

The impact of anthropogenic factors on aquatic ecosystems: the case of Kazakhstan

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Abstract. This article analyzes the impact of anthropogenic factors on aquatic ecosystems. Anthropogenic factors refer to those resulting from human activities. The authors examine factors that negatively affect the environment and the resulting consequences. It is highlighted that mining operations have a particularly detrimental effect, as wastewater from industrial enterprises introduces large amounts of toxic heavy metal compounds into the aquatic environment. The negative impact on aquatic ecosystems is also linked to agricultural production and inefficient irrigation systems. Additionally, thermal pollution, which occurs when excess energy is released during electricity generation, has serious environmental consequences. Water used for cooling is subsequently discharged into reservoirs, further degrading water quality. The condition of water bodies is a pressing environmental issue that requires urgent attention. The authors propose a set of measures to protect and restore aquatic ecosystems.

1 Introduction

The preservation of a clean ecological environment is one of the most pressing issues of our time. The deterioration of biosphere ecosystems due to anthropogenic factors has become a persistent trend. It is possible to regulate and limit the impact of human activity on the environment – referred to as anthropogenic impact – which may be direct and deliberate or indirect and unconscious, causing changes in the natural environment. Freshwater sources, such as rivers, lakes, wetlands, soil, and groundwater, are particularly vulnerable to active anthropogenic influence. It is important to determine whether the anthropogenic factors contributing to environmental degradation stem from routine human activities that are environmentally unsustainable and violate the laws of nature, or if they are the consequences of man-made accidents.

Negative anthropogenic impacts on the environment include activities such as mining and deforestation, which result in the extraction of substances and energy from nature. Simultaneously, the introduction of pollutants and energy into natural systems leads to

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geochemical contamination of environmental components. Human influence also manifests in the transformation of natural substances and energy, including the creation of artificial fields, the acceleration of exogenous geological processes, as well as the construction of transportation networks, urban development, and hydrotechnical structures.

2 Methods

In the course of addressing the research objectives, methods from various sciences were employed. The comparative method enables the analysis of the studied objects and phenomena by comparing them. System analysis helps identify the complex internal connections and components within the ecosystem, as well as the relationships between the ecosystem and its external environment, and examines the impact of anthropogenic factors on ecosystem functioning. Historical methods allow us to trace changes within the ecosystem over specific periods. These methods are crucial tools for studying ecosystems and the anthropogenic factors influencing them.

3 Discussion and results

3.1. Ecology of water systems

Aquatic ecosystems are constantly influenced by various types of hazards and pollution sources. The quality of groundwater and surface waters depends on both natural processes and human activities. Natural processes such as rock weathering, evaporation, wind-driven precipitation, leaching from soil, runoff due to hydrological factors, and biological processes within the aquatic environment all contribute to changes in water quality.

At present, human activity plays a key role in shaping the condition of modern aquatic ecosystems. Human influence on water bodies can be classified according to various aspects, including the nature and intensity of the impact.

Anthropogenic factors, including agriculture with its fertilizers and pesticides, inefficient resource use in animal husbandry, deforestation, aquaculture, and pollution from industrial and domestic wastewater, have a profoundly negative impact on the quality of water bodies. This leads to increased concentrations of heavy metals like mercury and the spread of *E. coli*, both of which pose significant threats to the health of ecosystems and humans.

Water pollution has catastrophic consequences for the entire ecosystem. The poor condition, general obsolescence, and low efficiency of industrial wastewater treatment plants lead to the discharge of liquid industrial waste into water bodies. To maintain the aquatic ecosystem in a healthy state, it is essential to implement and ensure the continuous operation of highly efficient industrial liquid waste treatment systems that meet modern standards.

The mining industry, particularly open-pit coal mining, negatively impacts ecosystems. Current wastewater treatment technologies for coal mines are insufficiently developed, and methods for treating other types of wastewater are not well-adapted to the specifics of mining industry wastewater. As a result, the urgent task of reducing water source pollution arises [1].

The negative impact on water resources is also caused by the toxic effects of pollutants on existing populations and by changes in the fundamental structural and functional characteristics of aquatic communities. Pollution sources can be divided into point (organized) and diffuse sources, both of which contribute to water quality deterioration. These pollutants mainly stem from key economic activities such as settlement development,

recreational facilities, industrial production, and agriculture. Atmospheric deposition of pollutants also has an effect. Without human intervention, natural freshwater communities are highly productive and capable of sustaining themselves over long periods. However, the intensive urbanization of watersheds has led to a sharp increase and acceleration of productivity processes in aquatic environments [2].

Studies have shown that sources of water body pollution can also include rural settlements and livestock farms (complexes) [3]. Research on water resources in urban environments has revealed increased levels of formaldehyde, volatile phenols, and oil in precipitation samples [4].

River water resources are actively used in various sectors of the economy, including hydropower, industrial and rural water supply, irrigation, fishing, and recreation. While they are essential for the electric power industry and flow regulation, their potential negative environmental impacts must also be considered. The sustainable use of water resources in transboundary basins requires careful consideration and coordinated efforts among all concerned countries to ensure a balanced and sustainable management approach for these vital resources.

One negative consequence of reservoir use is the displacement of local flora and fauna, as large areas of land, previously natural habitats, become flooded. This leads to a reduction in biodiversity. Another negative outcome is water pollution, as contaminants from agricultural lands and industrial enterprises enter reservoirs, decreasing water quality and worsening the living conditions for fish and other aquatic organisms. Furthermore, changes in the river's water regime, caused by the use of reservoirs in transboundary basins, alter the natural flow of rivers and other critical parameters for aquatic organisms [5].

One of the key environmental issues is thermal pollution, which has serious ecological consequences. The generation of electrical energy results in the release of a large amount of excess heat, with water used for cooling that is then discharged into external water bodies. These temperature changes negatively affect the life processes of aquatic organisms.

Different species of algae, competing for nutrients, light, and space, are particularly affected by fluctuations in temperature. Such fluctuations disrupt the competitive balance among species, leading to the death of some and the accelerated growth of others, causing ecological shifts.

Thermal pollution also alters species diversity in aquatic ecosystems. By reducing seasonal temperature fluctuations in water bodies, thermal pollution can affect the life cycles of certain fish and plants, sometimes even leading to their extinction. Thermal stress is particularly detrimental in hot climates, where organisms are often exposed to extreme temperatures.

Rivers, once reliable sources of fresh water, have increasingly become channels for waste transport. These harmful substances gradually travel along river systems, eventually reaching seas and oceans. A significant proportion of river water used by humans is returned as wastewater. However, the expansion of wastewater treatment facilities has not kept pace with increasing water consumption, becoming a major contributor to water pollution. Studies indicate that even the most advanced treatment methods, including biological purification, leave behind all dissolved inorganic substances and up to 10% of organic pollutants in wastewater [6].

For water to become suitable for consumption again, it must be repeatedly diluted with clean natural water. Therefore, it is crucial to consider the ratio of the total volume of wastewater, even after treatment, to the volume of river water flowing into reservoirs. Studies have shown that almost 20% of the world's freshwater resources are used to dilute wastewater. According to estimates, even if water consumption is reduced and all wastewater is treated, it would still require 30–35 thousand km³ of fresh water annually to dilute the wastewater. It is clear that the resources of the world's river flows are nearing

exhaustion, and in some regions, they are already completely depleted. Research indicates that 1 km³ of treated wastewater harms 10 km³ of river water, while untreated wastewater causes damage to 3–5 times more water [7]. Although the overall volume of fresh water does not decrease, its quality deteriorates, rendering it unfit for consumption.

Researchers forecast that by 2070, 80% of the world's population could face water supply issues and a real water resource crisis. Hydrologist Howard S. Wheater argues that we must abandon outdated approaches to water resource management, which depend not only on scientific advancements but also on political, managerial, and social considerations [8]. In this century, the world's freshwater reserves are under unprecedented stress. Hydrological parameters and water quality are being altered by urbanization, deforestation, and the expansion of irrigated lands, which now cover approximately 1.5 billion hectares [9].

The problem of water scarcity is one of the most pressing issues of the 21st century, leading to the deterioration of ecological conditions in many regions, the drying up and pollution of lake and river ecosystems, and an increase in population-related diseases. Despite the potentially large reserves of freshwater globally, there is still a risk of depletion due to irrational water use or pollution. A water crisis is currently affecting large geographic regions, with 20% of the urban population and 75% of the rural population worldwide lacking adequate access to water. Depending on location and living standards, daily water consumption per person varies widely, from 3 to 700 liters [7].

The protection of water resources from pollution is an urgent issue requiring immediate attention. Since industrial wastewater accounts for the largest volume and causes the most damage, addressing its discharge into water bodies must be a priority. Protective measures should include reducing the pollution load on water bodies by limiting wastewater discharge into water sources and improving production, purification, and disposal technologies [10, 11].

To restore water bodies, it is essential to first reduce the so-called external load, which means decreasing the volume of industrial and stormwater wastewater. These sources introduce pollutants into water bodies, increasing the levels of phosphorus, nitrogen, and other biogenic and harmful substances in the aquatic ecosystem. Without appropriate actions to address this issue, no restoration efforts will lead to significant or lasting improvements. In some cases, simply reducing external loads may be sufficient to restore the normal functioning of aquatic ecosystems.

However, many alternative sources of biogen input can quickly compensate for these reductions, necessitating additional restoration measures. It is important to consider that phosphorus reserves in bottom sediments can become a significant internal source of this biogenic element. These reserves may compete with external influences, quickly compensating for the deficit caused by the reduction in external phosphorus input [12].

Basically, other sources of biogens often quickly compensate for their reduction through additional measures. For example, phosphorus reserves in sediments can act as a significant internal reserve of this nutrient, comparable to external sources, quickly making up for deficiencies caused by a reduction in external inputs.

It is known that deep reservoirs respond more quickly to a decrease in external load compared to shallow ones. In contrast, recovery in shallow lakes is slower due to constant wind mixing, which leads to the frequent resuspension of substances, including biogens, from bottom sediments into the photic layer, triggering the recurrence of algal blooms. In such reservoirs, the release of substances from sediments often exceeds recovery rates seen in stratified lakes [13].

If necessary, targeted measures can be taken to protect against specific pollution sources. Reducing external impacts can lead to noticeable improvements in water bodies,

such as lower nutrient concentrations, a reduction in phytoplankton, and increased water transparency.

When pollutants are removed, their concentration in the receiving reservoir also decreases. The most effective way to reduce external pressure is to minimize discharges from structured (point) sources of wastewater and decrease the load from catchments (diffuse sources). This can be achieved by constructing sewage treatment plants and organizing the collection and discharge of stormwater runoff around the perimeter of the water body.

Protection against diffuse sources of pollution is also an effective method. Although the primary impact on reservoirs typically comes from organized wastewater discharges, the influence of diffuse pollution, especially in urban areas, should not be underestimated. This type of pollution is difficult to track and manage, complicating efforts to control it.

Neglecting diffuse pollution can significantly hinder and slow down ecosystem recovery, even when planned restoration activities are already underway.

3.2. Aquatic ecosystem of Kazakhstan

In Kazakhstan, the situation with water resources remains critical and reflects global challenges. The condition of reservoirs is a key environmental issue that obstructs the sustainable development of the country. Despite the current low level of irrigation, water resources are being used close to their maximum capacity, which negatively impacts both social and economic progress.

Most of Kazakhstan's territory experiences a lack of moisture. Despite the country's wealth of natural resources, particularly oil and gas, water scarcity remains a critical issue. The availability and quality of water resources are vital factors that influence the Republic's economic development. However, the condition of reservoirs is rapidly deteriorating, and their pollution could have severe environmental consequences [14].

According to a United Nations special report on the state of global water resources published in 2019, water consumption worldwide has been steadily increasing by about 1% per year since the 1980s. This growth is driven by a combination of population increase, socio-economic development, and changing water consumption patterns.

Kazakhstan ranks last among CIS countries in terms of water availability. On average, the country's river water resources amount to 100.5 km³ per year, with only 56.5 km³ generated within the republic itself, while 44.0 km³ comes from neighboring states.

The instability of river flow is linked to global and regional climate changes, as well as economic activities carried out in watersheds and river valleys, including those in neighboring countries. Kazakhstan's surface water resources are nearing complete exhaustion [15, 16].

Groundwater is primarily used for household and drinking needs, accounting for only 3-5% of the total water consumption. Addressing the country's water management challenges is possible only through the rational use of surface waters and the development of underground water resources. About 50% of Kazakhstan's groundwater reserves are located in the southern region, while the western part of the country has significantly fewer resources – up to 20%. Central, northern, and eastern Kazakhstan together hold around 30% of all underground water resources.

A major issue is that seven of Kazakhstan's eight water basins are transboundary. The country is highly dependent on the water policies of its neighbors – China, Kyrgyzstan, Uzbekistan, and Russia. The main challenge in Kazakhstan's relations with China is the absence of a formal agreement on transboundary river water resources. To date, Kazakhstan is the first and only country with which China is negotiating on this issue. Kazakhstan is

seeking an agreement aimed at preserving the ecosystems of transboundary rivers, but China has shown little interest. Work on the agreement began in 2015 and is still ongoing.

There is an acute shortage of water resources in the Ili River, which runs along the border with China. Currently, China's water intake from the Ili River for the Xinjiang Uygur Autonomous Region is approximately 3.5 km³ per year, and this is projected to increase to 5 km³ per year in the coming years. This, in turn, will lead to the shallowing and salinization of Kazakhstan's largest lake, Lake Balkhash. Over the past 20 years, the volume of the Ili River's flow has already decreased from 17.8 km³ to 12.7 km³ per year. Experts predict that current projects may reduce the river's flow in Kazakhstan by 40% by 2050. Additionally, the construction of industrial (mainly oil extraction and refining) plants in the river basin on the Chinese side is expected to increase water pollution. This will further exacerbate environmental problems in the Kazakh section of the river, which is already considered unfavorable due to pollution from household and agricultural waste in the tributaries, as well as the spread of degraded and saline areas. Overall, water withdrawals by neighboring countries negatively affect water availability in Kazakhstan. As populations in neighboring countries grow, these withdrawals will likely increase, with serious consequences for Kazakhstan [17].

The Irtysh River, one of Kazakhstan's key transboundary waterways and an essential river for the entire Eurasian region, is a vital waterway for the country. This major river supplies drinking water not only to its own basin but also to vast low-water areas of Central Kazakhstan through the Satpayev Canal. The river sustains the livelihoods of a large industrial region, covering three regions – East Kazakhstan, Pavlodar, and Karaganda. These lands, with a total area of over 836,000 square kilometers, are home to more than 4 million people, or about a quarter of Kazakhstan's population. Thus, the river serves not only as a source of water but also as a crucial lifeline for millions of people.

Table 1. The main characteristics of the Irtysh River [18].

Length		The total area of the basin (catchment area, thousand square kilometers)	The volume of annual runoff, km ³	
total length	on the territory of the Republic of Kazakhstan		2022	average long-term
4 248	1700	210 (16430)	25.9 (Semiyaarka)	27.3

The deterioration of the water situation is caused by both natural factors and human activity. Natural causes include the uneven distribution of water resources in the territory, fluctuations in runoff throughout the year and over a long time, as well as the negative impact of wastewater, the damage from which increases with the development of the economy.

Human activity also leads to a significant increase in water use and pollution of reservoirs. In addition, the growing interconnection of regional water problems should be taken into account.

Table 2. The level of pressure on water resources in Kazakhstan [18].

Indicators	2018	2019	2020	2021	2022
Renewable freshwater resources (river runoff resources), m ³	110 700	107 600	87 300	76 800	82 700
Fresh water intake, million m ³	23 542	23 516	24 585	24 518	24 966.7
The level of pressure on water resources, %	21.3	21.9	28.2	34.9	30.2
Fresh water intake per capita, m ³	1 288.1	1 270.2	1 307.8	1 290.4	1 271.5

The largest basin of the Irtysh River is significantly affected by anthropogenic factors, including the discharge of wastewater with pollutants. Toxic waste from industrial enterprises penetrates into underground aquifers, polluting them with lead, cadmium and other harmful substances.

An analysis of the location of enterprises that negatively affect the quality of water resources shows that they are concentrated in areas with a high density of the river network. The river is most heavily polluted with heavy metals in a large technogenic biogeochemical province associated with urbanized territories.

Among the systemic problems of water use in the transboundary Irtysh basin, the depletion of water resources due to increased water intakes in China and Kazakhstan, as well as losses from evaporation from reservoirs of the Verkhneirtyshsky hydroelectric power plants and other hydraulic structures can be identified. A high level of pollution of reservoirs with heavy metals and petroleum products is observed against the background of the work of 63 industrial enterprises in the upper reaches of the river. There is also an urgent problem of radiation pollution caused by the activities of the Semipalatinsk test site, the Lob-Nor test site in China, the Mayak Republican Association and other facilities. Special attention should be paid to the emergency condition of hydraulic structures and the insufficient development of legal mechanisms for regulating water use in transboundary states [19].

The level of manifestation of these problems varies in different national segments. In the basin of the Kara-Irtysh River (Black Irtysh), where Kazakh-Chinese cooperation is actively developing, the most acute problem is the depletion of water resources as a result of increased consumption in China, including the transfer of water through the Irtysh canals to the cities of Karamai and Urumqi, as well as the growth of irrigated areas. Water allocation issues remain unresolved in this zone, and if the Chinese government's plans are implemented, the volume of withdrawal may reach 50% of the water runoff, which will lead to a crisis situation. Radioactive contamination caused by tests at the Chinese nuclear test site near Lake Lob-Nor (1964–1980 – ground tests, until 1996 – underground ones) has not been sufficiently investigated to date, however, signs of radioactive contamination were recorded on the territory of Kazakhstan and the Far East just a few days after the tests. The procedure for upgrading the Test Site is currently underway.

The Kazakhstani segment of the Irtysh River has a high population density and a concentration of economic activity. The mining industry dominates in the upper reaches of the basin, located in the territory of the East Kazakhstan region. A significant part of the river is regulated by three large hydroelectric power plants, functioning as a geotechnical system. In the Pavlodar region, the emphasis is on thermal energy and processing. Below the city of Pavlodar, water is taken from the Irtysh canal to provide water resources for the city of Karaganda and the further needs of Astana, as well as for irrigation and water supply of agriculture in the northern territories of Pavlodar, where there are no other sources of water supply.

The water resources of the Irtysh River in Kazakhstan are characterized by unstable interannual dynamics and a high degree of pollution. The Brexa, Glubochanka and Krasnoyarka tributaries are characterized by a high degree of pollution, and the water in the Brexa River has an “extremely high level of pollution” (grade 5 quality with indicators from 10.2 to 28.2). It is also impossible to ignore the storm drains coming from the territory of the Semipalatinsk test site and urban areas of the industrial centers of East Kazakhstan, which contribute to the deterioration of the quality of the waters of the Irtysh.

The environmental situation in the Irtysh River is deteriorating due to an increase in the discharge of untreated wastewater from enterprises. These wastewaters contain significant amounts of petroleum products, phenols and synthetically active substances. In Kazakhstan, 53 large enterprises discharge about 260 million m³ of wastewater into the Irtysh [20].

The problems of the Irtysh basin are not limited only to water shortages, but are also associated with a deterioration in its quality. This is due to the regulation of runoff, which negatively affects the aquatic ecosystem as a whole.

In general, this area represents a complex natural and economic system that faces numerous challenges related to both the quantity and quality of water resources, as well as the processes governing their formation and use.

To improve and stabilize the ecological situation, it is necessary to conduct regular, comprehensive analysis and assessment of the ecosystem's state. Preventive measures must be implemented, along with financial support for environmental projects. This includes both the reconstruction of old and the construction of new wastewater treatment plants, equipping them with modern equipment and devices for monitoring water resources, and introducing technologies to restore the original properties of water and purify it from mechanical and chemical pollutants.

Modern wastewater treatment methods can significantly reduce the levels of organic pollution in water bodies. Additionally, it is crucial to adopt a rational approach to water resource management, reduce the anthropogenic impact on rivers and groundwater caused by industrial and agricultural activities, and clean recreational areas of household waste.

Table 3. Investments in environmental protection in Kazakhstan [18].

Indicators	2018	2019	2020	2021	2022
for wastewater treatment	6 179 506	2 909 014	11 775 069	31 016 559	43 455 884
for the protection and rehabilitation of soil, groundwater and surface waters	9 882 630	8 775 234	7 108 863	10 485 558	11 292 452
Total	16062136	11684248	18883932	41502117	54748336

Investments allocated to environmental protection, in particular for wastewater treatment and for the protection and rehabilitation of soil, groundwater and surface waters, are increasing annually in Kazakhstan).

4 Conclusion

Thus, no trends were observed towards an increase in the concentration of trace elements included in the association of pollutants [21]. The excess standards for the total content of gallium, cobalt, arsenic, copper, and zinc noted in spectral analyses are typically not confirmed by chemical analyses. The work carried out by the Scientific and Technical Society of Non-Ferrous Metallurgy of the Republic of Kazakhstan allowed for an objective assessment of the environmental components in the area of industrial waste storage, concluding the absence of dangerous trends in their changes. The assessment of environmental components in the area of waste storage facilities at the Vostochny section of the Eurasian Energy Corporation Open Joint-Stock Company supports the continuation of waste storage at present.

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