talas River basins. It was indicated that sustainable development is possible if a balance is achieved between economic needs and environmental requirements. Similarly, the results of the study showed that the growing anthropogenic burden on water resources, both in Kyrgyzstan and Kazakhstan, threatens the ability of forest ecosystems to perform ecosystem functions.

Research by A.N. Rakhimzhanov *et al.* (2021) was devoted to the assessment of the state of turang forests in the south-east of Kazakhstan, which has certain common aspects with the results obtained on the ecological sustainability of forest ecosystems. The main difference is that the researcher focuses on local changes in the structure of forest cover and degradation under the influence of anthropogenic and natural factors, while the current study analyses the relationship between the state of forests and the dynamics of water resources at the broader regional level. A. Aidaraliev *et al.* (2024) highlighted Kyrgyzstan's contribution to solving global problems of sustainable mountain development. Special attention was paid to the need to conserve water resources in the context of growing climate challenges. The results confirm this approach, because the melting of glaciers and the reduction of water resources in Kyrgyzstan, recorded in the study, are key factors affecting the ecological sustainability of the region.

The study by A. Hamidov *et al.* (2022) analysed the integration of the water-energy-food approach to ensure the sustainable development of socio-ecological systems in Central Asia. The researchers emphasise the importance of an interdisciplinary approach for effective management of natural resources, which is also relevant for the Naryn and Ili River basins considered in the study. The results confirm that water scarcity negatively affects not only ecosystems, but also food security, which requires a comprehensive approach to developing adaptation strategies. E. Ahmadov (2020) considered the issues of water resources management for achieving sustainable development in Azerbaijan. The researcher focused on the need for rational use of water resources, modernisation of water infrastructure, and creation of water protection zones. This supplements the conclusions of this study, which also suggest the modernisation of irrigation systems and the creation of protected areas to preserve environmental sustainability.

In turn, the study by S. Kitaibekova *et al.* (2023) evaluated forest ecosystem services in "Burabai" national park, which provides valuable information about the socio-economic significance of forest ecosystems. Compared to the results obtained, which focus on the ecological aspects of the impact of water resources on forest ecosystems, this study is more focused on the economic assessment of ecosystem services, which complements the study, adding a practical perspective on the use of forest resources. Thus, the results confirm the conclusions of previous studies, emphasising the need for integrated water management, modernisation of irrigation systems, and adaptive reforestation to ensure the ecological sustainability of the region. The results of the study specify the scale of changes, in particular quantitative losses of water and forest resources, which complements the available literature with new data.

Conclusions

Analysis of the water resources of Kyrgyzstan and Kazakhstan for the period 2014-2024

revealed significant changes in water supply and water quality. In Kyrgyzstan, the average water level in the main rivers, in particular in Naryn River, decreased by 8% compared to the beginning of the study. This is conditioned by the intense melting of glaciers due to an increase in average annual temperatures, which leads to a decrease in the ice sheet and long-term water reserves. Anthropogenic impact, in particular, water intake for irrigation and hydropower, worsens the situation. Increasing the average summer water temperature by 1.2°C reduces the concentration of dissolved oxygen, negatively affecting the chemical composition of water and biodiversity. River pollution from industrial and agricultural discharges has increased by 15% over the past decade. In Kazakhstan, there is a similar trend: the water level in the Ili River basin decreased by 6% during the analysed period. This is conditioned by an increase in domestic water consumption, especially in agriculture, and a reduction in water inflows from China due to the intensive use of resources for Xinjiang's development. The decline in the water level in Lake Balkhash, which depends on the Ili River, has led to the degradation of coastal forests, reduced biodiversity and salinisation of soils. A 1.0°C increase in the lake's water temperature and a 10% increase in pollution exacerbate the negative environmental impacts, as the pollution is caused by chemicals from agricultural and industrial runoff.

The forest ecosystems of Kazakhstan and Kyrgyzstan are significantly affected by water scarcity and climate change. In Kyrgyzstan, a 5% reduction in forests is caused by melting glaciers and reduced humidity, which complicates their regeneration, reduces biodiversity and weakens ecosystem functionality. In Kazakhstan, a 7% decrease in forest area, in particular in the Ili River basin, is associated with a decrease in water levels, soil degradation, and loss of species diversity (by 12%). Positive local initiatives, such as the "Zhasyl El" programme in Kazakhstan and the restoration of forests in Kyrgyzstan, have limited impact. Long-term sustainability requires comprehensive strategies: water management modernisation, irrigation optimisation, and the introduction of modern natural resource management technologies.

The analysis shows that the water balance directly affects biodiversity conservation, soil stability, and the ability of forests to perform their ecosystem functions. The conditions of limited water availability typical of Central Asia are compounded by climate change, which leads to a decrease in water resources, a reduction in forest areas, and an increase in their vulnerability to degradation. In Kyrgyzstan, the biggest challenges relate to mountain forests, which depend on the stability of the river catchment area, while in Kazakhstan, significant pressure is caused by irrigation systems that reduce the availability of water for natural ecosystems.

Increasing water scarcity creates negative feedback, where reducing the area of forests increases water stress in the region. Projected forest cover losses over the next decade indicate the need for immediate action to mitigate this impact. Effective water management, modernisation of irrigation systems, creation of water protection zones and introduction of adaptive reforestation methods can help to stabilise the ecological balance. Strategic measures are aimed not only at preserving forest ecosystems, but also at ensuring their role as regulators of the hydrological cycle, which is important for the socio-economic well-being of the region.

International cooperation in water and forest management is key to ensuring environmental sustainability in Kyrgyzstan and Kazakhstan. The joint management of transboundary water resources, in particular the Naryn and Ili rivers, promotes water management and prevents environmental problems. The agreement between the governments of both countries

on the use of water management facilities on the Chu and Talas rivers is an important step for sustainable water use. The development of collaborative forest resource initiatives, in particular, research and adaptation strategies, will contribute to biodiversity conservation and ecosystem improvement. Investment in infrastructure and adaptation to climate change will help to improve environmental security and sustainable development in the region.

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Conflict of Interest

None.

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Водні ресурси як фактор екологічної стійкості лісових екосистем Киргизстану та Казахстану: Виклики та перспективи співпраці

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Анотація. Актуальність дослідження зумовлена зростаючим впливом зміни клімату та антропогенного навантаження на водні ресурси, які мають вирішальне значення для підтримання екологічної стійкості лісових екосистем Центральної Азії. Метою дослідження було оцінити зміни водних ресурсів Киргизстану і Казахстану протягом 2014-2024 рр. та визначити їх вплив на екологічну стійкість лісових екосистем. Методи дослідження включали аналіз гідрологічних даних щодо кількості та якості водних ресурсів за вказаний період, а також аналіз наукових джерел щодо взаємозв'язку між водним балансом, біорізноманіттям та станом ґрунтів. Зокрема, було проаналізовано рівень води у великих річках (Нарин, Ілі), зміни температури води, хімічне забруднення та динаміку лісових площ. Результати показали, що рівень води в річці Нарин знизився на 8 % через танення льодовиків і збільшення водозабору, в той час як в річці Ілі цей показник склав

6 % через зменшення припливу води з Китаю і збільшення водоспоживання. Середня температура води зросла на 1,0-1,2°C, що призвело до зниження концентрації розчиненого кисню та негативно вплинуло на біорізноманіття. Забруднення води промисловими та сільськогосподарськими скидами зросло на 10-15 %, що посилило деградацію прибережних екосистем та біорізноманіття. Дані свідчать про відносну стабільність загального лісового фонду Киргизстану, але спостерігається зменшення площі земель, вкритих лісом, що викликає занепокоєння щодо ефективності природоохоронних заходів. Лісовідновлення демонструє нестабільну динаміку через зміну клімату та дефіцит води. Скорочення лісових площ склало 5 % у Киргизстані та 7 % у Казахстані, причому найбільші втрати спостерігаються в басейні річки Ілі. Зменшення біорізноманіття в Казахстані досягло 12 %, а в Киргизстані скорочення площі лісів посилило водний стрес у гірських регіонах. Отримані дані підкреслюють тісний взаємозв'язок між станом водних ресурсів і здатністю лісових екосистем виконувати екологічні функції

Ключові слова: зміна клімату; біорізноманіття; біогеоценоз; річкові басейни; рослинність