



Optimized Use of Surface and Groundwater from Non-Traditional Sources with Artificial Replenishment in Circulating Irrigation Systems Amid Climate Change: A Case Study of Enbekshikazakh District, Almaty Region

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Abstract

With the growing deficit of water resources, utilizing non-traditional water sources for irrigation has become crucial for stable crop and livestock production. In the Yenbekshikazakh district, favorable natural and climatic conditions have facilitated the development of cascades of seasonal regulation ponds. The construction and reconstruction of these ponds, integrated into water recycling systems, have significantly enhanced irrigated agriculture. This initiative has resolved water supply issues for the villages of Baiterek, Alga, and Koishibek, restoring 1,420 hectares of previously abandoned arable land and boosting agricultural productivity. The cascades have increased water availability by 25–30%, reducing reliance on traditional irrigation sources during dry periods, with a total storage capacity of 850,000 m³. Consequently, average crop yields have risen by 15–18%, with wheat increasing from 2.5 t/ha to 3.1 t/ha, barley from 2.2 t/ha to 2.8 t/ha, and corn from 3.8 t/ha to 4.5 t/ha. Additionally, water availability has expanded fodder crop cultivation by 20–25%, enhancing livestock nutrition and decreasing dependence on imported feed. These measures support sustainable agricultural development and long-term food security in the region.

Keywords: Drainage and irrigation systems; Hydropower; Surface water; Winter runoff; Water recycling; Sustainable agriculture; Water resource management; Climate change adaptation.

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1. Introduction

In an address to the nation, the Head of State drew attention to the need to accumulate rain and melt water for agricultural use during growing season. The optimization of precipitation accumulation processes, especially in the winter–spring period, is a priority in arid climate conditions. Rising water temperatures and extreme weather events worsen water quality, increasing the risk of pollution and negatively affecting ecosystems.^[1–3] Climate change is accelerating the melting of glaciers, which will lead to serious water shortages in the region. By 2050, Kazakhstan may experience severe water shortages.^[4] Climate change will lead to water scarcity and a deterioration in water quality, with negative impacts on

agriculture and food security.

The combined use of groundwater and surface water will help reduce the risks associated with climate change and improve food security.^[5] The decreasing flow of rivers irrigating Kazakhstan and the growing needs of industry and the population create an acute water shortage problem. A possible solution is includes increasing the efficient use of water resources, including groundwater and floods. For this purpose, introducing modern irrigation technologies and improving water management are necessary measures, especially in the context of small-scale agriculture.^[6,7]

Economic incentives to offset the high cost of water are insufficient to encourage agricultural producers to implement resource-saving technologies. The prevalence of outdated irrigation systems leads to significant water losses and soil degradation, resulting in irrigation erosion and salinization.

Insufficient financing limits the large-scale introduction of water-saving technologies and the development of non-traditional irrigation sources. Under these conditions,

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searching for innovative approaches and mechanisms to minimize the risks associated with water scarcity in dry periods is the main priority. International studies of artificial groundwater recharge can provide a foundation for the development of effective solutions for arid regions of Kazakhstan.^[8]

Natural conditions in the Yenbekshikazakh district enable the creation of a system of ponds for collecting melt and flood waters, ensuring a sustainable water supply for agriculture and reducing the load on main water sources.^[9] To ensure the regular irrigation of agricultural lands, storage ponds were created. Narrow sections of river valleys, gullies, and ravines were chosen as optimal locations, allowing for the study of smaller dam lengths and areas of flooding. The ponds were surrounded by protective dams to prevent water overflow and reduce shallow water. Hydrological studies and calculations confirmed the effectiveness of this system, showing that the created ponds can accumulate sufficient water to meet the needs of agriculture even in dry years.^[10-12]

Green technologies combined with effective water management have not only diversified agricultural production but also reduced disaster risks. The modernization of irrigation systems, including the reinforcement of dams, cleaning water reservoirs, and installing innovative equipment, improved soil amelioration and crop yields.^[13] Mechanical cleaning and deepening the main irrigation canal increased its flow capacity up to 450 L/s and reduced filtration losses by 25%. As a result, saving about 2.5 million m³ of water from the water-deficient Big Almaty Canal was possible during the growing season.^[14]

Integrated environmental analyses allowed for an in-depth assessment of the quality of water resources, revealing the presence of pollutants. Based on the obtained data, optimal water treatment methods combining mechanical, biological, and other technologies were proposed. This study's results helped ensure compliance with domestic standards for water quality, guaranteeing its safety for irrigation. The study addresses the problem of water scarcity and deteriorating water quality in the context of climate change, which poses significant challenges to agriculture and food security in the Yenbekshikazakh district of Kazakhstan. The key contributing factors include:

- Declining river flow due to the accelerated melting of glaciers and changing precipitation patterns, leading to reduced water availability for irrigation.
- Increasing demand for water from industrial sectors and a growing population, exacerbating the competition for limited water resources.
- Degraded irrigation infrastructure with outdated systems causing high filtration losses, soil erosion, and salinization of arable land.
- Lack of financial incentives to encourage the adoption of water-saving technologies and the development of non-traditional irrigation methods, hindering progress toward sustainable agriculture.

2. Experiment

The quality and suitability of water accumulated for the irrigation of cultivated crops were determined.

For the Shelkarsky storage pond, the following results were determined for the entire period of use of accumulated and replenished irrigation waters from non-traditional sources (melt water, temporary streams, the accumulation of infiltration irrigation waters from irrigation fields, drainage, and wedging groundwater).

2.1 Summary chemical composition

For the pond, the following composition was determined: M 0.47-0.58-0.54; HCO₃ 56-61-49; SO₄ 39-26-47; Cl 5-13-14; pH 7.6-7.8-7.8; and scientific article report (SAR) 1.0-2.7-1.7. The chemical composition of "Storage pond Shelkar" was Ca 48-25-32, Na 33-49-49, and Mg 19-26-19. For agricultural crop irrigation, until the end of the growing season, irrigation waters belonged to classes I and II, which are ultrafresh and fresh waters, respectively, the mineralization of which varied from 0.47 to 0.58 g/L, according to the chemical composition of hydrocarbonate sulfate calcium sodium (2.1). Additional outcomes were also determined: the reactivity of groundwater is neutral due to the concentration of hydrogen ions (7.6–7.8); the risk of alkalization for irrigation water based on the sodium equilibrium (SAR, from 1.0 to 2.7) is low; the water, which was assessed for its quality and risk of alkalization according to Antipov-Karataev,^[15] is a suitable irrigation

Table 1: Assessment of quality of surface water accumulated in seasonal regulation storage ponds for irrigation of zoned cultivated agricultural crops in Enbekshikazakh district, Almaty region.

Name of irrigation source selection date water class		Min, g/L		Water reaction (pH)	Stabler quality assessment	Sodium adsorption ratio (SAR)	Assessment of quality and risk of sedimentation according to Antipov-karataev
			Quality assessment by total mineralization				
Shelkar storage pond	15 June 2024	I	0.47 ultrafresh	7.6 neutral	82.2 very good	1.0 low	$C \geq Tk \ 1.5 \geq 0$, suitable
	15 July 2024	II	0.58 fresh	7.6 neutral	31.6 very good	2.7 low	$C \geq Tk \ 0.64 \geq 0.14$, suitable
	15 September 2024	II	0.54 fresh	7.8 neutral	52.4 very good	1.7 low	$C \geq Tk \ 0.25 \geq 0.13$, suitable

source for any agricultural crop (Table 1); and the quality of the groundwater, which was assessed for the risk of negative processes such as chloride salinization, sodium and magnesium alkalization, and soda formation, is excellent.

The evaluation of surface water quality stored in seasonal regulation ponds for irrigation in the Enbekshikazakh district of Almaty region reveals favorable conditions for agricultural use. According to Table 1, the total mineralization (Min) ranges from 0.47 to 0.58 g/L, classifying the water as Class I (ultrafresh) in June and Class II (fresh) in July and September, indicating consistently high-water quality throughout the irrigation season. The pH values, ranging from 7.6 to 7.8, fall within the neutral to slightly alkaline range, confirming the water's chemical stability and its suitability for irrigation without risk of soil acidification or alkalization. The Stabler Quality Assessment categorizes all samples as "very good", reflecting an optimal ionic balance conducive to preserving soil structure and supporting plant growth. Furthermore, the Sodium Adsorption Ratio (SAR) remains low, between 1.0 and 2.7, indicating a minimal risk of sodium-induced soil degradation, thereby ensuring the safety of water for most crops and soil types. Finally, all water samples satisfy the Antipov-Karataev Criterion ($C \geq T_k$), demonstrating a low risk of soil salinization and sedimentation. These combined parameters confirm that the irrigation water meets agronomic standards and poses no significant environmental threats when used for cultivating zoned crops in this region.

2.2 Dynamics of the main heavy metals (copper and zinc) in the water during the observation period from 2020 to 2024

The content and dynamics of copper and zinc, the main heavy metals in the water, for the observation period from 2019 to 2024 (Fig. 1) indicate a stable gradual decrease, with values within the maximum allowable concentrations (MAC) limits.

2.3 Results of river salinity regimes of groundwater of the seasonal regulation storage facility of the «storage pond

silkar» using local temporary water sources and flood flows

Analysis of the quality and determination of the degree of suitability of the groundwater, which formed as a result of accumulated infiltration water levels in storage ponds, from the first surface aquifer for the irrigation of cultivated agricultural crops yielded the following results.

In the studied region, from 2019 to 2024, on arable irrigated lands adjacent to the ends of the retaining and regulating structures and in the lower pool of the «Storage pond Shelkar» pond, after testing in well No. 1, groundwater, which rises during the growing season, decreased in total mineralization from 0.77 to 0.49 g/L and transitioned from class II, fresh, to class I, ultrafresh, water (Fig. 2), making it suitable for the irrigation of all crops as it does not worsen the physical properties of the soil nor reduce the yield of agricultural crops. Regarding its chemical composition, groundwater comprises sodium–magnesium hydrocarbonate-sulfate (3.4) and is neutral (pH 7.4–7.9); the water's total hardness value ranges from soft to medium-hard (2.2–7.1 mg-eq/L). For well 1 (Fig. 3), the following composition was determined: M 0.77-0.74-0.49; HCO_3 55-58-40; SO_4 38-34-49; CI 7-8-11; pH 7.9-7.4-7.5; and SAR 1.8-0.3-0.4. In addition, values of Na 43-6-43, Mg 34-69-60, and Ca 23-25-29 were found.

According to Stebler, the irrigation coefficient is very good; the risk of alkalization according to SAR is low; the water, assessed for its quality and risk of alkalization according to Antipov-Karataev is a suitable source of irrigation for any agricultural crop (Table 2);^[15] and the quality of the groundwater according to the risk of developing negative processes, such as chloride salinization, sodium and magnesium alkalization, and soda formation, is excellent and good (Table 3). Water sources in the region are generally suitable for irrigation, with low risk of negative processes. However, continued seasonal monitoring is recommended, especially for soda formation in late-season groundwater samples.

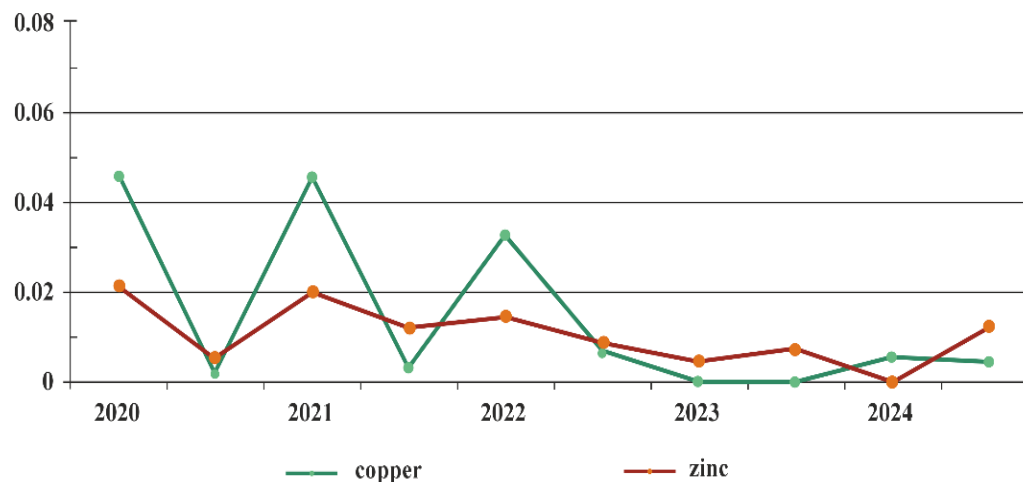


Fig. 1: Dynamics of heavy metal content in the «Storage pond Skelkar» for 2020–2024, mg/dm³.

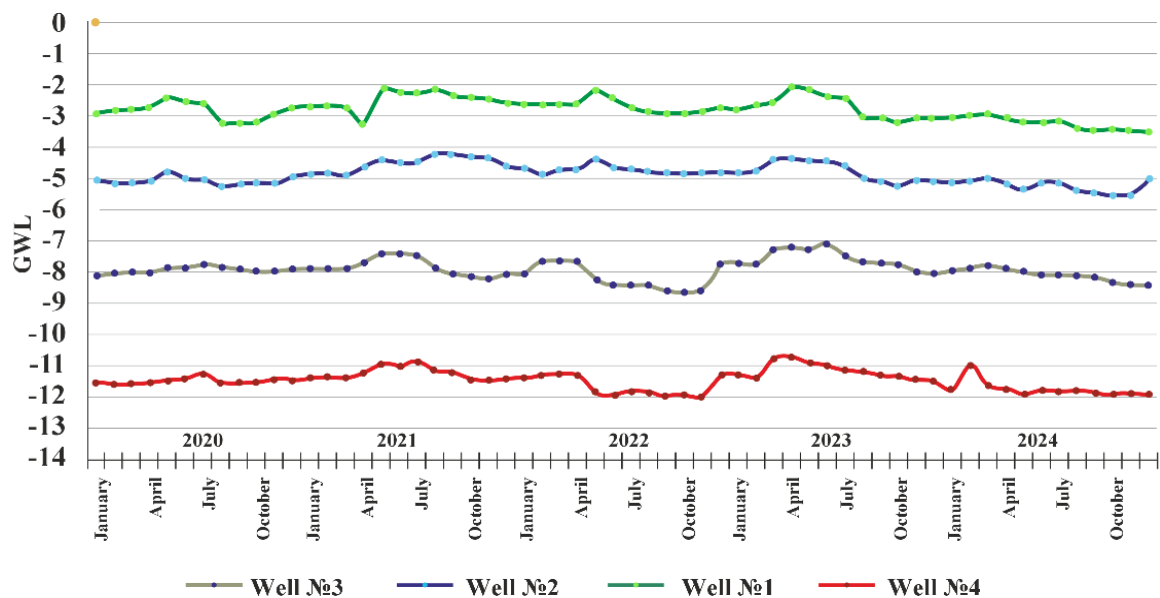


Fig. 2: Dynamics of groundwater levels in the study area for 2019–2024.

Table 2: Assessment of the quality of ground and surface waters accumulated in seasonal regulation storage ponds for irrigation of zoned cultivated agricultural crops in Enbekshikazakh district, Almaty region, in terms of the risk of developing negative processes.

Name of Irrigation Source	№ Well	Selection Date	Chloride Salinity Cl-, mg/L:	Sodium Solonization Ca++/Na+ Ratio, mg- eq/L:	Magnesium Salinization Ca ²⁺ /Mg ²⁺ ratio, mg-eq/L	Soda Formation (CO ₃ + HCO ₃)—(Ca + Mg), mg-eq/L	Water Quality Assessment
Groundwater	1	15 May 2024	0.8(I)	7.0(I)	6.0 (I)	0.2 (II)	(I) excellent
		15 September 2024	0.6(I)	9.3(I)	5.1 (I)	1.5 (III)	(II) good
	2	15 May 2023	1.2 (I)	5.5 (I)	3.3 (I)	0.3 (I)	(I) excellent
		15 September 2024	1.2 (I)	6.0(I)	3.4 (I)	0.8(I)	(I) excellent
	3	15 May 2023	1.2 (I)	7.3 (I)	2.5 (I)	0.5 (I)	(I) excellent
		15 September 2024	1.2 (I)	7.7 (I)	2.6 (I)	1.8 (III)	(II) good
	4	15 May 2024	0.4 (I)	12.1 (I)	10.1 (I)	0.9 (I)	(I) excellent
		15 September 2024	1.2 (I)	10.0 (I)	7.7 (I)	1.1 (II)	(I) excellent
Storage pond	Shelkar	15 May 2024	0.7 (I)	5.2 (I)	4.3 (I)	0.3 (I)	(I) excellent
		15 July 2024	0.6 (I)	5.5 (I)	3.3 (I)	0.7 (I)	(I) excellent
		15 September 2024	1.1 (I)	4.3 (I)	7.0 (I)	0.5 (I)	(I) excellent

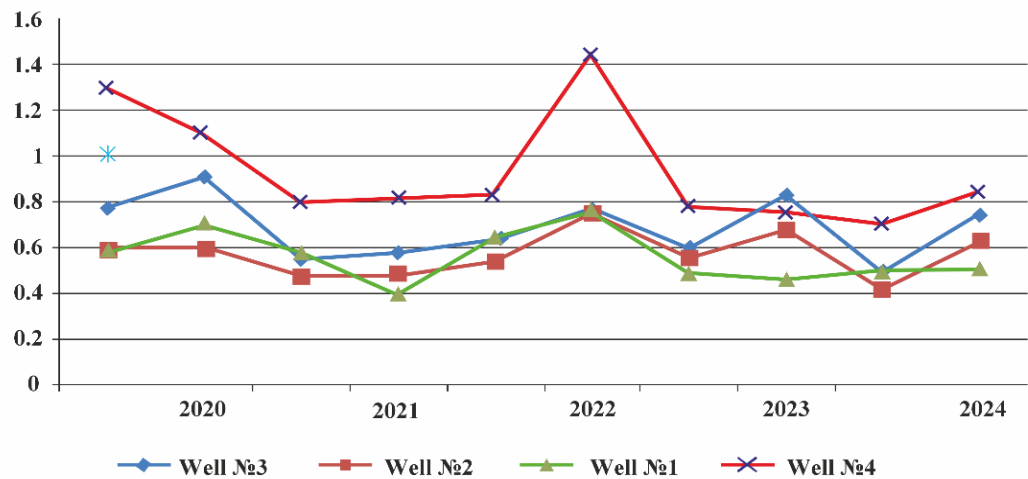


Fig. 3: Dynamics of changes in mineralization (g/dm³) of groundwater in the study area for 2020–2024.

Table 3: Assessment of the quality of groundwater formed during the growing season of agricultural crops on irrigated arable land due to the accumulation of local runoff in the Enbekshikazakh district of the Almaty region.

Name of irrigation source	№ Well	Selection date	Water class	Mineralization, g/L Quality assessment by total mineralization	Water reaction (pH)	Quality assessment according to stabler	SAR	Assessment of quality and risk of salinity according to antipov
Groundwater	1	15 May 2024	II	0.77 fresh	7.9 Neutral	36.9 very good	1.80 Low	C > Tk 1.19 > 0.18 suitable
			II	0.74 fresh	7.4 Neutral	96.0 very good	0.30 Low	C > Tk 12.75 > 0.18 suitable
		15 July 2024	I	0.50 ultrafresh	7.5 neutral	61.0 very good	0.40 low	C > Tk 7.06 > 0.12 suitable
			II	0.58 fresh	7.6 neutral	48.0 very good	2.8 low	C > Tk 0.65 > 0.14 suitable
		15 September 2024	I	0.40 ultrafresh	7.5 neutral	48.0 very good	1.4 low	C > Tk 1.95 > 0.1 suitable
			II	0.61 fresh	8.1 slightly alkaline	48.0 very good	3.2 low	C > Tk 0.84 > 0.15 suitable
	2	15 May 2024	II	0.59 fresh	8.7 slightly alkaline	48.0 very good	4.3 low	C > Tk 0.68 > 0.14 suitable
			II	0.70 fresh	8.0 slightly alkaline	31.0 very good	4.4 low	C > Tk 0.35 > 0.17 suitable
		15 July 2024	II	0.70 fresh	7.6 neutral	144.0 very good	1.3 low	C > Tk 4.29 > 0.17 suitable
			II	0.84 fresh	7.0 neutral	48.0 very good	3.2 low	C > Tk 5.77 > 0.20 suitable
		15 September 2024	II	1.07 fresh	7.4 neutral	48.0 very good	2.6 low	C > Tk 2.82 > 0.25 suitable
			II	0.84 fresh	7.0 neutral	48.0 very good	3.2 low	C > Tk 5.77 > 0.20 suitable

All groundwater samples collected from different wells and dates are classified as fresh or ultrafresh, based on total mineralization ranging from 0.40 to 1.07 g/L, which makes them suitable for irrigation purposes. According to water classification standards, Class I represents ultrafresh water (mineralization < 0.5 g/L), and Class II corresponds to fresh water (0.5–1.0 g/L). The pH values of the samples range from 7.0 to 8.7, indicating neutral to slightly alkaline conditions; this range is considered optimal for irrigation and poses no risk to crops. Based on the Stabler quality assessment, the water shows a very good balance of primary cations and anions, confirming its favorable composition for agricultural use. The

sodium adsorption ratio (SAR) values are below 3, indicating a low risk of soil degradation due to sodium accumulation. Using Antipov-Karataev's method for assessing salinity risk ($C > Tk$), where C is the actual concentration of dissolved salts and Tk is the threshold value, all groundwater samples fall within acceptable limits, further confirming the water's suitability for irrigation and minimal risk of salinization. The groundwater formed during the irrigation season in the Enbekshikazakh district demonstrates consistently high quality, with low salinity and sodium hazards, making it appropriate for long-term agricultural use. Regarding pollution indicators, the content of heavy metals such as lead,

Table 4: Content of microcomponents in groundwater in research area in 2023 for catalytic activity evaluation.

Place of selection	Selection date	Copper	Zinc	Lead	Cadmium	Petroleum products
Well 1	24 June 2024	0.0003	0.480	0.0030	0.0001	0.0879
	20 August 2024	0.0005	0.009	0.0003	0.0000	0.0683
Well 3	24 June 2024	0.0006	0.500	0.0045	0.0000	0.0942
	20 August 2024	0.0000	0.006	0.0002	0.0000	0.0269
Well 4	24 June 2024	0.0001	0.530	0.0030	0.0000	0.0896
	20 August 2024	0.0065	0.001	0.0003	0.0000	0.0127

copper, and cadmium remains below the maximum allowable concentration (MAC), while zinc and oil product levels are slightly above the MAC thresholds (Table 4).

Creating a seasonal regulation cascade for the Shelkar storage pond, as planned, led to artificial backwater and increased groundwater levels. The water was confined to the ends of the retaining and regulating structures and in the lower pool of the storage pond due to the infiltration of irrigation water through earthen and embankment dams during irrigation (comprising up to 60% of the water supply); this was due to the natural discharge of local springs such as “Karasu” and the infiltration of melt water and runoff from temporary water sources. At the same time, the regional groundwater level at the end of the retaining and regulating structures and in the lower pool of the storage pond was stable at 3 m (well no. 1—“Storage pond Shelkar”).

The methodology of this study is based on a combination of field measurements, laboratory analyses, and hydrological modeling aimed at assessing the quality, dynamics, and suitability of surface and groundwater accumulated in the Shelkarsky seasonal storage pond and the surrounding irrigation area. Below is a detailed breakdown of the procedures and equipment used during the research period (2019–2024).

3. Results and discussion

3.1 Results of the reconstruction and transition of the on-farm irrigation network and the creation of three reservoirs for recirculating systems using local temporary water sources and flood runoff

For the organization, testing, and adaptation of a representative section of circulating water use systems in the context of an increasing deficit of river water resources, using the example of the Baiterek rural district, Enbekshikazakh district, Almaty region, this study on the reconstruction and modernization of the reservoir’s on-farm irrigation network enabled the creation of a unique cascade for a seasonal regulation storage pond using local temporary water sources and flood runoff.

In order to increase the efficiency of the main channel in the earthen bed, which is 5 km long, as well as reduce water losses and increase its capacity, mechanical cleaning and deepening of the channel were carried out by increasing the channel’s capacity to 450 L/s, replacing three regulating retaining gates, and installing three connecting structures in

the lower and upper pools at the water outlet points.

The following occurred at the «Storage pond Shelkar» seasonal regulation storage pond:

- The dam height and width along the dam crest were increased to 8.0 m and 7.0 m, respectively (Fig. 4 and Table 5).
- The normal retaining level (NRL), originally 671.0 m, was increased to 672.5 m, while the forced retaining level (FRL), initially 671.5 m, was increased to 673.0 m.
- The total filling volume of the pond increased by +0.238 million m³ and amounted to 0.964 million m³ (initially 0.726 million m³). The useful volume changed in a positive direction by +0.238 million m³ and amounted to 0.462 million m³ with an initial average value of 0.396 million m³.
- The volume of the area of the open water surface used to fill the pond amounted to 3.65 hectares, which is 4.05 hectares more than the previous value (7.35 hectares).
- The serviced area increased from 1125 hectares to 1475 hectares, providing the opportunity to create about 35–40 new farming and peasant households using abandoned areas of irrigated arable land.

Over the past few years, large-scale work has been carried out to develop and subsequently implement mechanisms for the efficient use of local runoff and groundwater using seasonally regulated storage ponds, which are created depending on soil, hydrological conditions, and terrain. Local runoff includes temporary surface watercourses formed from spring snowmelt and heavy rains and small rivers that do not have a constant flow or independent economic significance without regulation. Local runoff is characterized by strong variations in time and short-term high-flow rates. The retention of surface runoff during periods of maximum flow reduces the peak of flooding in rivers, balances their regime, and reduces the risk of soil erosion and gully growth. The creation of reservoirs improves the landscape and provides economic and health benefits.

Research on one of the most strategically important irrigation areas with respect to ensuring food security in the Almaty metropolis demonstrated the economic efficiency of our proposal.^[16] This primarily includes saving irrigation water from a “risky” river irrigation source by more than 30% of the amount of water supplied for the entire growing season.

The location of the irrigated areas of peasant farms close to the outlets of the seasonal regulation storage pond contributed to a decrease in the transit time of irrigation canals and a reduction in seepage losses by 50%.

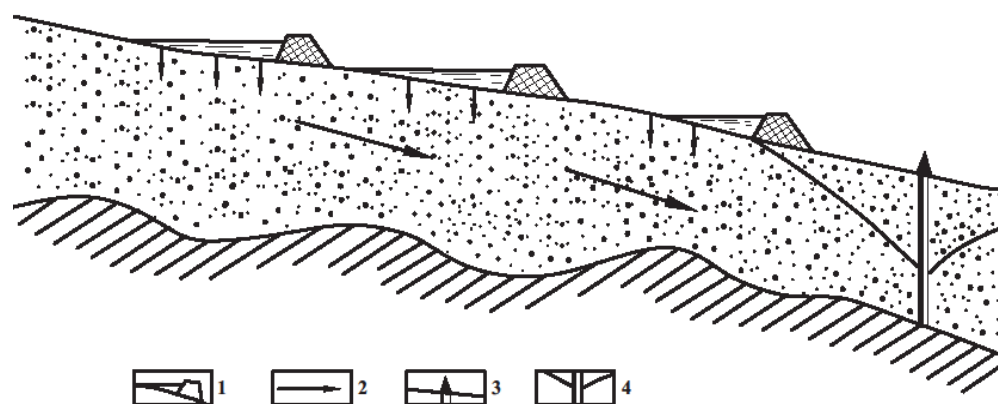


Fig. 4: Cascade of water-retaining dams, 1) transverse section of retaining dams in the cascade of infiltration reservoirs of seasonal regulation, 2) the direction of groundwater flow, taking into account infiltration feeding from reservoirs, 3) hydrogeological production well, completed by opening an aquifer with a bottom in a water seal, 4) formation of a depression funnel during groundwater intake.

Table 5: Technical characteristics of «Storage pond Shelkar» storage pond before and after reconstruction and modernization.

Seasonal regulation “Storage pond Shelkar”, Almaty region, Enbekshikazakh district, Baiterek rural district, PC SPK “Margulan”

Coordinates: 43°24' 06" N, 77°14'02" E, Value achieved: 672 m

Normal support level	671.0 m	672.5 m	+1.5 m
Forced backwater level	671.5 m	673.0 m	+1.5 m
Full volume	0.726 million m ³	0.964 million m ³	+0.238 million m ³
Useful volume	0.396 million m ³	0.396 million m ³	+0.066 million m ³
Mirror area	2.98 ha	3.65 ha	+0.67 ha
Serviced area	1125 ha	1475 ha	+350 ha
Length	600 m	600 m	-
Width	220 m	220 m	-
Max depth	5.80 m	7.30	+1.5
Dam	Height	7.0 m 8.5 m	+1.5
	bottom		
	width at the ridge	6.0 m 7.0 m	+1.0
	width at the bottom	9.0 m 10.5 m	+1.5

Analytical, statistical, and laboratory methods for hydrogeological and hydrochemical research were used to assess the quality characteristics of non-traditional local water sources such as melt water, rainwater, flood water, wedging groundwater, perched water, river runoff, and groundwater.^[17] Programs for the environmental monitoring of the hydrological regime and recommendations for conducting visual observations and surveys at seasonal regulation storage ponds were developed.

3.2 Research site and geographical scope

This research was carried out in the southeastern part of the Republic of Kazakhstan, in the administrative boundaries of the Yenbekshikazakh district of the Almaty region, which is located in the desert–steppe zone according to its climatic conditions.

The climate of the study area is sharply continental and characterized by harsh winters and hot summers.

According to meteorological data, the average annual air temperature is 10 °C. The warmest months are July, June, and August, while the coldest months are December, January, and February. Summers, especially in the northern part, are hot and dry. High summer air temperatures lead to a sharp decrease in relative humidity. The maximum relative humidity occurs during the lower-temperature months—November and December—and reaches 88%. Due to increasing temperatures from winter to summer, the relative humidity drops rapidly, reaching an average of 29–38% in July, August, and September. This low relative humidity generates a humidity deficit, which sharply increases in April and reaches its maximum value in July and August.^[18–20] Spring is characterized by an intense heat increase and rapid snowfall. March can sometimes have a negative average monthly air temperature.

In the arid zone, most precipitation occurs during the winter–spring period, when there is no vegetation; therefore,

understanding accumulation patterns is important. For this purpose, geological structures for spring stormwater storage and its subsequent utilization during dry periods were examined.

The area under consideration includes the foothill plains of the northern slopes of Ile Alatau,^[21,22] the southern and northeastern slopes of Zhongar (Zhetysu) ridge,^[23,24] and small areas in the northeastern part of the Shu-Ile mountains (the main part belongs to the Zhambyl region). Structurally, this hydrogeological area is known as the Kopa-Ilei intermountain depression, which is a typical multilevel groundwater basin enclosed between the northern slopes of Tien Shan and Zhongar Alatau. The area of this basin is 27 thousand km².^[25-29]

3.3 Results of modernization

In the Baiterek rural district of the Yenbekshikazakh district, the unique and expensive Big Almaty Canal was built at the time of the creation of the Bartogai reservoir and the regulation of flow of the Shelek river, which was later named after D. A. Konayev. The situation changed dramatically after 40 years passed; the canal and its structures have “aged” and require extensive rearrangement and technical re-equipment. State programs have led restoration projects for the lost hydromeliorative fund, but these were carried out on large swaths of engineering-prepared land, which require significant increases in water consumption and create objective prerequisites for sharply reducing the water supply through on-farm irrigation systems with small-scale agricultural production by farmers and peasant farms.

At present, the method of using local river runoff, melt water, and flood waters that accumulate in the storage pond for seasonal regulation to meet the needs of the agricultural sector is the most acceptable direction for the preservation of

irrigated agriculture in the Baiterek rural district, Yenbekshikazakh district; importantly, it provides an incentive to adopt a careful attitude to the scarcity of surface sources for irrigation.

In order to address the main concern of this study, large-scale works were carried out over the last few years to develop and further implement effective methods for the use of local runoff water and groundwater. This was achieved using seasonal regulation storage ponds, which are created depending on soil, hydrological conditions, and terrain.

As a result of the project's implementation, the distribution irrigation canal was reconstructed, three seasonal regulation storage ponds were repaired, and a unique cascade of seasonal regulation storage ponds were created using local temporary water sources and flood runoff (Fig. 5).

Creating ponds for seasonal water storage and regulation resulted in an artificial groundwater supply from which operational reserves were formed due to the infiltration of water during irrigation (up to 60% of the water supply); this was due to the natural discharge of local springs of the Karasu type and the infiltration of melt water and runoff of temporary water sources.

In addition, the regional groundwater level at the ends of the retaining and regulating structures and in downstream storage ponds was stable at 3 to 6–8 m from the surface of the irrigated plots. Regarding groundwater, assessments of the quality and degree of its suitability showed a low degree of total mineralization (from 0.4 to 1.2 g/L), and experimental pumping data were used to determine these values by measuring shallow hydrogeological wells with flow rates from 1.0 to 1.5 L/s (Fig. 6). These are ideal conditions for the creation of small drip-irrigation plots, using water-saving methods, technical means, and crop irrigation technologies to improve the productivity of water and land use.

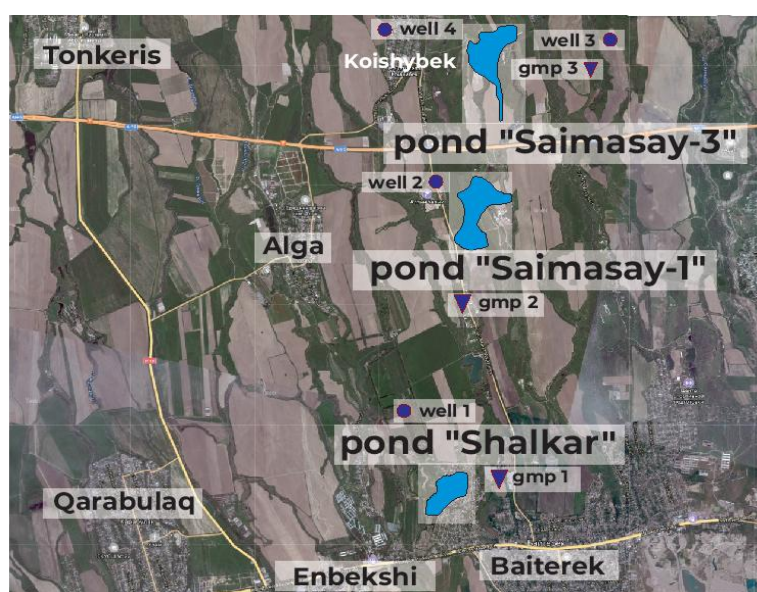


Fig. 5: Satellite map of the research area with the location of modernized ponds: seasonal regulation reservoirs; hydrological and hydrogeological points for stationary ecological and ameliorative monitoring and assessment of their environmental impact during operation (<https://earth.google.com/web>).

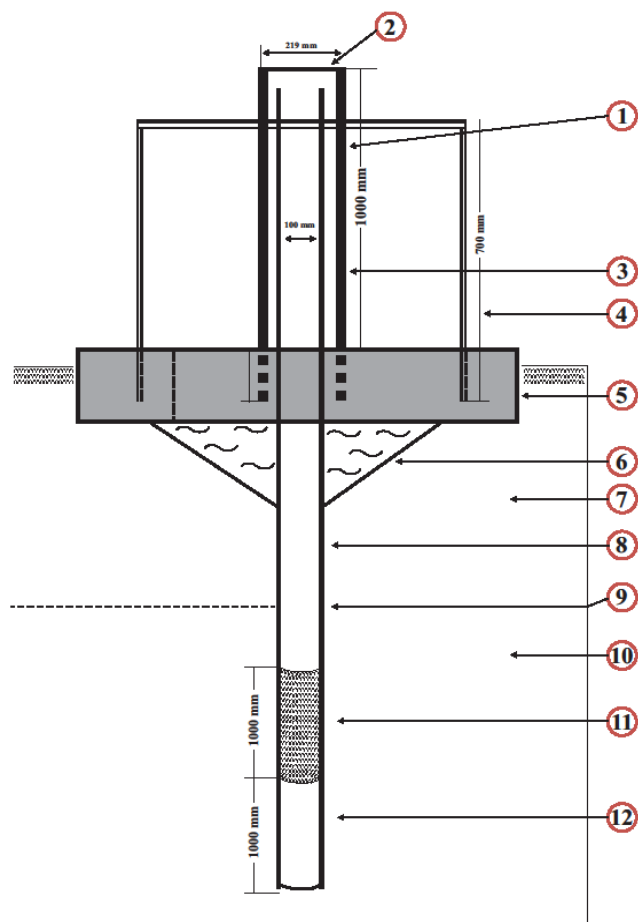


Fig. 6: Adopted exploration–exploitation design of well. Notation: 1—protective cover made of metal pipe 219 mm in diameter and 1300 mm in length, of which 300 mm extends into the concrete base and 1000 mm is brought to the ground surface; 2—cover of the protective cover, metal circle, 219 mm diameter, 3 mm thick, hinged or sliding, with a locking device; 3—well head, the upper part of which (well head) should be brought to the ground surface at a height of 900 mm with a concrete base of 100 mm; 5—concrete base of cement mortar, height 400 mm, of which 300 mm should be under the ground, with the rest of the length extending to the surface, with dimensions of 1000 × 1000 mm; 6—clay castle, made of bentonite clay, tamped around the casing to a depth of 300 mm below the concrete base; 7—aeration zone; 8—well casing made of chemically inert material (polyvinyl chloride), with a diameter of 100 mm and a depth of 15 m; 9—groundwater level; 10—aquifer; 11—filter, with slotted or round perforation with a diameter of 8–9 mm; distance between perforations: 50 mm vertically and 50 mm horizontally; on the perimeter of the perforated part of the pipe stainless steel mesh, the galloon weave (diameter of the mesh cross-section is 0.30 mm) is wound in two layers; the length of the filter is taken as 1000 mm; 12—settling tank, with a length not less than 1000 mm.

Local water sources, such as melt water, flood water, temporary watercourse runoff, and ejected groundwater with alternate routes to ponds, accumulate in the unique systems developed in this study for the seasonal regulation of the cascade. The quantitative composition and quality of irrigation

water sourced from these ponds and outlets distributing water to discharge points on farms are important.

Study demonstrates the successful reconstruction of on-farm irrigation infrastructure, resulting in a 30% reduction in irrigation water use, 50% reduction in seepage losses, and an increase in serviced area by 350 hectares. These outcomes are consistent with findings from similar projects in arid and semi-arid regions. Turkmenistan and Uzbekistan have implemented small reservoir cascades and on-farm canal modernization, showing water savings of 25–35% and reduced dependence on unstable river flows (FAO, 2020).

In India's Gujarat state, seasonal pond systems for capturing monsoon runoff achieved increased groundwater recharge and enabled multi-cropping, with well yields improved by up to 1.5 L/s, similar to your results (ICID, 2018). China's Loess Plateau projects reported landscape improvements and erosion control from check dams and regulated flood storage, aligning with your findings on reduced gully formation and improved microclimate (World Bank, 2015).

4. Conclusion

The scientific substantiation and implementation of the method of accumulating the river runoff of flood waters in storage ponds (small reservoirs that provide seasonal regulation) of melt waters for their subsequent use by the agricultural sector are important incentives for determining solutions to the scarcity of surface sources for irrigation. In summary, retaining surface runoff during periods of maximum discharge of rivers during the flood peak maintains their regime, reducing the risk of soil erosion and the growth of gullies. Creating reservoirs improves landscapes, providing economic and health benefits. The storage pond cascade creates conditions for the backwater of groundwater to increase, taking into account the capillary fringe of the lower level of the root system of some agricultural crops, which can be used as an additional source of irrigation due to the resulting subirrigation. Additionally, increasing groundwater levels will not cause secondary soil salinization, which has a negative impact. This initial experimental work on a strategically important irrigation array designed to ensure food security in the Almaty metropolis demonstrated the economic efficiency of our proposed approach. The assessment of groundwater quality and suitability, as previously described, showed a low degree of total mineralization (from 0.4 to 1.07 g/L), and experimental pumping data support their use, depicting them as shallow hydrogeological wells with flow rates of 1.0 to 1.5 l/sec. These are ideal conditions for creating small drip-irrigation areas, using water-saving techniques, technical means, and technologies for watering agricultural crops to improve the productivity of water and land use.

Develop and scale up similar storage pond systems in other districts with comparable hydroclimatic conditions to enhance irrigation reliability and water conservation. Promote drip and subsurface irrigation systems utilizing shallow groundwater,

especially in areas with low-flow wells, to maximize water-use efficiency and crop yield. Incorporate subirrigation principles into irrigation planning for crops with deeper root systems to take advantage of elevated groundwater tables. Encourage the integration of water storage with land reclamation projects, leveraging the dual benefits of erosion control and water availability. Support policy frameworks and local investment in small reservoir construction and maintenance to ensure long-term sustainability of irrigation infrastructure. The study confirms that a combination of nature-based solutions and modern irrigation technologies offers a viable strategy for improving agricultural resilience and optimizing land and water resources in regions vulnerable to climate-induced water scarcity. Demonstrates the effectiveness of cascade storage ponds in restoring 1,420 hectares of abandoned land, which was not achieved in earlier implementations. Confirms the role of subirrigation from raised groundwater levels without causing secondary salinization—an issue often overlooked in prior studies. Provides experimental data on shallow groundwater wells (1.0–1.5 L/s) as viable sources for small-scale drip irrigation systems, supporting practical application. Introduces an integrated approach combining flood runoff retention, groundwater recharge, and modern irrigation technologies for enhanced water-use efficiency. Offers scalable recommendations for replication in other regions with similar hydroclimatic conditions, filling the gap between theory and applied regional solutions.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

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