IRSTI 87.35.91
Section: Ecology
Review

Sustainable development of the Esil river basin: an intersectoral approach and scenario analysis

Tomaz Dentinho[1], Gulnur Saspugayeva[2], Assel Zhaken[2]*

[1]University of Azores, Angra do Heroísmo, Portugal;
tomas.lc.dentinho@uac.pt
[2]Eurasian National University, Astana, Kazakhstan;
gulnur_erzhanovna@mail.ru, zhaken.asel@gmail.com
***Correspondence:** zhaken.asel@gmail.com

Abstract: The Esil River Basin, located in northern and central Kazakhstan is a key industrial-agricultural region where agriculture dominates. The basin is characterized by high variability in annual runoff and uneven intra-annual water distribution, making water a critical factor for sustainable development. The region is facing some challenges that could potentially jeopardize its socio-economic and environmental stability, including increasing water scarcity, pollution, inefficient water management, and a growing demand, particularly from the capital city of Astana. This study presents the first integrated scenario analysis for the basin, combining inter-basin water transfer from the Irtysh River, the development of the Buzuluk Reservoir, the expansion of irrigated agriculture for high-value durum wheat, and small-scale hydropower generation. These measures are framed within an eco-engineering approach to enhance the region's sustainability and resilience.
Findings indicate that transferring up to 1.5 km^3 of water annually from the Irtysh River, supported by improved storage and renewable energy generation, could significantly strengthen water, food, and energy security while contributing to Kazakhstan's decarbonization goals. The proposed interventions demonstrate the practical application of the water-energy-food-ecosystem (WEFE) nexus and eco-engineering principles, providing policymakers with evidence-based strategies to enhance resilience against environmental and economic challenges.
Future research should incorporate environmental impact assessments, socio-economic feasibility studies, and participatory approaches to ensure the effective and sustainable implementation of these strategies.

Keywords: sustainable development; water resources management; territorial redistribution of water resources; sustainable agriculture; small hydro

Citation: Dentinho, T., Saspugayeva, G., Zhaken, A. (2025). Sustainable development of the Esil River Basin: an intersectoral approach and scenario analysis. Bulletin of the L.N. Gumilyov ENU. Chemistry. Geography. Ecology Series, 151(2), 237-254. https://doi.org/10.32523/2616-6771-2025-151-2-237-254

Academic Editor:
Zh.G. Berdenov

Received: 05.02.2025
Revised: 26.05.2025
Accepted: 02.06.2025
Published: 30.06.2025

1. Introduction

The Esil River Basin, situated in the northern and central parts of Kazakhstan, is a critical industrial and agricultural region, with agriculture being the predominant sector. Water availability plays a pivotal role in sustaining the region's economic activities, yet the basin experiences high variability in annual runoff and extreme irregularity in intra-annual water distribution (Kazhydromet, 2023). Such hydrological instability is further exacerbated by climate change impacts, which lead to prolonged droughts and pose serious threats to water security (Kakabayev et al., 2023).

Previous studies have addressed various aspects of water management and climate vulnerability in Northern Kazakhstan (Yessenzholov et al., 2024; Makhmudova et al., 2023). However, there remains a significant gap in integrated scenario-based assessments that combine water, energy, and food security strategies, particularly incorporating eco-engineering practices (Zeng et al., 2024). The relevance of applying water-energy-food nexus approaches in transboundary and arid regions has been well documented in the global literature (Ali & Acquaye, 2024; Bazilian et al., 2011), highlighting the need for holistic frameworks to address sectoral interdependencies.

At the same time, eco-engineering methods have shown promise in mitigating environmental degradation and enhancing sustainability in river basin management (Skoulikaris & Zafirakou, 2019). In Kazakhstan, water resource management remains fragmented, and the lack of comprehensive approaches integrating inter-basin water transfer, renewable energy development, and sustainable agriculture limits the region's capacity to adapt to emerging challenges (Ramazanova et al., 2019).

In this context, this study aims to provide the first integrated scenario analysis for the Esil River Basin, combining inter-basin water transfer from the Irtysh River, the construction of the Buzuluk Reservoir, the expansion of irrigated agriculture for high-value durum wheat production, and the development of small-scale hydropower facilities. The research applies eco-engineering principles and the water-energy-food-ecosystem (WEFE) nexus framework (Saidmamatov et al., 2023; Decoppet et al., 2023) to assess the potential of these measures to enhance regional resilience and support Kazakhstan's sustainability and decarbonization goals.

2. Materials and Methods

2.1. Materials

The materials used in this article included historical data on precipitation, air temperature, water use of the Esil River, hydrological maps of the region, data on soil cover and the proportion of irrigated land, as well as irrigation standards and gross yield of durum wheat. The economic data included market prices for wheat. The infrastructure data covered the existing water management infrastructure and plans for the construction of new water management facilities and an inter-basin water transfer project.

The Esil River basin is distinguished by a sharply continental and arid climate. During the warm months, the region experiences high temperatures, low precipitation, and significant air dryness. Precipitation distribution within the basin is strongly influenced by orographic features and altitude (Duskayev et al., 2021). The annual precipitation difference across various Esil stations can reach up to 75 mm (351 mm at the Petropavlovsk meteorological station, 276 mm at the Esil meteorological station). The primary water source for the basin's rivers is the seasonal precipitation, with 60-75% occurring in the warm months and 25-40% during the cold months (CAWater-Info, 2025). In this arid climate, a considerable portion of precipitation (300 to 325 mm) evaporates from the land surface

The Esil River originates on the northern edge of the Kazakh lowlands and discharges into the Irtysh River in the neighboring territory of the Russian Federation. The total length of the river is 2,450 km, and the catchment area is 155,000 km2 (Kazgiprovodkhoz Institute, 2006).

The primary tributaries of the Esil River, Kalkutan, Zhabai, and Terysakkan, originate in the Akmola region, which is also the river's primary feeding area. The Akkanburlyk and Imanburlyk tributaries in the North Kazakhstan region also have an impact on the river's path. The river runs west into the Siberian lowlands below the Imanburlyk confluence. No more tributaries enter the river until it reaches the lower sections after the point where it joins the Imanburlyk. The Esil River above the Astana reservoir experiences drought throughout the summer, but the river below the reservoir flows continuously.

The location map of the Esil water management basin is shown in Figure 1.

Figure 1. The Esil water management basin location (Source: compiled by the author based on basin boundary and hydrological data)

On the territory of the Republic of Kazakhstan, the Esil River traverses a valley that ranges in width from 2 to 12 kilometers. The river has a distinct floodplain that increases mostly downstream for almost its whole course. The water regime of rivers in the Esil River basin is characterized by a high degree of variability in annual runoff. The highest average annual discharge exceeds the average perennial discharge by a considerable margin, with extreme irregularity in the intra-annual distribution of runoff (85-98% of the annual runoff occurring in the spring). In the steppe part of the basin, very low minimum water discharges are observed, with river drying being a common phenomenon.

One of the peculiarities of the multi-year flow of the Esil River and its tributaries is the tendency to grouping of high-water and low-water years (Mustafaev et.al., 2023), which complicates its use in economic sectors. According to available data, the duration of low-water years can be up to eight years.

Total surface water resources in the Esil River basin amount to 2.46 km3 and decrease in low-water years with a frequency of once in 4 years (P=75%) to 1.16 km3, with a frequency of once in 20 years (P=95%), to 0.49 km3 (Kazhydromet, 2023).

The main water sources in the basin are the surface runoff of the Esil River and its tributaries. Underground waters of fresh and slightly brackish deposits are used mainly for domestic and drinking water supply, sometimes for irrigation and industrial and technical purposes, but they are characterized by relatively small operational reserves. Re-used treated wastewater is practically not involved in covering the needs of the economy due to the lack of necessary legislative, methodological, and technical tools (Bekniyazov, 2019).

At the same time, in the Esil water basin, there is a high pressure on local water resources, 96% of which are used for domestic needs.

The water supply of the city of Astana, the capital of Kazakhstan, is an acute problem due to the pressure on water quality (Sataeva et al., 2022; Makhmudova et al., 2023), but also the constant growth of the population, which increases water consumption. Until 2020, the water consumption of the capital’s residents was 269 thousand m3 per day, and in 2022, 311 thousand m3 per day. According to forecasts, due to the active development of the city with residential neighborhoods, water consumption will reach 340 thousand m3 per day by 2026.

The natural and climatic peculiarities of the zone determine its grain and cattle breeding specialization. However, given that the moisture regime is very severe, the sustainability of grain crop yields depends on the observance of agrotechnical practices aimed at accumulating and conserving soil moisture. The zone has high potential for the production of durum wheat varieties.

The following adverse climatic conditions have been identified as collectively affecting crop growth: inadequate precipitation, extremely low relative humidity, late spring and early autumn frosts, low winter temperatures accompanied by strong winds, and limited snow cover. These factors contribute to droughts, freezing, and crop destruction, all of which hinder crop development. As a result, agriculture in the region can only be viable with the implementation of irrigation systems.

Within the basin, the total area of irrigated land amounts to 116.11 thousand hectares, including 54.7 thousand hectares of land under regular irrigation and 61.41 thousand hectares with first irrigation. The proportion of irrigated land constitutes 0.55% of the total agricultural land, with irrigated arable land covering 0.27% of the total arable area. It is worth noting that, as depicted in the map below (Figure 2) (Ministry of Ecology and Natural Resources of the Republic of Kazakhstan, 2021), these figures are among the lowest in comparison to other regions of the country.

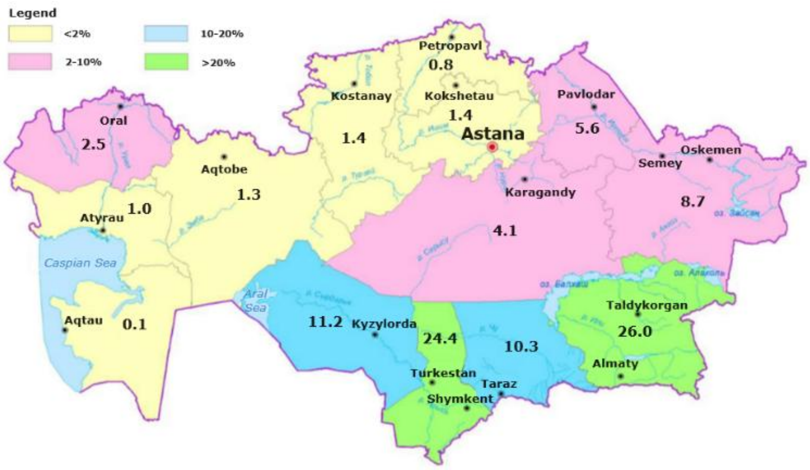

Figure 2. The share of irrigated land by region of their total area (Source: Ministry of Agriculture of the Republic of Kazakhstan (2023)

In the river basin, cereal crops predominate, occupying 86.58% of the cropped area structure, followed by forage crops (11.96%), industrial crops (0.69%), and potatoes, vegetables, and melons (0.77%). On irrigated lands, the main part of the cultivated area is occupied by forage crops (68.28%), while on irregularly irrigated plots potatoes, vegetables and melons account for 31.72%, according to the Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan (Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, 2023).

The territory under consideration is considered one of the leading industrial-agricultural regions of the republic, where agriculture is the dominant branch of the economy, being a large consumer of water resources (Mustafaev et al., 2023).

Surface water resources serve as the main water supply for various economic sectors. Approximately 45% of the total water consumed is allocated for agricultural needs, around 30-35% is used by public utilities, and about 20% is directed towards industrial use. As shown in Table 1 below, agriculture is a sector that shows a growing trend in water consumption.

Table 1. Summary of water consumption in the Esil River basin for the period 2020-2025*

Types of water consumption	**Total water withdrawal, mln m^3**	
	2020	**2025**
Utilities	151.399	199.854
Industry	86.344	103.389
Agriculture, including:	193.692	242.372
regular irrigation	71.300	90.0

limanic irrigation	60.740	87.0
agricultural water supply	49.85	52.750
pasture watering	11.802	12.622
Fishery	3.60	4.500
Recreation and other needs	3.99	4.460
Total	439.025	554.575

*Source: Developed by the author based on data from the Bureau of National Statistics, Agency for Strategic Planning and Reforms of the Republic of Kazakhstan

In this context, it is important to recognize that restricted access to water resources limits the economic development potential of the region, affecting sectors such as agriculture, utilities, and industry. At the same time, energy stability is crucial to ensuring the region's sustainability, even when water resources are adequate.

The energy sector in the study region is based on hydrocarbon fuels, particularly natural coal combustion. The energy sector in the study region is primarily reliant on hydrocarbon fuels, with natural coal combustion representing the predominant energy source (Huang et al., 2025).

In parallel, Kazakhstan is implementing a decarbonization strategy in alignment with the Paris Agreement. Kazakhstan has declared its objective of achieving zero CO_2 emissions by 2060. Nevertheless, the country continues to face significant challenges in reducing CO_2 emissions, with levels remaining high and reaching 271 Mt CO_2 in 2022. This places Kazakhstan in 24th place in the ranking of CO_2 emitting countries, according to the Global Carbon Atlas (n.d.). The goal of achieving carbon neutrality will be accomplished through the incorporation of alternative energy sources; nevertheless, the necessity for significant financial investments and the relatively short payback period have resulted in a relatively slow rate of implementation.

2.2. Methods

This study applied an integrative approach combining scenario analysis, engineering calculations, and eco-engineering principles to evaluate water, food, and energy security strategies for the Esil River Basin. The methodological approach incorporates eco-engineering techniques, such as optimizing water redistribution systems to minimize environmental impacts, enhancing local biodiversity through sustainable irrigation practices, and integrating small-scale hydropower solutions to support green infrastructure. This study will concentrate on the relationship between food, energy, and water security to thoroughly examine the sustainable development of the Esil River Basin. In order to achieve sustainable development in the most significant economic sectors in the region, an integrated strategy that transcends sectoral borders is required. Statistical processing of data (means, standard deviations, and errors) was not applied in this study, as the research relies primarily on official statistical reports, engineering calculations, and projected estimates, which do not involve variability from sampling or experimental uncertainty. This study did not involve experimental sampling or modeling uncertainties, as the analysis was based on engineering calculations and secondary data from official sources. This article does not take into account thorough modeling of inter-basin water transfer because it is a component of a broader study. Subject to the water transfer project's successful completion and the potential for local energy production, the primary focus is on the potential for developing sustainable irrigated lands.

Scenario analysis was used to assess potential interventions, including the inter-basin water transfer from the Irtysh River, the construction of the Buzuluk Reservoir, and the installation of a small hydropower plant at the Astana Reservoir. These scenarios were evaluated in terms of their contribution to regional sustainability, water security improvement, agricultural productivity enhancement, and energy diversification.

The hydropower potential was calculated using standard hydrological and energy conversion equations proposed by Subbotin and Khaustov (2012), considering available reservoir data (storage volume, discharge rates, head height). Estimates of irrigated land expansion and potential grain production were based on irrigation norms and durum wheat yield benchmarks derived from national and international sources.

This article provides an overview of the proposed measures using statistical analysis and forecasting methods, as well as a diagram of the transfer channel, aggregated calculations on gross wheat production, and the estimated potential of a small hydroelectric power plant in the region under study.

3. Results

3.1. Water security

In areas experiencing a deficit of water resources, it becomes necessary to employ a range of water management measures. The sequence of implementation of these measures is determined, firstly, by economic indicators, and secondly, by their environmental friendliness – that is to say, by the degree to which they result in adverse effects on the environment.

The study will explore the method of territorial redistribution of river flow as a strategy to ensure a sufficient water supply for water-scarce regions. This approach is also comprehensive and interconnected, transcending sectoral boundaries to foster the sustainable development of the region's key economic sectors (Ali et al., 2024; Bazilian et al., 2011). The comprehensive nature of the study emphasizes the interconnections and complementarities that exist between the different aspects of sustainable development in the Esil River Basin.

The Irtysh Donor River, which forms up to 33% of Kazakhstan's total surface runoff, is the only source that may expand the water supply of the Esil basin on its territory.

According to the United Nations Economic Commission for Europe's Committee on Water Problems' recommendations, water use intensity of less than 10% of river runoff is deemed satisfactory; if it exceeds 20%, water use must be limited and flow-regulating measures must be put in place; and if it exceeds 20%, the water body will not be able to support the socioeconomic development of the region.

With equal water allocation of this runoff with the Russian Federation, it is possible to take water from the Irtysh River for transfer to the central region of the country up to 4.5 km^3, which is less than 15% of the runoff.

In this sense, the maximum volume of withdrawal concept was used to evaluate the volume of transfers in this study, taking into consideration the economic, political, and environmental elements of water consumption. In this sense, the annual amount of water that can be drawn from the Irtysh River to serve Northern and Central Kazakhstan can range from 1 to 1.5 km^3, however, the amount of water that can be irrevocably taken out of the river cannot be greater than 10% allowed. The level of water use intensity will be categorized as moderate.

The proposed canal will draw water from the Shulba Hydroelectric Power Station (hereinafter referred to as the HPP). With a usable reservoir capacity of 7.5 km3, the second stage of the Shulba HPP will raise the normal retention level mark to 252.5 meters. The Kazakh shallow-slope, which is defined by the overall elevation of the region with a range of altitudes from 200 to 1500 meters, is where the proposed canal to serve the Esil River basin can be built. Figure 3 depicts the proposed canal's layout.

Figure 3. Scheme of the projected canal (Source: compiled by the author)

Water transfer schemes, when designed effectively, are widely recognized as beneficial from environmental, economic, social, and political perspectives. By adhering to established principles, correct methodologies, and efficient processes, major economic, ecological, social, cultural, and political concerns can be properly addressed. Water transfer planning should be guided by acceptable hydrologic, ecological, fiscal, and social values, most of which are already incorporated into water supply planning and management. Case studies highlight the importance of considering all principles, particularly the principles of solidarity and precaution. As a result, applying the right methods and approaches can lead to further improvements in the preparation of appropriate water transfers. These case studies illustrate how the meaning of water transfer evolves over time. Initially, the shift from unilateral to cooperative efforts presents both opportunities and challenges within changing political, governance, and trade environments. The transition from water sharing to hydro-solidarity, optimal joint use, and profit sharing is providing a new momentum for cooperative initiatives. Furthermore, land use intensification, such as runoff management and small dams, leads to increased evapotranspiration and groundwater recharge, unintentionally resulting in water transfers. There is also a growing recognition of the potential for areas facing water scarcity to adopt demand management strategies rather than relying on inter- or intra-basin water transfers. The demand for water transfers will fluctuate based on the import and export of water between basins and the impact of virtual water transfer on water demand.

Currently, there are two multi-year regulation reservoirs on the Esil River within Kazakhstan: the Astana and Sergeev reservoirs. Additionally, the Petropavlovsk water-engineering system includes a small reservoir that provides seasonal flow regulation. The Astana reservoir, situated in the upper reaches of the Esil River, has a total capacity of 419.4 million m³, with an annual effective yield of 95 percent, equating to 72.0 million m³ of water availability. The Sergeev and Petropavl reservoirs form a single water management complex, which has a total volume of 712.2 million m³ and an annual useful yield of 95% of security equal to 290.0 million m³. Thus, the total annual useful yield (95% availability) of these reservoirs is 362,0 million m³ of water per year.

In recent years, there have been cases of severe floods and droughts (Makhmudova et al., 2023), the trend of growing water shortage in the region, even for the municipal and drinking needs of the region and the capital. In this regard, the Government of the Republic of Kazakhstan (2024a, 2024b, 2024c, 2024d) is planning a set of measures aimed at increasing water availability in the region through additional regulation of the flow of the Esil River, in particular, the construction of the Buzuluk reservoir. The location of the proposed Buzuluk reservoir is shown on the map below (Figure 4).

The Buzuluk reservoir construction project on the Esil River allows solving the problem of using the basin's own resources by regulating and accumulating part of the flood flow, as well as ensuring the safe passage in the lower reaches of the Esil River and the stable operation of the downstream Sergeev and Petropavl reservoirs. The Government of the Republic of Kazakhstan planned to develop a project for the construction of the Buzuluk reservoir with expected commissioning by 2027 (Year results: Development of water infrastructure, 2024).

Figure 4. Map-scheme of the Buzuluk reservoir location (Source: adapted from Wikipedia with author modifications)

Meanwhile, it is planned that the reservoir be filled by drawing water from side streams on the Esil river – Akkanburlyk and Imanburlyk rivers, which do not provide guaranteed filling to cover all necessary water demands, especially in low-water years.

In this regard, within the framework of this article it is proposed to transfer part of the flow from the Irtysh River basin to the Esil River basin through part of the existing structures of the Kanysh Satpayev Canal from the water intake structure to the Hydrosystem No. 8, further – through the proposed new canal to the Astana Reservoir. At present, the capacity of the Kanysh Satpayev Canal is used not more than 40% of the design capacity, i.e., 0.7 km^3 per year on average.

3.2 Food security

The region of Central Kazakhstan boasts favorable agro-climatic conditions for the cultivation of hard wheat (durum), which has a higher market price than soft wheat on the global market. Durum wheat is characterized by resistance to drought and high temperatures, and also has resistance to diseases such as rust and hard heading. In addition, grain losses during cultivation are low compared to soft wheat.

International experience shows that the productivity of durum wheat in the zone of risky farming can be increased 5-6 times by irrigation and competent agrotechnology (Amanov et al., 2019; Golubova et al., 2022). Comparison shows that durum wheat yield on irrigated lands is significantly higher both in Kazakhstan and globally (Lobell et al., 2011; Karimov et al., 2014). In Kazakhstan, the difference in durum wheat yield between irrigated and rainfed lands can be up to 3 times, while globally this difference can be 2-3 times. In the region under study, irrigated farming for growing durum wheat varieties will be the most profitable.

In the agro-climatic conditions of the study region, under inconstant humidification, autumn irrigations for the accumulation of moisture in the soil are considered to be of higher priority, while vegetative irrigations are prescribed as necessary as additional measures. Moisture-charge irrigation rates for durum wheat varieties can vary between 600-1500 m^3/ha, irrigation rates can range from 600 to 800 m^3/ha, which is much less than required compared to other crops.

According to aggregated calculations, at the useful volume of the Buzuluk reservoir of 0.8 km^3 taking into account the attracted additional volume, which increases the guaranteed return of the reservoir, it is possible to irrigate about 200-330 thousand hectares of irrigated land, which at the projected yield per year of 4.8 t/ha gives a gross yield of wheat up to 1 million tons worth about 250 million USD.

3.3 Energy security

One of the most effective methods of utilizing small local energy resources of renewable energy sources in Kazakhstan is the use of energy from small watercourses, which have significant potential and can be used with comparative simplicity through the construction of small hydropower plants (hereinafter referred to as HPP). It should be noted that the economic potential of small hydropower exceeds the economic potential of such renewable energy sources as wind, solar, and biomass combined (Purwanto, A. et al, 2021; Rivotti, P. et al, 2019). The value of hydropower plants is that they utilize renewable natural resources to produce electricity. Because there is no need for additional fuel for hydropower, the final cost of the electricity generated is significantly lower than with other types of power plants.

As an example, we can consider the project of a small hydropower plant on the Astana reservoir and calculate its capacity, having the data of the reservoir.

Astana reservoir is one of the reservoirs of the Esil River basin, located in the Akmola region. Its length is 11 km and its width is 10 km.

The reservoir was built in the upper reaches of the Esil River in 1969. The area – 61 km², volume – 0.411 km³. It carries out perennial flow regulation and is used for energy and irrigation. In 2002, a water pipeline from the Irtysh-Karaganda canal, which was built in 1968 to supply water to industrial areas and agriculture in Central Kazakhstan, was laid to the reservoir to supply water to the capital of the country. Figure 5 below shows the dam on the Astana reservoir.

Figure 5. Spillway dam on the Astana reservoir

Having established the water head at the Astana reservoir by means of the level difference of the reservoir embankment (H), as well as the data of the average water discharge (Q), the calculations of the potential capacity of the proposed small HPP can be made. Using general formulas by A. Subbotin and V. Khaustov, “Hydraulic engineering and land reclamation” textbook (Subbotin et al., 2012), the aggregated potential capacity of the HPP can be calculated as follows: Eq. (1), (2):

$$N_{HPP} = 9{,}81 \cdot Q \cdot H \cdot \eta_t \cdot \eta_g, \quad (1)$$

where,

N_{HPP} – the generation capacity (kW);

Q – flow rate (m^3/s);

H – effective head (m);

η_t – turbine efficiency;
η_g – generator efficiency.
Then,
$N_{HPP} = 9.81 \cdot 24.32 \cdot 18 \cdot 0.75 = 3320.8$ kW
The annual energy production (AEP) will be equal to:

$$AEP = (W_{HPP} \cdot H_{HPP} \cdot \eta_t \cdot \eta_g)/367{,}2 \quad (2)$$

where,
W_{HPP} – flow volume;
H_{HPP} – actual power with which the HPP operates in the time interval ΔT.
Then,
$AEP = (767\,000\,000 \cdot 18 \cdot 0.88 \cdot 0.95)/367.2 = 31\,431\,960.8$ kW/h

The construction of small hydropower plants holds significant potential for development in various regions of the world with transboundary river basins. Small hydropower plants are free from many of the disadvantages of large HPPs and are considered one of the most cost-effective and environmentally friendly methods of generating electricity, especially when utilizing small watercourses.

The proposed inter-basin water transfer scheme and small-scale hydropower projects contribute directly to reducing regional CO_2 emissions, promoting ecological stability, and improving ecosystem health, demonstrating the practical application of eco-engineering principles.

4. Discussion

4.1. Water security

Growing water deficit, surface and groundwater pollution, excessive water losses in water management systems, escalating issues with providing the population with clean drinking water, and interstate water distribution issues all impede the development of economic sectors in the studied region.

The vulnerability of Astana, the capital of Kazakhstan, and the Esil River basin as a whole has also been identified. In this regard, attention should be paid to the ecological condition of the Esil River, the hydrological regime of which was changed as a result of the construction of the Astana reservoir. In fact, as part of the capital's territory improvement, a dam was built and the riverbed was significantly widened. At the same time, to maintain the water level, the river was divided into sections separated by a number of spillway-type dams, which significantly reduced the speed of water movement and, consequently, worsened the ecological condition of the Esil River.

Thus, at present, there are real threats to the sustainable development and environmental sustainability of the territory of the study region.

There are also problems with water supply to the residents of the capital city due to the increase in water consumption associated with population growth. Today water supply of the capital is carried out from the only source – Astana water reservoir, built in 1969 and designed for 500 thousand people. Due to the growth of the city's population (1.3 million people), the need to create a reserve source of drinking water for the city of Astana is becoming more acute. Therefore, to achieve sustainable development of the region, the priority task of the study is to develop recommendations to reduce water deficit in the Esil River basin.

Water resources redistribution can be defined as the complex of hydraulic and other structures that provide water withdrawal from regions with excessive water supply and its delivery through the watershed to low-water or remote catchments. The tasks of redistribution are associated with the solution of a wide range of environmental problems relevant for both the source and receiving areas (Zeng et al., 2024).

The classification of transfer systems depends on the geographical characteristics of the area and the distances over which water is transported. Inter-basin, which connects river basins with independent outlets to the sea, ocean, or inland water body; intra-basin (local), where the transfer system stays within the basin of a river with an independent outlet to the sea, ocean, or inland water body; and interregional (or interzonal), which connects river systems across different physiographic regions, are the three main categories.

It is also feasible to classify flow transfer systems according to the size of the water resources involved, in addition to geographical categorization. The average yearly volume of the transferred flow is the most important factor in this case. Systems that move less than 1 km^3 per year are roughly classified as small, those that transfer between 1 and 5 km^3 as medium, and those that transport more than 5 km^3 as large. Usually, the river that receives the runoff is referred to as the recipient, while the watercourse from which the runoff is redirected is called the donor.

Large-scale transfers are not always warranted, according to global experience, for a variety of reasons, such as substantial environmental effects, geopolitics, and expensive project implementation. However, a significant number of water transfers have been planned, built, and run globally. They have an annual worldwide volume of roughly 400 km^3. They solve issues with energy, transportation, irrigation, recreation, and employment while serving vast areas in conjunction with flow regulation. One of the most urgent problems in water management is the design and administration of such systems.

As practice shows, the most feasible projects are an inter-basin transfer of part of the runoff, which involves relatively small volumes of water intake. Many projects were not supported due to significant volumes of transfer, for example, the turn of the Siberian rivers to Central Asia and Kazakhstan.

The Kanysh Satpayev Canal, also known as the Irtysh-Karaganda Canal, is a prime example of how the territorial redistribution of river flow has been successfully implemented. By the end of 1940, Central Kazakhstan was experiencing an increasing number of water scarcity issues. Only 5.5 percent of Kazakhstan’s 2174 rivers – including the Irtysh, Syr Darya, Ili, Ural, Esil, and others – flow through the country’s central region. The canal’s construction took place during a ten-year period, from 1962 to 1974. The city of Karaganda’s water shortage issue was promptly resolved, and irrigated agriculture, mining, the chemical industry, heating, and power all started to grow quickly. Half of Kazakhstan’s electricity is produced by the Ekibastuz State District Power Plants 1 and 2, which use the canal’s water. Additionally, it is exported to Russia and supplies several other industrial firms as well as the nation’s largest metallurgical complex in Temirtau. These two instances show that it has been beneficial to shift a portion of the Irtysh River flow to the Nura-Sarysu and Esil river basins.

The development and building of new manufacturing facilities were made possible by the Kanysh Satpayev Canal, which emerged as a crucial strategic water management facility. The canal is 458 km long in total, with 272 km going through the Pavlodar district and 186 km via the Karaganda region. The canal contains 34 sections, 14 reservoirs and 22 pumping stations (Interstate Coordinating Water Management Commission of Central Asia, 2016). Moreover, the canal has water outlets, duckers, storm pipes, spillways, bridges and blocking structures. Currently, the canal is expected to supply 1200 million cubic meters of water annually. The Irtysh-Karaganda canal’s construction preserved nearby water supplies while promoting the active growth of metallurgical production. The development of ferrous metallurgy in Karaganda and coal mining and energy in Ekibastuz would not be feasible without the canal.

The canal route will primarily follow the western section of the Kazakh plateau, which features two low-lying massifs: the Kokshetau Upland (947 m) and Ulytau (1133 m), separated by the expansive Tengiz-Kurgaljin depression, characterized by a flat plain relief. The route is designed to use gravity transport for most of its length and to minimise the elevation of the pumping stations. This approach will undoubtedly increase construction costs, as it will require the construction of additional gravity transport structures (aqueducts, tunnels, and culverts). On the other hand, it will reduce the construction costs of the pumping stations and, most importantly, the operating costs of the mechanical lift.

More than half of the cost of water supplied by the Kanysh Satpayev Canal accounts for the payment of electricity consumed by pumping stations for lifting water. Tariffs for the payment of water supply services do not contribute to the use of it for the needs of irrigated agriculture, the profit is minimal, and it often brings losses. In this regard, at present, the Kanysh Satpayev Canal capacity is used by 30-40%, and only about 30-40% of the design capacity is provided. The irrigated area in agriculture decreased in the same way.

Furthermore, high energy costs contradict the green economy and low-carbon growth concepts. In this regard, the methods of gravity transfer and maximum use of the terrain were used when determining the canal's route.

An additional volume of 1 km3 proposed to be accumulated in the Buzuluk reservoir is expedient to be used for the creation of an irrigated array in the studied region. Also, in the ongoing study, the proposed reservoir is considered as a counter-regulator of the Sergeev reservoir. In this case, it is possible to ensure the long-term sustainable operation of the planned Buzuluk complex reservoir.

The inter-basin water transfer project and optimization of the Buzuluk reservoir resource use proposed in this article can become key tools for local executive bodies and farmers in planning and developing the agricultural sector in the region.

These measures will enable more efficient water management, which is critical for sustainable farming. The implementation of these projects will help improve irrigation infrastructure, increase crop yields and ensure a stable water supply, which ultimately contributes to economic growth and food security in the region.

4.2 Food security

The projected potential for durum wheat production under expanded irrigation in Central Kazakhstan demonstrates a promising scenario for strengthening both regional food security and economic diversification. Given the agro-climatic conditions of the region, the shift toward cultivating high-value, drought-resistant durum wheat varieties are not only agronomically justified but also economically advantageous. Studies from other semi-arid regions, such as southern Italy and parts of North Africa, have confirmed that targeted irrigation combined with advanced agronomic practices can significantly improve durum wheat yields while maintaining resource efficiency (De Vita et al., 2007; Katerji et al., 2008). Moreover, as global demand for durum wheat remains strong due to its use in pasta and premium semolina products, Kazakhstan's positioning as a net exporter of this crop aligns well with international market trends. However, the viability of this strategy depends on the timely implementation of water infrastructure projects such as the Buzuluk reservoir and the optimization of water use. The scenario analysis suggests that if irrigation development is scaled efficiently, the region could reduce its vulnerability to climatic fluctuations and stabilize grain output in the long term. Nevertheless, careful water budgeting, supportive policy mechanisms, and farmer training programs will be essential to ensure that increased irrigation does not compromise environmental sustainability. Therefore, the proposed expansion of irrigated durum wheat cultivation can be considered a robust element within the broader pathway toward sustainable development of the Esil River Basin.

4.3 Energy security

One of the key advantages of small HPPs is their contribution to reducing CO2 emissions, which helps mitigate the environmental impacts of global climate change. These stations require minimal flooding and development of surrounding areas, which significantly reduces their impact on the environment. They also contribute to local and regional development by creating jobs and improving infrastructure in rural areas. Additionally, small HPPs help in maintaining the health of river basins, which includes regulating water resources and improving water quality.

Another important aspect is the role of small HPPs in rural electrification, providing a stable and affordable power supply. During their construction and operation, the natural landscape is preserved, and the strain on ecosystems is minimal. Compared to coal and gas power plants, small HPPs have low electricity production costs and low operational expenses, as well as relatively inexpensive equipment replacement and longer service lives (40-50 years). Furthermore, these stations allow for the integrated use of water resources for multiple purposes, including power generation, water supply, irrigation, water protection, and fisheries. The disadvantages of small HPPs include slow return on investment, which is at the level of 5-10 years. For comparison, cogeneration plants and mini-TPPs built on their basis currently have a payback period of 2 to 4 years (depending on regional tariffs for electricity and heat, as well as gas prices).

The projected small HPP with a capacity of 3320.8 kW at the Astana reservoir will provide electricity generation of 31,431,960.8 kW/h for the neighboring settlements, which contributes to the regional development of green infrastructure. Moreover, the development of small hydropower plants contributes to Kazakhstan’s commitments under the Paris Agreement and the national strategy for carbon neutrality by 2060. By providing decentralized, clean energy, small HPPs support the diversification of the energy mix and facilitate the integration of low-carbon technologies in rural and peri-urban areas. Despite the slower payback period, the adoption of small hydropower aligns with sustainable energy goals and reduces dependence on fossil fuels, making it a viable alternative for regional energy security. However, further improvements in technology, financing models, and integration with other renewable sources are needed to enhance efficiency, reduce costs, and accelerate adoption.

Integration of eco-engineering approaches in water management practices and renewable energy development not only mitigates negative environmental impacts but also enhances ecological resilience, providing multiple benefits for biodiversity conservation, improved ecosystem services, and overall environmental sustainability.

5. Conclusion

This study assessed integrated strategies to enhance water, food, and energy security in the Esil River Basin, applying scenario analysis and engineering calculations within the eco-engineering framework. The proposed combination of inter-basin water transfer from the Irtysh River, development of the Buzuluk Reservoir, expansion of irrigated agriculture, and small-scale hydropower generation demonstrates a holistic approach to addressing the basin’s sustainability challenges.

These interventions, aligned with the water-energy-food-ecosystem (WEFE) nexus and Kazakhstan’s decarbonization commitments, offer an effective pathway to strengthen regional resilience, diversify the economy, and reduce environmental pressures. By integrating water resource management, sustainable agricultural intensification, and renewable energy development, the study contributes to a comprehensive framework for long-term sustainable development in the Esil River Basin.

Further research should focus on detailed environmental impact assessments, optimization of water transfer schemes under climate change scenarios, and socio-economic feasibility studies. Additionally, participatory planning involving local communities and stakeholders will be essential to ensure the sustainable and socially acceptable implementation of the proposed measures.

6. Supplementary Materials. No supplementary materials.

7. Author Contributions

Conceptualization, methodology, validation, data curation, formal analysis, investigation, resources, writing – original draft preparation, A.Zh.; data curation, writing – review and editing, supervision, T. D., G.S. All authors have read and agreed to the published version of the manuscript.

8. Author Information

Saspugayeva, Gulnur Yerzhanovna – PhD, Associate Professor, Department of Environmental Management and Engineering, L.N. Gumilyov Eurasian National University, 2 Satpayev str., 010000, Astana, Kazakhstan; email: gulnur_erzhanovna@mail.ru, https://orcid.org/0000-0003-3223-3602

Dentinho, Tomaz – PhD, Professor of Regional, Environmental and Agricultural Economics, University of Azores, Angra do Heroísmo, Portugal; email: tomas.lc.dentinho@uac.pt, https://orcid.org/0000-0002-7409-2345

Zhaken, Assel Mukhtarkyzy – doctoral student, Department of Environmental Management and Engineering, L.N. Gumilyov Eurasian National University, 2 Satpayev str., 010000, Astana, Kazakhstan; email: zhaken.asel@gmail.com, https://orcid.org/0009-0004-4498-0255

9. Funding: This research received no external funding.

10. Acknowledgements: The authors have no additional acknowledgments to report.

11. Conflicts of Interest: The authors declare no conflicts of interest.

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Есіл өзені бассейнінің тұрақты дамуы: салааралық тәсіл және сценарийлік талдау

Томаз Дентиньо, Гулнур Саспугаева, Әсел Жакен

Аңдатпа. Есіл өзенінің бассейні – Қазақстанның солтүстік және орталық аймақтарындағы маңызды өнеркәсіптік-аграрлық өңір, мұнда ауыл шаруашылығы басым. Бассейнде жылдық ағын су көлемінің жоғары өзгергіштігі және су ресурстарының біркелкі бөлінбеуі байқалады, бұл суды тұрақты дамудың басты факторы етеді. Су тапшылығының артуы, ластану, су ресурстарын тиімсіз басқару және әсіресе Астана қаласындағы су тұтынудың өсуі аймақтың әлеуметтік-экономикалық және экологиялық тұрақтылығына қатер төндіреді.
Бұл зерттеу Есіл өзенінің бассейні үшін алғаш рет интеграцияланған сценарийлік талдауды ұсынады. Ұсынылған шаралар Ертіс өзенінен жылына 1,5 км^3 дейін су тасымалдауды, Бұзылык су қоймасын салуды, суармалы егістікті кеңейтуді және шағын су электр станцияларын дамытуды қамтиды. Бұл шаралар экоинженерлік тәсіл негізінде өңірдің тұрақтылығын арттыруға бағытталған.
Нәтижелер көрсеткендей, ұсынылған шаралар су, азық-түлік және энергия қауіпсіздігін нығайтады және Қазақстанның декарбонизациялау мақсаттарына сәйкес келеді. Болашақ зерттеулер экологиялық әсерді бағалауды, әлеуметтік-экономикалық орындылықты және мүдделі тараптардың қатысуын қамтуы тиіс.

Түйін сөздер: тұрақты даму; су ресурстарын басқару; су ресурстарын аумақтық қайта бөлу; тұрақты ауыл шаруашылығы; шағын су электр станциялары

Устойчивое развитие бассейна реки Есиль: межсекторальный подход и сценарный анализ

Томаз Дентиньо, Гулнур Саспугаева, Асел Жакен

Аннотация: Бассейн реки Есиль, расположенный на севере и в центре Казахстана, является важным промышленным и сельскохозяйственным регионом, где доминирует сельское хозяйство. Бассейн отличается высокой изменчивостью годового стока и неравномерным внутригодовым распределением воды, что делает водные ресурсы ключевым фактором устойчивого развития. Усиливающийся дефицит воды, загрязнение, неэффективное управление водными ресурсами и растущий спрос, особенно со стороны столицы Астаны, создают серьезные угрозы социально-экономической и экологической устойчивости региона.
В статье представлено первое комплексное сценарное моделирование, объединяющее межбассейновую переброску воды из Иртыша, строительство водохранилища Бузулук, расширение орошаемого земледелия и развитие малой гидроэнергетики в рамках подхода экоинжиниринга. Результаты показывают, что переброска до 1,5 км^3 воды в год в сочетании с улучшением регулирования стока и возобновляемой энергетики может значительно повысить водную, продовольственную и энергетическую безопасность, а также поддержать цели декарбонизации Казахстана.

Предлагаемые меры демонстрируют практическое применение подхода вода-энергия-продовольствие-экосистема (WEFE) и экоинжиниринга, обеспечивая рекомендации для повышения устойчивости региона. В будущем исследования должны быть дополнены оценкой экологических последствий, социально-экономической эффективности и участием заинтересованных сторон.

Ключевые слова: устойчивое развитие; управление водными ресурсами; территориальное перераспределение водных ресурсов; устойчивое сельское хозяйство; малые гидроэлектростанции.