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Seasonal Water Chemistry and Reclamation Status of Irrigated Lands in the Syr Darya Basin

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ABSTRACT

This article addresses the deterioration of reclamation conditions and the decline in soil fertility in the middle and lower reaches of the Syr Darya River Basin, where the major irrigated agricultural lands of Kazakhstan are located. The paper presents the results of comprehensive studies conducted during 2023–2025 and summarizes seasonal changes in the chemical indicators of water resources within the Syr Darya River Basin, as well as assesses the impact of water quality on the reclamation status of irrigated lands. The quality of irrigation water primarily affects the "soil solution–soil adsorption complex" system and, through this mechanism, influences nearly all components of the soil reclamation regime. The study revealed that most water quality indicators in the Syr Darya River Basin do not exceed maximum permissible concentrations and generally remain within acceptable limits. However, in some cases, irrigation water is characterized by high mineralization (up to 1.5 g/L and higher), the predominance of toxic ions (Na^+, Mg^{2+}), and unfavorable magnesium cation concentrations, which contribute to soil magnesium sodification. Collector-drainage and wastewater discharges were identified as the main sources of irrigation water contamination in the basin. Analysis of the calculated data made it possible to assess changes in soil chemical properties at the beginning and end of the growing season. The results demonstrated the influence of irrigation water quality on the degree of soil salinization and sodification. Furthermore, irrigation with highly mineralized water leads to the accumulation of toxic salts in agricultural lands and contributes to the degradation of irrigated soils.

Keywords: *Irrigation water, Water quality, Irrigated lands, Land reclamation, Salinization, Groundwater*

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INTRODUCTION

The efficiency and sustainability of irrigated agriculture depend strongly on water availability, irrigation water quality, and the reclamation condition of soils. In southern and southeastern Kazakhstan, salinization and sodification are among the major causes of declining soil fertility and productivity. These processes are intensified by the deterioration of irrigation and collector-drainage infrastructure, the use of highly mineralized water, and the discharge of collector-drainage and wastewater into natural water bodies (Bekbayev, 2012; Bekbayev *et al.*, 2013; Magai, 2013).

The ecological and reclamation condition of irrigated lands in Kazakhstan remains problematic. Approximately 40% of irrigated lands are affected by salinization, while about 30% are subject to sodification, alkalization, and nutrient depletion, with particularly pronounced degradation in the Kyzylorda Region (Committee for Land Resources Management of the Ministry of Agriculture of the Republic of Kazakhstan, 2021; Republican State Institution "Kyzylorda Hydrogeological and Reclamation Expedition," Ministry of Agriculture of the Republic of Kazakhstan, 2021–2023; Republican State Institution "South Kazakhstan Hydrogeological and Reclamation Expedition," Ministry of Agriculture of the Republic of Kazakhstan, 2022–2023). Intensive irrigation, insufficient drainage, high evaporation, and the migration of salts within the soil–plant–groundwater system promote salt accumulation in the root zone and reduce the long-term stability of irrigated agroecosystems.

Previous studies conducted in CIS countries and internationally have demonstrated that irrigation water quality directly affects soil fertility, crop productivity, and reclamation status (IUPAC, 1972; Knoli *et al.*, 1989; Mirzadinov & Isakhodjayev, 2021;

Milchenkova *et al*., 2022). At the same time, irrigation practices may contribute to the pollution of surface and groundwater because collector-drainage effluents return dissolved salts and other contaminants to natural water systems (Qadir *et al*., 2008; Mustafayev *et al*., 2020; Ramos *et al*., 2021; Zhaparkulova *et al*., 2021; Imanaliyev *et al*., 2022; Kudaibergenova *et al*., 2023). This problem is relevant to the Syr Darya River basin, where collector-drainage waters from agricultural areas of the Turkestan Region are discharged into the river.

The situation is further complicated by the use of vertical drainage wells. More than 700 restored wells operate seasonally in the Turkestan Region, and analyses of groundwater from many of them indicate the predominance of toxic salts (Meybeck, 1987; Oster *et al*., 2016; Malakar *et al*., 2019; Klimaszyk *et al*., 2022). During periods of irrigation water shortage, such as in 2025, the intensive operation of these wells may increase the use of mineralized groundwater for agricultural purposes. Elevated mineralization and declining irrigation water quality are therefore important factors contributing to secondary salinization of irrigated lands in Kazakhstan (Gapparov *et al*., 2011; Satybaldiyev *et al*., 2023).

The effect of irrigation water on soils depends not only on total mineralization but also on the qualitative composition of dissolved salts. Harmful salts include chlorides, sulfates, carbonates, and bicarbonates of sodium and magnesium, whereas most calcium salts are considered less harmful (Vyshpolsky *et al*., 2008; Qadir *et al*., 2018). According to their relative toxicity, the main salts can be arranged as follows (Kovda, 1980; Vyshpolsky *et al*., 2010):

$Na_2CO_3 > NaHCO_3 > NaCl > CaCl_2 > Na_2SO_4 > MgCl_2 > MgSO_4$

Because salt composition influences soil physicochemical properties, plant development, crop productivity, and the choice of reclamation measures, its assessment is essential for evaluating irrigation water quality. For this purpose, water-extract data are commonly recalculated into qualitative salt composition by combining cations and anions according to the solubility of the resulting salts (Vyshpolsky *et al*., 2010; Dzhaisambekova *et al*., 2025). Accordingly, the present study investigates seasonal changes in irrigation water mineralization and salt composition in the Syr Darya River basin and evaluates their relationship with the reclamation status of irrigated soils.

MATERIALS AND METHODS

Soil sampling

To study changes in the chemical indicators of water resources and assess their impact on the reclamation status of irrigated lands, soil-reclamation sites and water sampling points were selected along irrigation canals in the Kazakhstan part of the Syr Darya River basin.

In accordance with GOST 17.4.4.02-2017 *Nature Conservation. Soils. Methods of sampling and preparation of samples for chemical, bacteriological, and helminthological analysis:* soil samples were collected from sampling plots designed to avoid distortion of analytical results under the influence of environmental factors. Sampling sites were established in areas with homogeneous soil and vegetation cover, taking into account the economic use of the main soil types (GOST 17.4.3.01-2017, 2017; GOST 17.4.4.02-2017, 2017).

To monitor soil contamination in agricultural lands depending on the nature of pollution sources, sampling plots measuring 10 × 10 m were selected (GOST 17.4.4.02-2017, 2017).

- Soil-reclamation site No. 1 is located on irrigated lands in the settlement of Myrzakent, Maktaaral District, Turkestan Region, adjacent to an irrigation canal (Point 1: 40°40'30"N 68°33'12"E).
- Soil-reclamation site No. 2 is located on irrigated lands in the village of Alatau Batyr, Shardara District, Turkestan Region, with a corresponding irrigation canal (Point 2: 41°46'04"N 67°56'02"E).
- Soil-reclamation site No. 3 is located on irrigated lands in the village of Karaultobe, Kyzylorda City, also adjacent to an irrigation canal (Point 3: 44°55'20"N 65°31'43"E).

Samples were collected by profile from soil horizons 0–20, 20–40, and 40–60 cm, ensuring that each sample represented soil material typical of the genetic horizons or layers of the respective soil type.

Soil sampling was carried out using an AM-26 auger at the beginning (April) and end (September) of the 2025 growing season. Composite samples were prepared by mixing individual point samples collected from the same sampling plot.

For chemical analysis, composite samples were formed from at least five subsamples taken within one sampling plot. The mass of the composite sample was not less than 1 kg.

Soil samples for chemical analysis were air-dried in accordance with GOST 5180. Air-dried samples were stored in cloth bags.

Water samples were collected from irrigation canals, i.e., from irrigation sources used on the selected soil-reclamation sites.

Sampling and analysis were carried out in accordance with current regulatory requirements and standard methodological guidelines for determining total mineralization, ionic composition (CO_3^{2-}, HCO_3^-, Cl^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, $Na^+ + K^+$), and calculated parameters such as SAR, K, Mg*, etc. (Antipov-Karataev & Kader, 1961; Stebler, 1965; Yakubov *et al*., 1982; Bezdnina, 1989). The purpose of sampling was to obtain a discrete sample representing the quality (composition and properties) of the studied water **(GOST 31861-2012, 2012)**. Sampling was performed manually at fixed irrigation canal points using a telescopic sampler MS-1-6000 with a cup-type device during the agricultural vegetation period (three times per year: spring, summer, and autumn). The sample volume ranged from 500 to 1000 mL, in accordance with methodological requirements for the determination of specific parameters and allowing for repeat analysis.

Collected samples were placed in glass containers without air bubbles, with the containers rinsed at least three times with the sampled water, labeled, and transported to the laboratory for chemical analysis. No preservation methods were applied; analysis was performed within 24 hours after sampling.

Chemical analysis and evaluation criteria

Chemical analyses of irrigation water and soil samples were performed in the chemical laboratory of LLP “KazSRIVH.” Irrigation water was analyzed for total mineralization, pH, and ionic composition, including CO_3^{2-}, HCO_3^-, Cl^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, and $Na^+ + K^+$. Mineralization was determined conductometrically using electrical conductivity measurements and calibration curves, while ionic composition was determined by titration and flame photometry. The pH was measured potentiometrically at 20 ± 2 °C using a laboratory pH meter calibrated with standard buffer solutions of pH 4.00, 7.00, and 9.18. All analyses were performed in duplicate, and mean values were reported. Analytical validity was verified by ion balance, with an acceptable deviation of no more than 5%.

Irrigation-water suitability was evaluated using total mineralization, the irrigation coefficient (K), sodium adsorption ratio (SAR), Na_2CO_3 concentration, pH, and the relative magnesium content (Mg*). According to total dissolved salt content, water was classified as fresh (<1 g/L), slightly saline (1–3 g/L), moderately saline (3–10 g/L), saline (10–35 g/L), or brine (>35 g/L) (Yakubov *et al*., 1982; Bezdnina, 1989; Amanbayeva *et al*., 2022).

The irrigation coefficient was calculated according to the method of I.N. Antipov-Karataev and G.M. Kader (Antipov-Karataev & Kader, 1961; Amanbayeva *et al*., 2022; Tumlert *et al*., 2023):

$$K = (Ca^{2+} + Mg^{2+})/(Na^{+} + 0.23C), \quad (1)$$

where C is water mineralization (g/L), and Ca^{2+}, Mg^{2+}, and Na^{+} are expressed in milliequivalents per liter. A value of K > 1 indicated no risk of soil sodification, whereas K < 1 indicated that the water was unsuitable for irrigation.

The sodium adsorption ratio was calculated as follows (Stebler, 1965; Yakubov *et al*., 1982; Altynbay *et al*., 2024):

$$SAR = Na^{+}/\sqrt{[(Ca^{2+} + Mg^{2+})/2]}, \quad (2)$$

where all cations are expressed in milliequivalents per liter. SAR values below 10 indicated a low sodification risk, values of 10–18 indicated a moderate risk, values of 18–26 indicated a high risk, and values above 26 indicated a very high risk.

The risk associated with sodium carbonate was evaluated according to Na_2CO_3 concentration: values below 0.3 meq/L indicated water safe for irrigation, values of 0.3–0.6 meq/L indicated water suitable for irrigation, and values above 0.6 meq/L indicated water unsuitable for irrigation without amendments (Yakubov *et al*., 1982; Cuevas *et al*., 2019; Abdrahimov *et al*., 2020). Water pH was used as an additional indicator of alkalinity (Yakubov *et al*., 1982).

The relative magnesium content was calculated as follows (Yakubov *et al*., 1982; Mirdadayev *et al*., 2022; Allen *et al*., 2023):

$$Mg = [Mg^{2+}/(Ca^{2+} + Mg^{2+})] \times 100,* \quad (3)$$

where Ca^{2+} and Mg^{2+} are expressed in milliequivalents per liter. Magnesium was considered potentially harmful to soil when its relative content exceeded 50% (Stebler, 1965; Asarin *et al*., 2010).

To determine the degree and chemical type of soil salinization, water extracts from the 0–60 cm root zone were analyzed for dry residue, CO_3^{2-}, HCO_3^{-}, Cl^{-}, SO_4^{2-}, Ca^{2+}, Mg^{2+}, and $Na^{+} + K^{+}$. Ion concentrations were converted into milliequivalents, and the qualitative salt composition was calculated according to the method of N.I. Bazilevich and E.I. Pankova by sequentially combining cations and anions based on the solubility of the resulting salts (Bekbaev *et al*., 2005; Dzhaisambekova *et al*., 2025). The calculated composition included non-toxic and toxic salts, particularly $Ca(HCO_3)_2$, $CaSO_4$, Na_2CO_3, $NaHCO_3$, $MgSO_4$, Na_2SO_4, $CaCl_2$, $MgCl_2$, and NaCl. The sum of the calculated salts was compared with the measured dry residue; a discrepancy exceeding 10–15% required verification and recalculation.

RESULTS AND DISCUSSION

According to chemical analysis (soil water extract) of water samples for 2025, the mineralization of irrigation water in the Syr Darya River basin ranged from 0.914 g/L to 1.454 g/L, while pH varied from 7.37 to 8.27. The minimum mineralization values were observed in the middle reaches of the Syr Darya River, while the maximum values were recorded in the lower reaches **(Table 1)**.

Table 1. Dynamics of mineralization of irrigation waters in the Syr Darya River basin

Sampling location	Sampling time	Anions				Cations			Mineralization (total salts)
		CO_3^{2-}	HCO_3^{-}	Cl^{-}	SO_4^{2-}	Ca^{2+}	Mg^{2+}	$Na^{+}+K^{+}$	
Irrigation canal of Site No. 1	Spring	0,007 0,51	0,239 17,0	0,094 6,86	0,641 46,75	0,324 23,64	0,012 0,88	0,064 4,66	1,381 100
	Summer	0,002 0,20	0,161 16,97	0,287 28,91	0,207 20,85	0,124 12,49	0,061 6,14	0,107 10,77	0,949 100
	Autumn	0,010 1,09	0,200 22,43	0,315 34,46	0,131 14,33	0,108 11,82	0,087 9,52	0,058 6,35	0,909 100
Irrigation canal of Site No. 2	Spring	0,005 0,37	0,247 18,6	0,102 7,67	0,611 45,93	0,108 8,12	0,080 6,01	0,177 13,30	1,330 100
	Summer	отс.	0,171 15,66	0,284 26	0,307 28,11	0,108 9,89	0,056 5,13	0,166 15,21	1,092 100
	Autumn	отс.	0,283 19,46	0,373 25,65	0,379 26,06	0,152 10,45	0,100 6,89	0,167 11,49	1,454 100
Irrigation canal of Site No. 3	Spring	отс.	0,264 21,29	0,125 10,08	0,503 40,56	0,124 10	0,061 4,92	0,163 13,15	1,24 100
	Summer	0,007 0,74	0,215 22,80	0,310 32,87	0,138 14,63	0,100 10,6	0,073 7,74	0,100 10,6	0,943 100
	Autumn	0,005 0,40	0,239 19,33	0,596 47,23	0,019 1,51	0,116 9,19	0,085 6,73	0,197 15,61	1,257 100

Note: In numerator — g/L; in denominator — percentage of total salts

The chemistry of irrigation water salinization in the Syr Darya River basin and water quality indicators based on total mineralization (C) and sodium adsorption ratio (SAR) are presented in **Figure 1**.

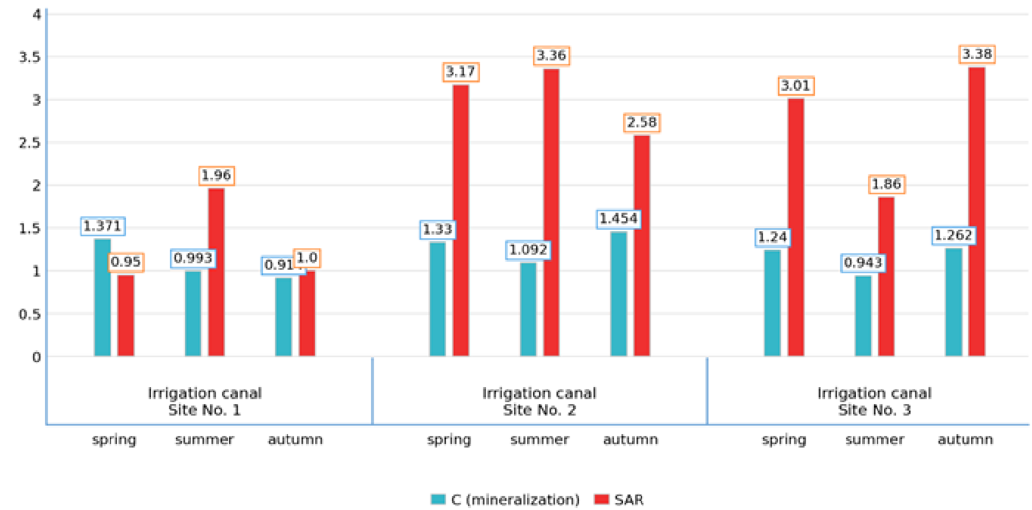

Figure 1. Chemical quality indicators of irrigation water in the Syr Darya River basin according to total mineralization (C) and sodium adsorption ratio (SAR)

Chemical quality indicators of irrigation water according to the irrigation coefficient K, pH, and the percentage of magnesium cations relative to the sum of calcium and magnesium cations (Mg^{2+}) are presented in **Figure 2**.

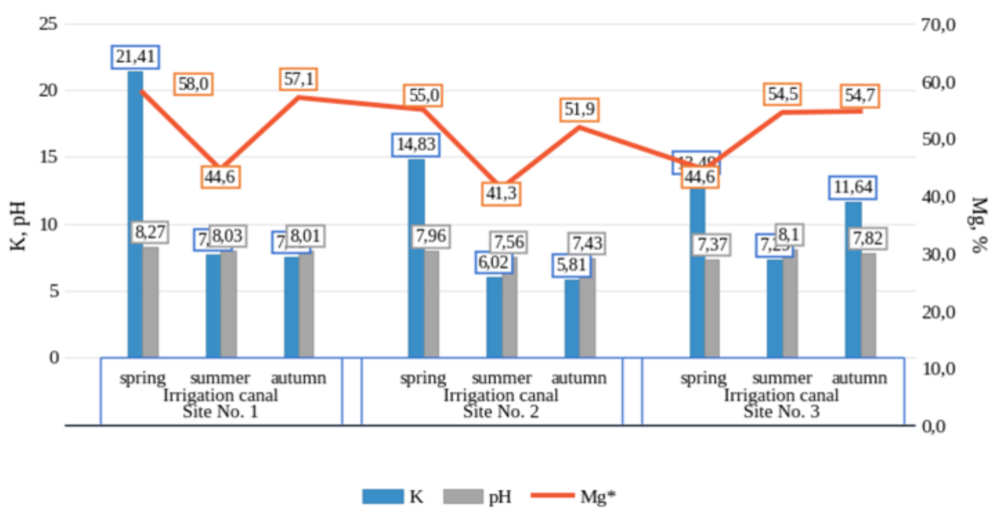

Figure 2. Chemical quality indicators of irrigation water in the Syr Darya River basin according to K, pH, and Mg^{2+}

According to many quality indicators, the irrigation water of the Syr Darya River basin does not exceed the maximum permissible limits or remains within the standard ranges, except for magnesium indicators. An increased content of magnesium cations in irrigation water has a harmful effect on the chemical properties of soils and, during irrigation, leads to magnesium-induced soil sodification (Kinsman, 1967; Yakubov *et al*., 1982; Hovland *et al*., 2018; Turdiyeva & Lee, 2023).

The salinity chemistry of irrigation water in the Syr Darya River basin was also determined by the ratio of chloride ions to sulfate ions (Cl^-/SO_4^{2-}) (Yakubov *et al*., 1982; Bezdnina, 1989; Ma *et al*., 2019; Salehi & Kussainova, 2023).

According to the chloride-to-sulfate ion ratio, the water in the irrigation canals of Sites No. 1, No. 2, and No. 3 was classified as satisfactory in spring and slightly satisfactory in summer and autumn. Such water can be used under conditions of very high drainage capacity of the territory, with annual leaching, and mainly on light-textured soils.

Analysis of the ionic composition of waters in the Syr Darya River basin shows that SO_4^{2-} dominates among the anions, with its content ranging from 0.019 to 0.641 g/L. Its share in the total salt content varies from 1.5 to 46.7%. The minimum value was recorded in autumn in the irrigation canal of Site No. 3, while the maximum value was observed in spring in the irrigation canal of Site No. 1.

The chloride content ranges from 0.094 to 0.596 g/L. The lowest value was recorded in spring in the irrigation canal of Site No. 1, while the highest value was observed in autumn in the irrigation canal of Site No. 3. The bicarbonate content exceeds the chloride content only in spring in all three irrigation canals and ranges from 0.171 to 0.283 g/L, whereas in all other cases toxic chloride predominates **(Table 1)**.

The qualitative mineral composition of irrigation water was established by assessing water extract data. Evaluations of the Syr Darya River basin reveal that hazardous salts, specifically NaCl, $MgSO_4$, and $MgCl_2$, prevail throughout most samples. For instance, observations at Site No. 1 during summer and autumn indicate that non-toxic components constitute 45.5% of total salinity, whereas toxic salts represent 54.5%, with NaCl and $MgCl_2$ contributing 27.9% and 17.5%, respectively. Simultaneously, irrigation channels at Sites No. 2 and No. 3 exhibit an even higher concentration of harmful substances, as toxic salts comprise between 58.8% and 72.0% of the total mineral profile, with non-toxic variants accounting for only 28.0–41.2%. These findings confirm the significant salinity risks present within the regional water supply systems for agricultural use.

Table 2. Qualitative salt composition of irrigation waters in the Syr Darya River basin

Sampling location	Sampling time	Non-toxic salts			Toxic salts								Sum of salts
		Ca(HCO₃)₂	CaSO₄	Sum	Na₂CO₃	NaHCO₃	MgSO₄	Na₂SO₄	CaCl₂	MgCl₂	NaCl	Sum	
Irrigation canal of Site No. 1	Spring	0,303 22,0	0,858 62,10	1,161 84,10	0,012 0,86		0,055 3,98			0,004 0,28	0,149 10,78	0,220 15,90	1,381 100
	Summer	0,232 24,45	0,196 20,65	0,428 45,10	0,001 0,11		0,089 9,38			0,166 17,49	0,265 27,92	0,521 54,90	0,949 100
	Autumn	0,273 30,04	0,141 15,51	0,414 45,55	0,009 0,99		0,049 5,39			0,339 37,29	0,098 10,78	0,495 54,45	0,909 100
Irrigation canal of Site No. 2	Spring	0,324 24,36	0,097 7,29	0,421 31,65	0,009 0,68		0,224 16,84	0,540 40,60		0,136 10,23		0,909 58,12	1,330 100
	Summer	0,227 20,79	0,180 16,48	0,407 37,27				0,270 24,73		0,217 19,87	0,198 18,13	0,685 62,73	1,092 100
	Autumn	0,376 25,9	0,205 14,1	0,581 40,0				0,351 24,2		0,386 26,6	0,134 9,2	0,871 60,0	1,454 100
Irrigation canal of Site No. 3	Spring	0,350 28,23	0,130 10,48	0,480 38,71			0,300 24,19	0,256 20,65			0,204 16,45	0,760 61,29	1,240 100
	Summer	0,286 30,33	0,103 10,92	0,389 41,25		0,013 1,38	0,084 8,91			0,217 23,01	0,240 25,45	0,554 58,75	0,943 100
	Autumn	0,324 25,77	0,028 2,23	0,352 28,0		0,009 0,72			0,078 6,21	0,330 26,25	0,488 38,82	0,905 72,0	1,257 100

Note: numerator — g/L; denominator — percentage of total salts.

The analysis of the performed calculations made it possible to assess the dynamics of seasonal changes in the chemical properties of irrigation waters in the Syr Darya River basin **(Table 2)**.

Thus, analysis of the ion-salt composition of waters in the Syr Darya River basin shows that the main factors deteriorating the quality of irrigation waters are the predominance of toxic salts over non-toxic salts and the presence of alkaline salts in their composition — Na_2CO_3 (normal soda) and $NaHCO_3$ (sodium bicarbonate).

To assess the effect of irrigation water on the reclamation status of irrigated lands, soil samples were collected from the selected soil-reclamation sites for chemical analysis at the beginning and at the end of the growing season. The ionic composition was determined for the 0–20, 20–40, and 40–60 cm horizons; then the average value was calculated for the 0–60 cm horizon, i.e., the root zone of the soil.

At the beginning of the growing season, the total salt content at Site No. 1 was 0.225% of the dry soil mass; therefore, the soil was classified as non-saline. This is a favorable indicator for most agricultural crops **(Table 3)**.

Analysis of the ionic composition of soils at Site No. 1 shows that, at the beginning of the growing season, SO_4^{2-} dominates among the anions, with a content of 0.091% of the dry soil mass, or 40.4% of the total salt content. The bicarbonate content exceeds the chloride content and amounts to 0.053% of the dry soil mass, or 23.5% of the total salt content.

Table 3. Ionic composition of salts in the root zone of soils (0–60 cm) of the experimental plots, % of dry soil mass

Place and date of soil sampling	Anions			Cations			Sum of salts
	HCO₃	Chloride Cl	SO₄	Ca	Mg	Na+K by difference	
Site No. 1, beginning of the growing season	0,053 23,56	0,019 8,44	0,091 40,44	0,027 12	0,013 5,78	0,022 9,78	0,225 100
Site No. 1, end of the growing season	0,052 18,57	0,088 31,43	0,055 19,65	0,033 11,79	0,017 6,08	0,035 12,5	0,280 100

Site No. 2, beginning of the growing season	0,044 7,356	0,047 7,853	0,340 56,01	0,075 12,25	0,027 4,456	0,070 12,076	0,583 100
Site No. 2, end of the growing season	0,051 24,64	0,067 32,37	0,026 12,56	0,014 6,76	0,009 4,35	0,040 19,32	0,207 100
Site No. 3, beginning of the growing season	0,051 18,0	0,115 30,46	0,116 20,57	0,063 13,25	0,013 3,61	0,051 14,11	0,409 100
Site No. 3, end of the growing season	0,065 11,13	0,217 37,16	0,112 19,18	0,06 10,27	0,023 3,94	0,107 18,32	0,584 100

Note: numerator — % of dry soil mass; denominator — % of total salts

The ionic composition of the water extract of soil samples from Site No. 1 at the end of the growing season shows that, with a total salt content of 0.280% of dry soil mass, Cl^- dominates among the anions, with a content of 0.088% of dry soil mass, or 31.4% of the total salt content. The bicarbonate content is approximately equal to the sulfate content: HCO_3^- amounts to 0.052% of dry soil mass, or 18.6% of the total salt content, while SO_4^{2-} amounts to 0.055% of dry soil mass, or 19.6% of the total salt content.

The results of the water extract analysis make it possible to determine the qualitative salt composition in the root zone of soils. The analysis of the performed calculations made it possible to assess changes in the chemical properties of soils between the beginning and the end of the growing season **(Table 4)**.

Table 4. Analysis of calculations based on chemical analyses of the root zone of soils (0–60 cm) of the experimental plots, conducted at the beginning and end of the growing season on irrigated lands of the Syr darya River basin

Place and date of sampling	Non-toxic salts			Toxic salts							Sum of salts
	$Ca(HCO_3)_2$	$CaSO_4$	sum	$NaHCO_3$	$MgSO_4$	Na_2SO_4	$CaCl_2$	$MgCl_2$	NaCl	sum	
Site No. 1, beginning of the growing season	0,072 28,93	0,036 14,34	0,108 43,27		0,06 26,47	0,029 12,84			0,032 14,35	0,121 53,66	0,225 100
Site No. 1, end of the growing season	0,069 26,06	0,054 20,52	0,123 46,58		0,022 7,43			0,046 17,91	0,088 28,08	0,156 53,42	0,279 100
Site No. 2, beginning of the growing season	0,057 9,71	0,209 33,74	0,267 43,46	0,085 16,57	0,112 17,53	0,068 10,66		0,018 3,61	0,032 8,16	0,316 56,54	0,583 100
Site No. 2, end of the growing season	0,050 24,13	0,006 3,26	0,056 27,39	0,019 9,14		0,031 14,6		0,038 18,29	0,063 30,57	0,151 72,61	0,207 100
Site No. 3, beginning of the growing season	0,067 23,90	0,155 24,55	0,222 48,45		0,009 4,18		0,005 0,59	0,044 10,82	0,129 35,96	0,187 51,55	0,409 100
Site No. 3, end of the growing season	0,087 15,59	0,095 14,26	0,182 29,85		0,048 8,66	0,012 2,58	0,031 5,89	0,052 9,07	0,259 43,95	0,402 70,15	0,584 100

Note: numerator — % of dry soil mass; denominator — % of total salts

The analysis of the performed calculations made it possible to assess the dynamics of changes in the chemical properties of soils at the beginning and at the end of the growing season.

The ionic composition of the water extract of soil samples and the analysis of the calculations performed for the selected soil-reclamation sites at the end of the growing season showed that, according to the assessment of the qualitative composition of irrigated soils in the Syr Darya River basin, toxic salts predominate and account for more than 50% of the total salt content **(Table 3)**. Using soil-reclamation site No. 3 as an example, it can be observed that the average values in the 0–60 cm layer indicate salinity and amount to 0.584% of the dry soil mass.

The presence of $NaHCO_3$ (sodium bicarbonate) was observed at soil-reclamation Site No. 2. This is the most dangerous type of salinization, since soda causes strong alkalization of the soil.

At all soil-reclamation sites, highly soluble and toxic chlorides (NaCl, $MgCl_2$, $CaCl_2$) and sulfates (Na_2SO_4, $MgSO_4$) accounted for a significant share. An increase in total salinity in the 0–60 cm soil layer was recorded at Sites No. 1 and No. 3. This is a significant increase, shifting the soil from the slightly saline category to the moderately saline category (Belfiore *et al.*, 2024; Bukhary, 2024; Figueroa-Valverde *et al.*, 2024; Karatas, 2024; Negreiros & Ory, 2024; Samaranayake *et al.*, 2024; Wolderslund *et al.*, 2024; Alexandrovna *et al.*, 2025; Fritea *et al.*, 2025; Narayana *et al.*, 2025; Nguyen *et al.*, 2025; Mesquita *et al.*, 2026; Phan, 2026; Zeried, 2026). The content of non-toxic salts at the end of the growing season decreased at all three soil-reclamation sites. The content of toxic salts at the end of the growing season increased at all three soil-reclamation sites. At Site No. 3, the content of toxic salts increased sharply, more than doubling from 0.187 to 0.402%, and accounted for 70.1% of the total salt content (Kęska & Suchy, 2024; Kounatidis *et al.*, 2024; Lee & Ferreira, 2024; Abdullah *et al.*, 2025; Jagsi *et al.*, 2025; Petronis *et al.*, 2025; Schneider & Krüger, 2025; Wong *et al.*, 2025; Yu *et al.*, 2025).

An active process of secondary salinization is observed, mainly due to the accumulation of the most harmful toxic salts for plants (Csep *et al.*, 2024; Ghiga *et al.*, 2024; Jin *et al.*, 2024; Osluf *et al.*, 2024; Musa *et al.*, 2025; Raza *et al.*, 2025).

Salinization and sodification are among the main factors reducing the fertility and productivity of irrigated lands in southern Kazakhstan. These processes are closely associated with the quality of irrigation water, which is affected by collector-drainage and wastewater discharges and by elevated mineralization. The use of such water promotes the accumulation of toxic salts in soils and contributes to the deterioration of their reclamation status. Therefore, the selected soil-reclamation sites in the Syr Darya River basin were examined to assess the relationship between irrigation water quality and changes in soil salinity and sodification.

In 2025, irrigation water mineralization in the studied part of the Syr Darya River basin ranged from 0.914 to 1.454 g/L, while pH varied from 7.37 to 8.27. The lowest mineralization was observed in the middle reaches and the highest in the lower reaches of the river. According to the chloride-to-sulfate ratio, irrigation water was generally satisfactory in spring and slightly satisfactory in summer and autumn. However, elevated magnesium concentrations indicate a risk of magnesium-induced soil sodification. The presence of toxic and alkaline salts, including Na_2CO_3 and $NaHCO_3$, further reduces irrigation water quality, which is consistent with previous studies (Zhaparkulova *et al*., 2021; Salehi & Kussainova, 2023; Dzhaisambekova *et al*., 2025).

The soil analyses confirmed that irrigation water quality is reflected in the seasonal transformation of the salt composition of irrigated soils. By the end of the growing season, toxic salts accounted for more than half of the total salt content at the studied sites. Highly soluble chlorides (NaCl, $MgCl_2$, $CaCl_2$) and sulfates (Na_2SO_4, $MgSO_4$) represented a substantial proportion of the salt composition, while $NaHCO_3$ was detected at Site No. 2, indicating an additional risk of soil alkalization.

Seasonal changes were especially pronounced at Sites No. 1 and No. 3, where an increase in total soil salinity was recorded. At all three sites, the proportion of non-toxic salts decreased, whereas the content of toxic salts increased by the end of the growing season. The most pronounced deterioration occurred at Site No. 3, where toxic salt content increased from 0.187% to 0.402% and reached 70.1% of the total salt content. This trend is consistent with previously reported patterns of salt accumulation in irrigated soils (Salehi & Kussainova, 2023; Tumlert *et al*., 2023).

Overall, the results indicate an active process of secondary salinization associated with the accumulation and redistribution of readily soluble toxic salts in the soil profile. High evaporation, saline groundwater, and the continuous input of salts with irrigation water are likely to intensify these processes. The observed sulfate-chloride type of salinization and the increasing proportion of toxic salts demonstrate a gradual deterioration of the reclamation condition of the studied soils and emphasize the need for improved drainage, water-quality control, and appropriate reclamation measures.

CONCLUSION

Evaluating the natural and economic status of the Syr Darya River basin demonstrates a vital requirement for expanding irrigated agriculture to secure consistent crop output. Nevertheless, agricultural efficiency is hindered by severe water scarcity and contamination issues. The ongoing application of mineralized water, compounded by insufficient drainage infrastructure, accelerates land degradation through desertification and salinization. Furthermore, the discharge of untreated return flows significantly degrades water quality by elevating ionic concentrations in downstream regions. In environments characterized by high evaporation, capillary action draws shallow, saline groundwater toward the surface. This process, largely triggered by intensive irrigation practices, ultimately results in the problematic secondary salinization of productive agricultural lands, necessitating urgent improvements in water management and irrigation policy within the region.

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