








Original scientific paper

UDC: 631.413.3:556:502.131.1
<https://doi.org/10.2298/IJGI260112009K>

Received: January 12, 2026
Reviewed: February 25, 2026
Accepted: April 29, 2026



INTEGRAL ASSESSMENT OF SOIL SALINIZATION AND WATER RESOURCE USE CONDITION FOR THE PURPOSE OF SUSTAINABLE LAND USE

Kulyash Kaimuldinova¹ , Shakhislam Laiskhanov² , Gulbanu Alimbekova^{1*} ,
Zhanerke Sharapkhanova³ , Saken Kerimsheev⁴ 

¹Abai Kazakh National Pedagogical University, Faculty of Natural Sciences and Geography, Department of Geography and Ecology, Almaty, Kazakhstan; e-mails: kaimuldinovakulyash@gmail.com; gulbanu.alimbekova1@gmail.com

²International Educational Corporation (KazGASA), Department of Science and Innovation, Almaty, Kazakhstan; e-mail: laiskhanov@gmail.com

³JSC "Institute of Geography and Water Security", Laboratory of Geotourism and Geomorphology, Almaty, Kazakhstan; e-mail: sharapkhanova@gmail.com

⁴Republican State Institution "South Kazakhstan Hydrogeological and Land Reclamation Expedition", Committee of State Inspection in the Agro-Industrial Complex, Ministry of Agriculture of the Republic of Kazakhstan, Shymkent, Kazakhstan; e-mail: s.kerimsheev@mail.ru

Abstract: Soil salinization and inefficient use of water resources in irrigated areas of South Kazakhstan pose a significant threat to the sustainability of agro-industrial systems. This study aims to comprehensively assess soil salinization processes, irrigation system efficiency, and their impact on agricultural crop biomass in the Zhetysai district, located in a water-scarce region. The research covers the period 2015–2024 and integrates geographic information systems (GIS), Sentinel-2 satellite remote sensing data, field observations, and hydromelioration statistical monitoring information. Spatial analysis showed that approximately 45–50% of irrigated lands exhibit signs of salinization, including 15–20% classified as moderately and strongly saline soils. Irrigation water losses during conveyance were significant, with the calculated water delivery coefficient ranging from 0.61 to 0.68, indicating substantial inefficiencies in canal systems. Groundwater levels increased during the observation period, contributing to intensified secondary salinization processes. Areas with high salinity demonstrated Normalized Difference Vegetation Index (NDVI) values reduced by 10–25%, reflecting a decline in vegetation biomass and agricultural productivity. The results provide a deeper understanding of the spatial patterns and driving factors of soil salinization in the Zhetysai district and form a scientific basis for optimizing water resource management, improving drainage system performance, and planning sustainable land reclamation measures. The proposed integrated assessment approach can be applied to other irrigated regions of Kazakhstan to enhance agroecosystem resilience and ecological sustainability.

Keywords: soil salinization; irrigated lands; integrated assessment; geographic information system (GIS); Zhetysai district (Kazakhstan)

¹ Corresponding author, e-mail: gulbanu.alimbekova1@gmail.com

1. Introduction

According to the experts' estimation, approximately 932 million ha of land globally have been subjected to salinization, which corresponds to 25–30% of the world's irrigated land (Smanov et al., 2025). Soil salinization and inefficient water use represent a major global challenge that reduces agricultural productivity and accelerates land degradation, particularly in arid and semi-arid regions where salinity significantly limits soil fertility and crop yields (Ba et al., 2024; Food and Agriculture Organization of the United Nations [FAO], 2023).

Soil salinization is a widespread problem in Kazakhstan, affecting about 43% of agricultural land (Smanov et al., 2025). Under conditions of water scarcity, secondary salinization has become particularly acute in South Kazakhstan, including the Myrzashol region where Zhetysai district is located. Long-term studies indicate that the area of salinized arable land in Myrzashol increased from 50.4 to 99.2 thousand ha over the past 25 years, while the share of moderately and highly saline soils rose from about 25% in the mid-1990s to 38–39% by 2020 (Duanbekova et al., 2024; Tokbergenova, Zulpykharov, Taukebayev et al., 2023). Intensive irrigation for water-demanding crops such as cotton, combined with deterioration of irrigation–drainage systems, has contributed to groundwater rise and accelerated soil salinization (Laiskhanov et al., 2016; Tokbergenova, Zulpykharov, Taukebayev et al., 2023). Hydrological changes in the Syr Darya basin and inefficient water use further aggravate land degradation processes (Jakiyayev et al., 2021; Yessymkhanova et al., 2021; Zhupankhan et al., 2018). As a result, salt accumulation reduces soil fertility and crop productivity, with yield losses ranging from 10% to 100% depending on the degree of salinization (Laiskhanov et al., 2022; Poshanov et al., 2022; Rakhmanov et al., 2024).

The processes of salt accumulation in the soil are closely related to water regime: excessive irrigation or insufficient rinsing of the soil will cause salt to accumulate in the soil (Greene et al., 2016). Therefore, there is a need for a comprehensive assessment of soil condition, considering soil and water factors as a whole. Researchers emphasize the importance of integrated approaches that take into account the interaction of soil and water (Greene et al., 2016; Murtazin et al., 2022). Previous research has often evaluated soil and water quality based on individual parameters, such as soil salt content, electrical conductivity, or salt concentration in irrigation water. Such an approach may overlook interactions between hydrological and soil processes. Therefore, comprehensive soil assessment requires the combined analysis of groundwater regime, irrigation practices, and vegetation indicators (Murtazin et al., 2022). In addition, as a model for a comprehensive assessment, a combined index that includes various natural and anthropogenic factors—the Combined Salinization Risk Indicator (CRI) provided a spatial representation of the risk of soil salinization in a particular region (Maab et al., 2025).

In Kazakhstan, the first steps are being taken toward a comprehensive land assessment: in the western region, the reclamation situation of irrigated land has been comprehensively analyzed, taking into account both groundwater and soil salinity together (Murtazin et al., 2022). It is important to consider the processes of soil salinization and water use in their interrelation, conduct a comprehensive (integrated) assessment and find ways to effectively use them. Such an approach is an important condition for sustainable land use and ensuring long-term productivity of agroecosystems.

The aim of this study is to provide an integrated assessment of soil salinization and water resource use in the Zhetysai district under conditions of water scarcity, and to determine their impact on agricultural crop biomass. To achieve this goal, the following research questions were formulated: (1) What is the level of water resource availability in the study area, and what

key problems have emerged in relation to water use practices? (2) How does inefficient water use affect groundwater regimes and soil salinization, and to what extent do these processes influence agricultural crop biomass? The findings of this study are expected to contribute to a better understanding of similar processes in other irrigated regions of Kazakhstan and to support the development of conceptual approaches for addressing the identified challenges.

2. Research materials and methods

2.1. Study area

The study area is the Zhetysai district located in the Turkestan Region of southern Kazakhstan, on the left bank of the Syr Darya River. The district borders the Republic of Uzbekistan to the south and southwest, the Maktaaral district to the east and southeast, and the Shardara district to the north (Figure 1).

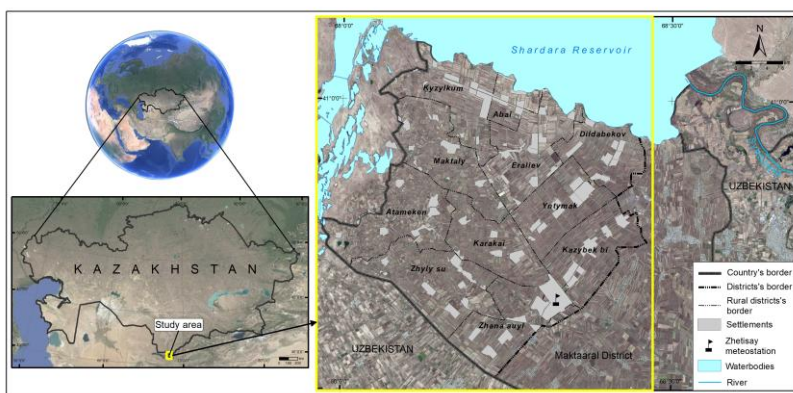


Figure 1. Study area.

Note. Contains modified data from *Sentinel-2 MSI Level 2-A* (Collection 1) [Data set] (images acquired in 2024), by European Union, European Space Agency, and Copernicus (2021).
<https://dataspace.copernicus.eu/>. CC BY-SA 4.0.

The natural conditions of the region are characterized by a predominantly flat relief, semi-desert and desert climate, and soil–climatic resources suitable for irrigated agriculture. Zhetysai district is located in the northern part of the Myrzashol desert. The terrain has slight slopes toward the Syr Darya River and the Arnasai depression, with elevations ranging from 240 to 280 m a.s.l. Weak natural drainage and minimal slope gradients contribute to groundwater accumulation and limit natural salt leaching, which significantly influences the water regime and spatial distribution of soil salinization.

The climate of the Myrzashol region is characterized by high heat availability and significant daily and annual air temperature fluctuations. Precipitation occurs mainly in winter and spring. In 2024, the average annual air temperature reached +15.5 °C, exceeding the long-term average (1991–2024) by 3.9 °C. Based on data from the Ministry of Agriculture of the Republic of Kazakhstan, State Institution “South Kazakhstan Hydrogeological–Reclamation Expedition” (LAC), the warm period lasts about 230–250 days, with a sum of positive temperatures of 4,600–5,000 °C (2024).

Air humidity plays an important role in the movement of water-soluble salts and soil moisture. According to long-term observations (1991–2024), the hydrothermal coefficient of

the study area ranges from 0.22 to 0.48, indicating insufficient moisture conditions. The Vysotsky–Ivanov moisture coefficient varies from 0.12 to 0.22 annually and decreases to 0.02–0.10 during the April–September growing season. The aridity coefficient ranges from 19 to 39, confirming that the territory belongs to the semi-desert landscape zone (LAC, 2024).

The soil cover of the Zhetysai district is mainly composed of gray desert soils (Serozems), which correspond to Calcisols and partly Gypsisols in the WRB soil classification system (ISRIC – World Soil Information, 2025). These soils are characterized by light and medium-textured mechanical composition and relatively low organic matter (humus) content. The soils of the study area are characterized by sulfate (hydrocarbonate–sulfate) and sulfate–chloride types of salinization (Tokbergenova, Zulpykharov, Taukebayev et al., 2023).

Vegetation cover of the area consists of xerophytic and semi-xerophytic species typical of desert and semi-desert zones. Cotton, clover, corn, vegetable crops and vegetables are grown in irrigated fields. According to the data, in 2024, cotton was sown on 40.8 thousand ha, horticultural crops on 19.7 thousand ha, 3.4 thousand ha of vegetables, 7.3 thousand ha of grain corn, 6.6 thousand ha of fodder crops and 0.8 thousand ha of rice crops in the district. The productivity of agricultural crops largely depends on soil salinity conditions and irrigation water availability (Bureau of National Statistics of the Republic of Kazakhstan, 2025).

According to LAC (2024), in Zhetysai district, there are 83,399 ha of irrigated land. Agriculture is carried out here – by irrigation. The only source of irrigation in the region is the Syr Darya River, where annual water releases are regulated under intergovernmental agreements (Zhupankhan et al., 2018). The 49-km Dostyk Canal (120 m³/s capacity) and the “20 Years of Independence” pumping canal supply irrigation water to 86.7 thousand ha of farmland in Zhetysai and Maktaaral districts (LAC, 2024).

2.2. Methods of data collection and processing

The study used comprehensive methods that combined geographic information system (GIS), remote sensing data and field observation data to assess the degree of soil salinity and water use conditions. Data from the Zhetysai meteorological station (Kazhydromet, 2025) were used to characterize agroclimatic conditions of the study area. A permanent monitoring network consisting of 279 observation and piezometric wells, operated by the South Kazakhstan Hydrogeological-Reclamation Expedition (LAC, 2024), was used to monitor groundwater level and mineralization dynamics in irrigated lands. Archival monitoring data covering the period 2015–2024 were analyzed, including monthly groundwater depth measurements, groundwater mineralization values, and soil-reclamation indicators. These institutional monitoring records served as the primary basis for assessing groundwater conditions and evaluating soil salinity development within the district.

To assess the efficiency of water use, information was collected from the district water management department on the volume of water supplied during the irrigation campaign. For the 2024 irrigation season (April–October), data on water withdrawal from the Dostyk Canal and its distribution across rural districts of Zhetysai were analyzed.

The volumes of irrigation water withdrawn and water supplied to irrigated fields were analyzed using official reports from regional water management authorities (LAC, 2024). Due to the availability of aggregated statistical data, the assessment was conducted at the district level rather than for individual rural administrative units. Irrigation efficiency was evaluated using the water delivery coefficient (WDC), calculated as follows:

$$WDC = \frac{V_{field}}{V_{withdrawn}} \quad (1)$$

- WDC – water delivery coefficient (-);
- V_{field} – volume of water supplied to irrigated fields (million m³);
- $V_{withdrawn}$ – total volume of water withdrawn from the irrigation source (million m³).

The coefficient characterizes water losses occurring during conveyance through irrigation canals and distribution networks. The calculated WDC values are presented in Table 1.

As part of the study, various spatial data were superimposed and cartographic analysis was conducted. In the ArcGIS software environment, the digital soil map of the Zhetysai district, contours of irrigated lands, network of water supply canals and collector-drainage system maps were combined. This integration enabled the development of a meliorative zoning map (melioration cartogram) identifying spatial patterns of salinity and groundwater conditions.

Multispectral Sentinel-2A/B satellite imagery from the European Space Agency (ESA) Copernicus program (European Space Agency [ESA], 2025) was used for remote sensing analysis. Sentinel-2 data were selected due to the availability of four Red-Edge spectral bands (705–783 nm), which are sensitive to vegetation stress associated with soil salinity.

Sentinel-2 satellite data were selected for three key periods of the 2024 vegetation season: 23 May 2024, 22 July 2024, and 20 October 2024. Due to the relatively small size of the study area, a single satellite scene was used for each observation date. Images with low cloud cover were selected for spectral index calculation. The May and October scenes were used to assess soil conditions before sowing and after the vegetation period, whereas the July imagery, corresponding to peak crop development, was applied to evaluate vegetation status.

Several spectral indices were calculated to assess vegetation condition and soil salinity, including the Normalized Difference Vegetation Index (NDVI), Normalized Difference Salinity Index (NDSI), Vegetation Soil Salinity Index (VSSI), Salinity Index 1 (SI1), and Salinity Index 2 (SI2). These indices were derived from Sentinel-2 Level-2A multispectral imagery.

The following spectral bands were used for index calculation:

- $NDVI = (B8 - B4) / (B8 + B4)$;
- $NDSI = (B3 - B11) / (B3 + B11)$;
- $VSSI = (B8 - B4) / (B8 + B4 + B2)$;
- $SI1 = B11 / B8$;
- $SI2 = B11 / B4$.

All indices were calculated from Sentinel-2 Level-2A atmospherically corrected imagery with a spatial resolution of 10–20 m depending on spectral band characteristics. NDVI was used to assess vegetation condition, while salinity indices were applied to identify surface soil salinity patterns. Image preprocessing, index calculation, and map generation were performed in ArcGIS Pro 3.x. NDVI was derived from summer Sentinel-2 imagery (July) representing peak crop growth and was used to indicate vegetation response to salinity stress rather than direct soil salinity. Salinity indices were calculated from images with reduced vegetation cover, enabling indirect assessment of salinity impacts on crop productivity.

NDVI and SI1 class boundaries were defined through expert interpretation considering literature data, seasonal conditions, crop presence, and visual salinity indicators in RGB

composites. NDVI was classified into five categories (≤ 0 ; 0–0.2; 0.2–0.4; 0.4–0.6; 0.6–0.8), while salinity levels on S11 maps were determined using the Jenks natural breaks method. Resulting maps were converted to vector format to calculate class areas and conduct comparative analysis. NDVI values were calibrated with field observations, and overlay analysis of NDVI and salinity maps was used to assess vegetation response to different salinization levels.

The relationship between salinity intensity and vegetation condition was assessed through descriptive comparison of NDVI distributions across salinity classes. Integration of hydrogeological monitoring, irrigation statistics, GIS analysis, and remote sensing indicators enabled a comprehensive evaluation of water use efficiency, groundwater dynamics, and soil salinization processes in the study area.

3. Results

3.1. Water supply level and conditions of its use in the study area

In Zhetysai district, 539.02 million m³ of wastewater was received in 2024, of which 112 million m³ was received by machine-operated water lifting canal. Since the vast majority of farms in the district are engaged in cotton cultivation, the irrigation period also comes at the same time. The load on irrigation networks is also uneven, and two burden peaks are observed in the annual cycle. Irrigation networks are designed for 9 types of rotational crops, including 55–56% of cotton crops, and at the peak of the irrigation period (LAC, 2024), they are subjected to a very large load and cannot deliver irrigation water in a timely manner. Moreover, a substantial discrepancy exists between the volume of withdrawn irrigation water and the amount of water actually supplied to irrigated fields, indicating conveyance losses within the irrigation system (Figure 2).

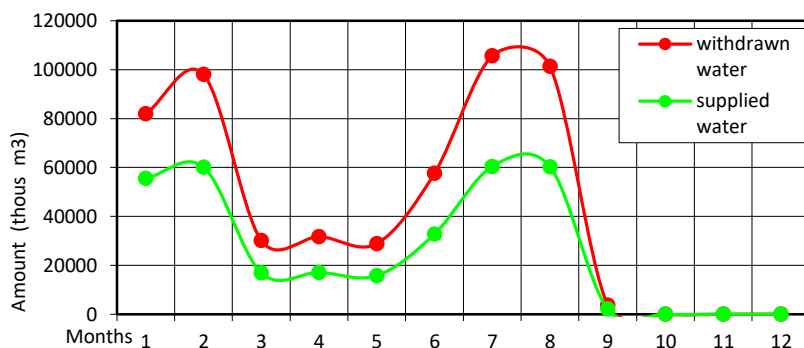


Figure 2. Graph of running water collection and supply in Zhetysai district for 2024.

Water supply of irrigated lands of Zhetysai district is mainly carried out through one large main canal – Dostyk. Dostyk canal is formed from local soil in the same place, half dug and half raised, and the useful effect coefficient of the canal has a permeability of 0.85÷0.90. The total length of the canal is 113 km, the initial estimated water intake is 230 m³/s, including the length of the section in Zhetysai and Maktaaral districts of the Turkestan region of the Republic of Kazakhstan is 49 km. The canal consists of four hydro-section sections, and three horizontal dams and about 45 primary inter-farm water systems receive water from this canal. During the

2024 growing season, a total of 539.02 million m³ of water was withdrawn from the district, of which approximately 320.87 million m³ was actually used and reached the fields (LAC, 2024). The volume and limit volume of running water withdrawn and released by are given in Table 1.

Table 1. Irrigation water withdrawn and released to fields by Zhetysai district in 2023–2024

Years	Irrigated land area (ha)		Fixed limited water volume (thous. m ³)	Volume (million m ³)			Water delivery coefficient
	Total	Used		Extracted water	Water supplied to the fields	Shared water, m ³ /ha	
2023	83.82	83.57	663.00	528.46	364.70	4.363	0.69
2024	83.40	83.14	663.00	539.02	320.87	3.859	0.60

Note. Adapted from *Information report on the reclamation status of irrigated lands in Zhetysai district, Turkestan region* (p. 27), by Land Administration Committee of the Ministry of Agriculture of the Republic of Kazakhstan & State Institution “South Kazakhstan Hydrogeological–Reclamation Expedition”, 2024, <https://www.gov.kz/memleket/entities/land?lang=en>. Copyright 2024 by Land Administration Committee of the Ministry of Agriculture of the Republic of Kazakhstan.

The analysis of irrigation water uses efficiency shows a decrease in the water delivery coefficient from 0.69 in 2023 to 0.60 in 2024, indicating increasing water losses within the irrigation network. Although the total volume of water withdrawn increased slightly in 2024, the amount of water actually delivered to irrigated fields decreased from 364.70 million m³ to 320.87 million m³. This reflects significant conveyance losses occurring during water transport through canals and distribution systems.

The results demonstrate spatial inequality in water distribution: farms located at the tail-end of irrigation canals experience water shortages, while upstream areas receive excessive irrigation water, leading to groundwater rise and increased risk of secondary soil salinization. Overall, these findings confirm the low efficiency of irrigation water use in the study area.

The main types of water losses are filtration losses (absorption during flow through the canal channels) and evaporation from open water surfaces. In most parts of the district irrigation system, the canals are covered in the form of open channels dug into the soil, while only some sections of highway are covered with concrete. Table 2 presents data on the extent of concrete lining of canals within the district.

Table 2. The condition in the lining of canals with concrete in Zhetysai district

№	Canal name	Located rural district	Not covered with concrete (km)	Covered with concrete (km)
1	K-21	Zhana auyl, Zhyly su	271.35	75.00
2	K-25	Atameken, Karakai	242.83	106.55
3	K-26	Kazybek bi	53.17	31.89
4	K-27	Maktaly	18.27	-
5	K-28	Dildabekov, Yntymak	78.24	63.40
6	K-30	Abai, Kyzylkum, Eraliev	185.59	53.61
7	K-32	Eraliev	22.50	16.87
8	K-34	Maktaly	157.32	28.70

Note. Ministry of Water Resources and Irrigation of the RSE “KazVodkhoz”. (2024). Technical characteristics of the canals managed by the Zhetysai Production Department of the Turkestan Branch [Personal communication/Database]. Republic of Kazakhstan, Turkestan region, Zhetysai city.

The data presented in Table 2 indicate that a substantial proportion of irrigation canals within Zhetysai district remain unlined. In several canal sections, the length of earthen channels significantly exceeds concreted segments, which increases filtration losses during water conveyance. For example, canals K-21 and K-25 contain more than twice the length of unlined sections compared to concreted parts. Such technical conditions of irrigation infrastructure contribute to inefficient water delivery and substantial water losses before reaching agricultural fields.

Due to the existing meliorative conditions in the region, irrigated agriculture is possible only with good artificial dams. For this reason, there are horizontal irrigation ditch systems in the valley to remove groundwater and waste water from arable land and reduce groundwater levels. Irrigation technology is mainly based on traditional methods – surface irrigation through irrigated fields. In such cases, if water is supplied in excess of the norm, it contributes to soil salinization and erosion. There are 479 irrigation ditches in the Myrzashol region with a length of 1,156.16 km, of which 183.56 km belong to Zhetysai district (Figure 3).

Currently, the water throughput capacity of the drainage systems has decreased due to silting and reed growth. Only 173 of the 392 vertical drainage wells in the region are operational. The volume of water discharged from the controlled irrigation ditches in the reporting year was 120.29 million m³, of which 25.19 million m³ flowed into the Syr Darya River and 95.10 million m³ into the Central Myrzashol irrigation ditch (LAC, 2024).

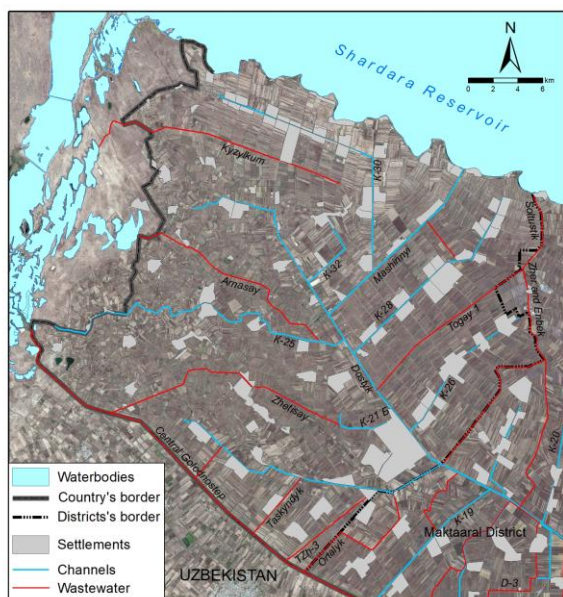


Figure 3. Schematic map of the main water and irrigation ditch systems in the Myrzashol valley.

Note. Contains modified data from *Sentinel-2 MSI Level 2-A (Collection 1)* [Data set] (images acquired in 2024), by European Union, European Space Agency, and Copernicus (2021).

<https://dataspace.copernicus.eu/>. CC BY-SA 4.0. Processed by the authors.

Two peaks are observed in the annual discharge of the collector–drainage system. Seasonal discharge peaks were identified based on official monthly monitoring data (2015–

2024) from the South Kazakhstan Hydrogeological-Reclamation Expedition (LAC, 2024). The February–March and July–August maxima were derived from the analysis of aggregated monthly discharge volumes. The study relies on institutional monitoring data; no independent measurements were conducted by the authors. The first occurs in February–March and is associated with large-scale leaching of saline soils or pre-irrigation moistening, while the second takes place in July–August and is related to summer irrigation activities.

3.2. The impact of irrigation on groundwater regime and soil salinization

Before the Myrzashol district was converted into an irrigated area, groundwater lay at a depth of 15 to 30 m and was initially ignored, as it was believed to have no impact on irrigation. The initial transformation into general irrigated area led to an increase in the groundwater level due to the weak infiltration capacity of the soils. According to hydrogeological monitoring data, groundwater levels in the Myrzashol district have been gradually rising in recent decades. In the 1980s, toward the end of the growing season (in October), the groundwater level was on average 3–5 m deep, at present it is rising above 2 m in many fields (LAC, 2024).

The groundwater level varies depending on the time of the year. The seasonal groundwater regime was established based on official monthly monitoring data from a network of 279 observation and piezometric wells operated by the South Kazakhstan Hydrogeological-Reclamation Expedition (LAC, 2024). The analysis covered the period 2015–2024, which allowed the identification of stable intra-annual groundwater dynamics. Monthly average groundwater levels were calculated and analyzed to determine seasonal distribution patterns. The lowest groundwater levels were consistently recorded at the end of the vegetation period (September–October), prior to autumn–winter leaching activities. In contrast, maximum groundwater levels were observed in February–March following large-scale leaching operations and winter irrigation for soil moistening. These seasonal fluctuations reflect the direct influence of irrigation and leaching practices on groundwater recharge processes.

According to the results of hydrogeological monitoring in the Zhetysai district, after the irrigation period, groundwater level in the district amounted to 15.77 ha (19%) of irrigated land at the level of 0–2 m, and the area of irrigated land at the level of 2–5 m and above was 67.50 ha (81%). Compared with the data of the 2023, it was found that the area of irrigated land with a groundwater level within 2 m was 4.91 ha less (LAC, 2024).

Table 3. Underground water level and salinity

Years	General irrigated lands (ha)	Groundwater salinity (ha)			
		0–1 g/l	1–3 g/l	3–5 g/l	> 5 g/l
2023	83.82	1.03	62.70	14.25	5.84
2024	83.40	1.18	62.07	14.26	5.87

Note. Adapted from *Information report on the reclamation status of irrigated lands in Zhetysai district, Turkestan region* (p. 27), by Land Administration Committee of the Ministry of Agriculture of the Republic of Kazakhstan & State Institution “South Kazakhstan Hydrogeological–Reclamation Expedition”, 2024, <https://www.gov.kz/memleket/entities/land?lang=en>. Copyright 2024 by Land Administration Committee of the Ministry of Agriculture of the Republic of Kazakhstan.

Based on the average groundwater level data during the growing season in the district, the area of the GLV above the threshold level was 38,806 ha. This indicator increased by 6,595 ha

compared to the area of the GLV above the threshold level during the growing season in 2023 (32,21 ha in 2023). This situation can be explained by the high rainfall 2024. In the areas adjacent to Dostyk canal, the groundwater level is somewhat higher due to the influence of filtration flows. Since the northern part of the region is adjacent to the Arnasai lowland, the groundwater level is always deeper than in the rest of the region. The results demonstrate variability in groundwater mineralization among salinity classes within the irrigated area (Table 3).

The increase of GLV in pre-vegetation and vegetation period can be explained by the extension of winter wash-off salinity, humidification works until April and irrigation works in summer. The GLV has a significant impact on improving the meliorative conditions of the valley and obtaining high-quality products. Therefore, low GLV is one of the main problems.

3.3. *The impact of inefficient use of water resources on soil salinization*

Effective soil salinity control requires diverting 10–20% of irrigation water through drainage systems to leach salts and prevent their accumulation in soils (Anuarbekov et al., 2023). However, inefficient irrigation can raise mineralized groundwater levels and intensify secondary salinization. While traditional field methods are costly and spatially limited, remote sensing provides continuous information on soil and vegetation conditions related to moisture, salinity, and plant stress (Laiskhanov et al., 2022). Studies have shown that satellite data from Landsat-8 OLI and Sentinel-2 MSI are effective for detecting soil salinity (Bandak et al., 2024; Nguyen et al., 2020). Spectral indices such as NDVI, NDSI, SAVI, and VSSI enable assessment of both direct and indirect salinity indicators, while integration with machine learning methods improves the accuracy of regional salinity mapping (Mukhamediev et al., 2023).

Numerous satellite-derived salinity indices have been developed to detect saline soils based on their spectral characteristics (Alexakis et al., 2018; Elhag, 2016; Rafik et al., 2022). Visible and near-infrared satellite data are widely used for this purpose, although their effectiveness varies depending on local landscape conditions (Gorji et al., 2017; Scudiero et al., 2015; Vermeulen & Niekerk, 2016; Wu et al., 2014). Therefore, modern studies often apply several vegetation and salinity indices and select those most strongly related to salinity patterns (Nguyen et al., 2020). Comparative analysis of Sentinel-2 indices (SI1, SI2, VSSI, and NDSI) showed that SI1 provides the highest sensitivity to saline soils and clearly distinguishes salt crusts in RGB composites. Due to its stability and resistance to vegetation and texture effects, SI1 was used as a key indicator for salinity monitoring, consistent with findings for the Myrzashol massif (Zulpykharov, 2025). The resulting index maps reveal significant spatial variability of salinization in the irrigated landscape of Zhetysai district, where about half of the territory shows salinity signs and approximately 15–20% is classified as moderately to highly saline, mainly in areas with shallow groundwater and poor drainage conditions.

The soils of irrigated lands of rural districts located in the central part of the Myrzashol irrigation area and located in its southern part bordering Uzbekistan are highly saline, particularly the soil cover of the Karakai, Yntymak, and Zhylysu rural districts which is located in the central part. For example, 24% of irrigated lands of the Yntymak rural district are moderately saline, 13% are strongly saline, and 14% are very strongly saline (Figure 4).

Namely, more than 50% of the total 7.82 ha of irrigated lands are saline. In addition, in the southern part of the irrigated massif of strong and very strong salinity of irrigated lands in Zh. Nurlybaev, Zhana zhol, Enbekshi, Zhana auyl and Atameken rural districts is 10–20%.

Meanwhile, the level of soil salinity in irrigated lands of Irlzhar, Zhambyl, Sh. Dildabekov, Eraliev, Abai, and Kyzylkum rural districts, located along the border of the Syr Darya River in the Myrzashol irrigation area is lower. In these rural areas, the non-salinized and slightly salinized soil cover reaches 75%, and there are no soils with a very high degree of salinity. This, in turn, is due to the fact that the relief of the Myrzashol irrigated area slopes toward the Syr Darya River, which prevents groundwater from moving toward the river and from being located close to the surface (Figure 4).

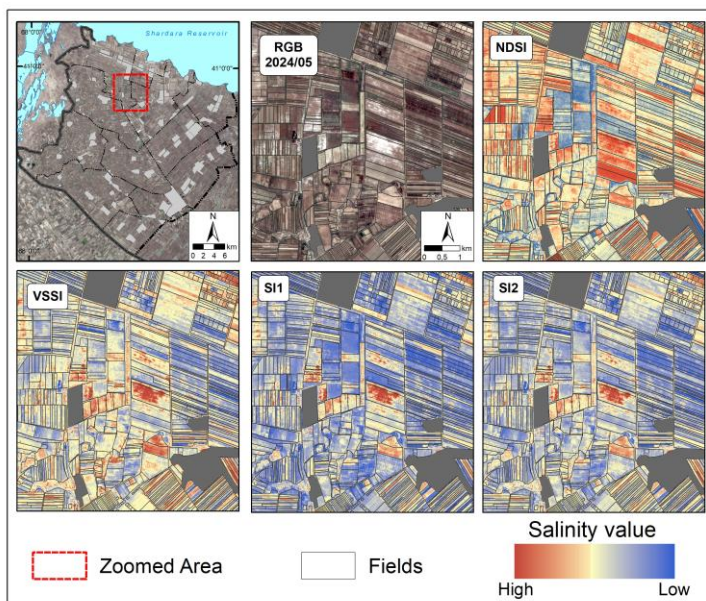


Figure 4. Comparative assessment of soil salinity indices (NDSI, VSSI, SI1, SI2) according to Sentinel-2 data for May 2024.

Note. Contains modified data from *Sentinel-2 MSI Level 2-A (Collection 1)* [Data set] (images acquired in 2024), by European Union, European Space Agency, and Copernicus (2021). <https://dataspace.copernicus.eu/>. CC BY-SA 4.0.

The data presented above show that the level of soil salinity in the irrigated fields of Zhetysai district varies dramatically depending on the rural districts. For example, in Karakai, Yntymak, and Kazybek bi rural districts, the level of salinity reaches 84%, 69%, and 71%, respectively. These conditions are often due to the shallow location of groundwater, insufficient drainage systems and secondary salinization resulting from over-irrigation. On the contrary, in Irlzhar, Zhambyl, Sh. Dildabekov, Abai, and Kyzylkum rural districts, there is a predominance of weakly salinized or completely non-saline soils. The slope of the terrain of these areas is directed toward the Syr Darya River, groundwater moves downwards and does not allow it to rise back into the soil, preventing salt accumulation. The clear difference between the amount of water supplied through irrigation canals and the amount of water extracted indicates the loss and inefficient allocation of water resources. For example, in Atameken rural district, 70.07 thousand m³ of water was supplied, of which only 36.97 thousand m³ was used effectively, which is only 52.8% of the total supplied water. In general, the level of salinization in the irrigated area is directly

related to the technical condition of the canals, the morphology of the terrain, the absorption capacity of the soil and irrigation management practices of farms. As a result of inefficient irrigation, the groundwater level rises, which in turn increases the accumulation of salts in the soil. If the drainage system is insufficient or worn out, these processes are further accelerated.

3.4. The impact of salinization on agricultural plant biomass

Sentinel-2 multispectral satellite images for the territory of Zhetyysai district 2024 were processed in the ArcGIS Pro environment, allowing to assess the spatiotemporal dynamics of the S11 (spectral index) and NDVI indices of soil salinization (Figure 5). The S11 index was calculated for two seasonal periods – based on satellite images of May (before the start of field work) and October (after the end of harvesting) and the NDVI was calculated on the basis of images of July, which corresponds to the peak period of vegetation of agricultural crops.

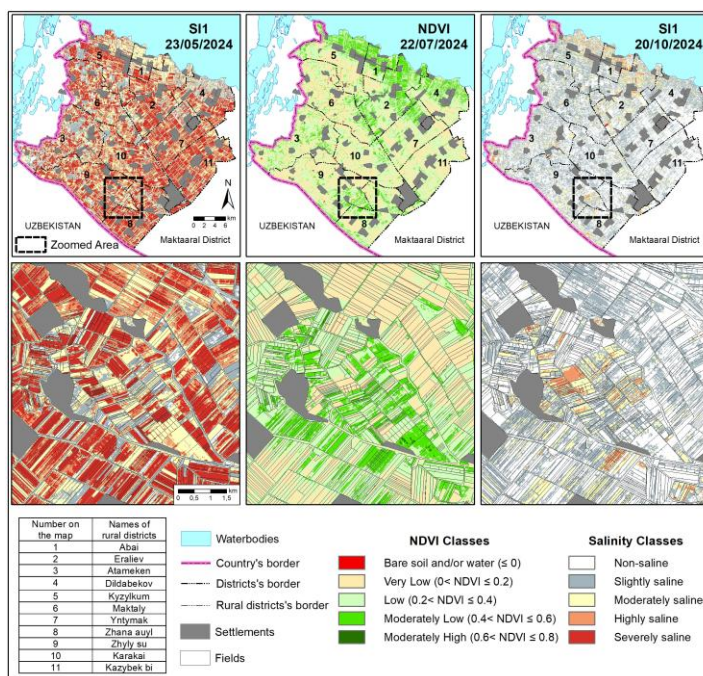


Figure 5. Comparative analysis of the spatial-temporal dynamics of soil salinization (S11) and NDVI indices for 2024.

Note. Contains modified data from *Sentinel-2 MSI Level 2-A (Collection 1)* [Data set] (images acquired in 2024), by European Union, European Space Agency, and Copernicus (2021).
<https://dataspace.copernicus.eu/>. CC BY-SA 4.0.

Almost all highly saline soils correspond to areas of mineralized (>3 g/l) waters. The relationship between groundwater mineralization and soil salinity was assessed through GIS-based spatial overlay analysis. Groundwater monitoring points with mineralization values exceeding 3 g/L were compared with mapped salinity classes, demonstrating strong spatial coincidence between highly mineralized groundwater zones and strongly saline soils. The rise of such saline waters to the upper layers enriches the soil profile with dissolved salts. The

analysis showed that in areas with high salinity, the NDVI values of cotton, clover and corn crops are on average 0.08–0.15 lower, which indicates a weakening of vegetation and a decrease in productivity by at least 10–25%. In addition, insufficient drainage networks increase the mineralization of groundwater over time and further increase soil salinization. The spatial combination of all considered factors clearly demonstrates the relationship between the increase in the level of mineralized groundwater, the irrigated condition of plot of land, and the development of the soil layer salinity process.

The salinity patterns obtained from remote sensing analysis are consistent with hydro-meliorative monitoring data and previously published studies confirming the salt-affected status of irrigated soils in the Zhetysai district (LAC, 2024; Laiskhanov et al., 2016; Tokbergenova, Zulpykharov, Kaliyeva et al., 2023). The results indicate that inefficient water use contributes to the development of soil salinization and is associated with reduced vegetation biomass, as reflected by lower NDVI values in highly saline areas.

4. Discussion and conclusion

Numerous studies indicate that intensive irrigation combined with inefficient water management contributes to groundwater rise and accelerates secondary soil salinization in irrigated regions of Central Asia and southern Kazakhstan (Laiskhanov et al., 2016; Smanov et al., 2025; Tokbergenova, Zulpykharov, Kaliyeva et al., 2023; Yessymkhanova et al., 2021; Zhupankhan et al., 2018). Significant water losses occurring during conveyance through open canal systems further aggravate salinization processes (LAC, 2024).

It is known that in the irrigated regions of Kazakhstan and Central Asia, up to 30–50% of the water transported through open channels does not reach the fields and it is known that losses occur through filtration and evaporation. For example, the lack of concrete in the canal beds, the lack of leveling of the land in the fields and traditional irrigation methods (ditch, flood irrigation) lead to a large amount of water loss. The long-term efficiency of hydraulic structures is directly related to their material strength and water permeability properties (Kabdushev et al., 2023). Yessymkhanova et al. (2021) estimate that the efficiency of irrigation systems in Kazakhstan's agriculture is low (efficiency coefficient 0.6–0.65) and this indicates a high cost of water transportation (Zhupankhan et al., 2018). This is likely to exacerbate environmental problems in the region in the context of climate change (Zhupankhan et al., 2018). In the assessment of current soil reclamation situation in Myrzashol, inefficient water use directly leads to the rise of groundwater and salinization of arable soils. Tokbergenova, Zulpykharov, Taukebayev et al. (2023) reported that the dominant soil salinization types in the Zhetysai district are mainly sulfate (hydrocarbonate-sulfate) and sulfate-chloride types. In the upper reaches of the Dostyk Canal, hydrocarbonate-sulfate sodium water predominates, which leads to the development of sulfate salinization in adjacent soils. Downstream along the canal, the concentration of chloride ions in irrigation water increases, resulting in a transition toward sulfate-chloride salinization. Due to the high mineralization and shallow occurrence of groundwater, salts accumulate within the soil profile, contributing to an increase in moderately, strongly, and very strongly saline lands, particularly in areas such as the Yntymak rural district.

Sustainable mitigation of soil salinization requires improved irrigation management practices, reduction of water losses in canal networks, optimization of irrigation regimes, and restoration of drainage system efficiency (Tokbergenova, Zulpykharov, Kaliyeva et al., 2023; Zhupankhan et al., 2018).

Our study shows that the groundwater level is the main factor contributing to the high salinity level. This is often associated with irrigation practices in the past. Similar patterns have been reported in other irrigated regions of Kazakhstan. For example, despite relatively high-water availability in the Shoulder irrigated massif, large areas remain affected by soil salinization, and the extent of saline soils continues to increase over time (Laiskhanov et al., 2022; Poshanov et al., 2022). In addition, autumn irrigation of rice fields is used in the Kazybek bi, Atameken and Zhyly su rural districts of Zhetysai district as a method of washing the soil and removing salts. In 2024, the area of rice cultivation in the district reached 791.50 ha (Bureau of National Statistics of the Republic of Kazakhstan, 2025).

During the Soviet era, hundreds of vertical drainage wells were installed in the Myrzashol massif to lower the groundwater level. They pumped excess water from the ground and directed it into the collector-drainage system, washing out the salt. At present, most of these drainage wells are either out of service or not in use. This contributes to the salinization process, which is confirmed by the results obtained in this study. Tokbergenova, Zulpykharov, Taukebayev et al. (2023) highlighted the importance of restoring vertical drainage wells and maintaining drainage systems alongside meliorative and agrotechnical practices to ensure sustainable land use in the Myrzashol irrigated area.

The results of the study revealed that inefficient water use not only leads to soil salinization, but also negatively affects agricultural yields over time. For example, in the rural districts of Karakai, Yntymak, and Kazybek bi, the specific water supply is significantly higher than in other regions and the share of saline lands in these districts reaches 69–84%. Therefore, it is clear that the high losses in irrigation systems and persistence of the practice of over-watering directly contribute to the deterioration of the melioration condition of the soil and the decrease in agricultural productivity. Laiskhanov et al. (2022) in their studies conducted in the Shoulder irrigated field found that, compared to corn grown in non-saline soil, the growth of corn on slightly saline soil slowed down by 11 days, on moderately saline soil by 35 days, and on highly saline soil by 45 days. Poshanov et al. (2022) studied the yield of corn in soils with different degrees of salinity and the effect of using a special biological preparation in Shoulder irrigated land. As a result, it turned out that as the salinity of the soil increases, the yield of corn decreases significantly, but the introduction of some biological preparations slightly increases the plant's resistance to salt and prevents yield decline.

Many scientists (Ba et al., 2024; Duanbekova et al., 2024; Laiskhanov et al., 2022; Murtazin et al., 2022) have studied the ways of sustainable development of agriculture in conditions of soil salinization. Among them, there are works that should be taken as a basis for improving the condition of soils of the study area (Anuarbekov et al., 2023; Cao et al., 2024; Zulpykharov, 2025). According to Amanbaeva et al. (2024), water deficit conditions accelerate degradation processes in the plant root zone. The reuse of phosphogypsum in combination with drainage water was proposed as an effective measure to improve irrigation water quality and reclamation conditions.

This may also be an interesting solution for the research area, as the Zhetysai district is faced with situations where it is necessary to reuse drainage water during periods of water scarcity (especially at the end of the growing season). In this case, if the drainage water is pre-treated and the effects of harmful salts (especially soda) are neutralized, it can be used as an additional irrigation. One of the innovative soil reclamation technologies is deep soil loosening. This method has demonstrated high effectiveness in irrigated regions of neighboring Uzbekistan, where breaking the compacted plow pan formed at certain tillage depths improves soil permeability and water–salt exchange processes. Studies conducted in Kazakhstan also

emphasize that loosening the dense subsurface layer is an important component of resource-saving agricultural technologies and is recommended for application in saline irrigated lands (Anuarbekov et al., 2023; Duanbekova et al., 2024; FAO, 2023; Smanov et al., 2025).

Despite the comprehensive approach applied in this study, several limitations should be acknowledged. First, the analysis relied primarily on institutional monitoring data and aggregated statistical information available at the district scale, which limited the possibility of assessing water use efficiency and groundwater dynamics at finer farm-level or rural administrative unit scales. Second, satellite-based salinity assessment reflects surface conditions and vegetation response, while subsurface salinity processes may not be fully captured without extensive soil sampling campaigns. Third, the study period, although covering recent monitoring years (2015–2024), represents medium-term observations and may not fully reflect long-term climatic variability and irrigation modernization effects. Finally, independent field measurements were limited, and the research depended largely on official hydro-meliorative monitoring datasets. Future studies should integrate continuous field observations, high-resolution groundwater monitoring, and long-term experimental validation to improve the accuracy of salinity risk assessment.

This study revealed that soil salinization and water resource use in the irrigated lands of Zhetysai district are complex processes that are closely related. Integration of GIS analysis, remote sensing materials, field observations and statistical data revealed that secondary salinization is widespread, especially in areas with shallow groundwater and weak drainage systems.

Analysis at the level of rural districts showed that there are significant water losses during water supply and distribution, which, together with over-irrigation and deterioration of infrastructure, accelerates the accumulation of salts in the soil. The high level of salinity in districts such as Yntymak, Karakai, and Zhana-aul is a clear manifestation of these processes. This situation negatively affects the vegetative state and productivity of agricultural crops, as evidenced by a decrease in NDVI indicators. The results of the study indicate that optimizing irrigation and drainage systems in the region, introducing effective water resource management methods, and widespread use of water-saving technologies are key areas for sustainable agricultural development. These data give possibility to scientifically substantiate the planning of land reclamation measures and effective land use strategies. The proposed integrated assessment methodology is also applicable to other irrigated regions of Kazakhstan and can serve as a valuable information tool in making management decisions aimed at increasing the productivity and environmental sustainability of agroecosystems.

Acknowledgments

This research was funded by Abai Kazakh National Pedagogical University, research project titled “Spatial Planning of Border Settlements and Integration of Research Results into the Educational Process through GIS Technology for Sustainable Development (Case Study of Zhetysai District)”. The authors express their sincere gratitude to Abai Kazakh National Pedagogical University for its support provided throughout the research process.

References

- Alexakis, D. D., Daliakopoulos, I. N., Panagea, I. S., & Tsanis, I. K. (2018). Assessing soil salinity using WorldView-2 multispectral images in Timpaki, Crete, Greece. *Geocarto International*, 33(4), 321–338. <https://doi.org/10.1080/10106049.2016.1250826>

- Anuarbekov, K. K., Kuvatova, G. M., & Aldiyarova, A. E. (2023). Assessment of physical condition of saline soils and their rational use in irrigated agriculture. *Izdenister Natigeler*, 3(99), 308–319. <https://doi.org/10.37884/3-2023/31>
- Ba, Y., Zhang, Z., Xie, P., Fan, S., Du, R., Guo, F., Qian, L., Bai, X., He, Y., & Fan, S. (2024). Inverting soil salinity of farmland in Xinjiang by integrating Sentinel-1/2 and environmental variables. *Transactions of the Chinese Society of Agricultural Engineering*, 40(16), 171–179. <https://doi.org/10.11975/j.issn.1002-6819.202401070>
- Bandak, S., Movahedi-Naeini, S. A., Mehri, S., & Lotfata, A. (2024). A longitudinal analysis of soil salinity changes using remotely sensed imageries. *Scientific Reports*, 14, Article 10383. <https://doi.org/10.1038/s41598-024-60033-6>
- Bureau of National Statistics of the Republic of Kazakhstan. (2025). *Gross output and physical volume index*. <https://stat.gov.kz/ru/region/turkestan/dynamic-tables/1485/>
- Cao, Z. D., Zhu, T., Cai, X., Wang, J., Zhao, Y., & Zhao, X. (2024). Optimization of Integrated Water and Salinity Management in an Arid Agricultural Region. *Journal of Water Resources Planning and Management*, 150(10). <https://doi.org/10.1061/JWRMD5.WRENG-6098>
- Duanbekova, A., Tokbergenova, A., Sultanbekova, P., Essanbekov, M., Zulpykharov, K., Sarkynov, Y., Taukebayev, O., Kaliyeva, D., & Kozhabekova, Z. (2024). Collector-drainage water reuse for crop irrigation: Experiment on saline lands of southern Kazakhstan. *Soil Science Annual*, 75(2), Article 187978. <https://doi.org/10.37501/soilsa/187978>
- Elhag, M. (2016). Evaluation of Different Soil Salinity Mapping Using Remote Sensing Techniques in Arid Ecosystems, Saudi Arabia. *Journal of Sensors*, 1, Article 7596175. <https://doi.org/10.1155/2016/7596175>
- European Union, European Space Agency, & Copernicus. (2021). *Sentinel-2 MSI Level 2-A* (Collection 1) [Data set]. CDSE. <https://dataspace.copernicus.eu>
- Food and Agriculture Organization of the United Nations (FAO). (2023). *Global map of salt-affected soils (INSAS)*. <https://www.fao.org/soils-portal/soil-management/insas>
- Gorji, T., Sertel, E., & Tanik, A. (2017). Monitoring soil salinity via remote sensing technology under data scarce conditions: A case study from Turkey. *Ecological Indicators*, 74, 384–391. <https://doi.org/10.1016/j.ecolind.2016.11.043>
- Greene, R., Timms, W., Rengasamy, P., Arshad, M., & Cresswell, R. (2016). Soil and Aquifer Salinization: Toward an Integrated Approach for Salinity Management of Groundwater. In A. J. Jakeman, O. Barretheau, R. J. Hunt, J. D. Rinaudo, & A. Ross (Eds.), *Integrated Groundwater Management* (pp. 377–412). Springer. https://doi.org/10.1007/978-3-319-23576-9_15
- ISRIC – World Soil Information. (2025). *World soil distribution*. <https://shorturl.at/OhO6n>
- Jakiyayev, Z., Amirgaliyev, Y., Kurmanaliyev, B., & Assylbek, A. (2021). Study of local erosion and development of effective methods for the protection of river banks. *Periodicals of Engineering and Natural Sciences*, 9(3), 457–473. <https://doi.org/10.21533/pen.v9i3.863>
- Kabdushev, A. A., Agzamov, F. A., Manapbayev, B. Z., & Moldamuratov, Z. N. (2023). Microstructural analysis of strain-resistant cement designed for well construction. *Nanotechnology in Construction*, 15(6), 564–573. <https://doi.org/10.15828/2075-8545-2023-15-6-564-573>
- Kazhydromet. (2025). *National hydrometeorological service of Kazakhstan*. <https://www.kazhydromet.kz/en>
- Laiskhanov, S. U., Otarov, A., Savin, I. Y., Tanirbergenov, S. I., Mamutov, Z. U., Duisekov, S. N., & Zhogolev, A. (2016). Dynamics of Soil Salinity in Irrigation Areas in South Kazakhstan. *Polish Journal of Environmental Studies*, 25(6), 2469–2475. <https://doi.org/10.15244/pjoes/61629>
- Laiskhanov, S. U., Smanov, Z. M., Kaimuldinova, K. D., Myrzaly, N. B., Ussenov, N. E., & Poshanov, M. N. (2022). A Study of the Effects of Soil Salinity on the Growth and Development of Maize (*Zea Mays* L.) by using Sentinel-2 Imagery. *OnLine Journal of Biological Sciences*, 22(3), 323–332. <https://doi.org/10.3844/ojbsci.2022.323.332>
- Land Administration Committee of the Ministry of Agriculture of the Republic of Kazakhstan, State Institution “South Kazakhstan Hydrogeological–Reclamation Expedition”. (2024). *Information report on the reclamation status of irrigated lands in Zhetysai district, Turkestan region*. <https://www.gov.kz/memleket/entities/land?lang=en>

- Maab, Z., Smolenaars, W. J., Jamil, M. K., & Biemans, H. (2025). Assessing the risk of soil salinization in an intensively irrigated area of Pakistan. *Discover Water*, 5(1), Article 64. <https://doi.org/10.1007/s43832-025-00268-0>
- Ministry of Water Resources and Irrigation of the RSE "KazVodkhoz". (2024). Technical characteristics of the canals managed by the Zhetysai Production Department of the Turkestan Branch [Personal communication/Database]. Republic of Kazakhstan, Turkestan region, Zhetysai city.
- Mukhamediev, R. I., Merembayev, T., Kuchin, Y., Malakhov, D., Zaitseva, E., Levashenko, V., Popova, Y., Symagulov, A., Sagatdinova, G., & Amirgaliyev, Y. (2023). Soil Salinity Estimation for South Kazakhstan Based on SAR Sentinel-1 and Landsat-8,9 OLI Data with Machine Learning Models. *Remote Sensing*, 15(17), Article 4269. <https://doi.org/10.3390/rs15174269>
- Murtazin, Y., Kulagin, V., Mirilas, V., Anker, Y., Rakhimov, T., Onglassynov, Z., & Rakhimova, V. (2025). Integrated Assessment of Groundwater Quality for Water-Saving Irrigation Technology (Western Kazakhstan). *Water*, 17(8), Article 1232. <https://doi.org/10.3390/w17081232>
- Nguyen, K. A., Liou, Y. A., Tran, H. P., Hoang, P. P., & Nguyen, T. H. (2020). Soil salinity assessment using near-infrared channel and vegetation soil salinity index derived from Landsat 8 OLI data: A case study in the Tra Vinh Province, Mekong Delta, Vietnam. *Progress in Earth and Planetary Science*, 7(1), Article 1. <https://doi.org/10.1186/s40645-019-0311-0>
- Poshanov, M. N., Laiskhanov, S. U., Smanov, Z. M., Kenenbayev, S. B., Aliaskarov, D. T., Abikbayev, Y. R., Vyrakhmanova, A. S., & Askanbek, A. (2022). The Effects of the Degree of Soil Salinity and the Bio preparation on Productivity of Maize in the Shoulder Irrigated Massif. *OnLine Journal of Biological Sciences*, 22(1), 58–67. <https://doi.org/10.3844/ojbsci.2022.58.67>
- Rafik, A., Ibouh, H., El Alaoui El Fels, A., Eddahby, L., Mezzane, D., Bousfoul, M., Amazirh, A., Ouhamdouch, S., Bahir, M., Gourfi, A., Dhiba, D., & Chehbouni, A. (2022). Soil Salinity Detection and Mapping in an Environment under Water Stress between 1984 and 2018 (Case of the Largest Oasis in Africa-Morocco). *Remote Sensing*, 14(7), Article 1606. <https://doi.org/10.3390/rs14071606>
- Rakhmanov, D., Šarapatka, B., Alibekova, K., Černohorský, J., Hekera, P., & Smanov, Z. (2024). Assessment of agricultural land salinization via soil analysis and remote sensing data: Case study in Pavlodar region, Kazakhstan. *Soil & Water Research*, 19(2), 111–121. <https://doi.org/10.17221/5/2024-SWR>
- Scudiero, E., Skaggs, T. H., & Corwin, D. L. (2015). Regional-scale soil salinity assessment using Landsat ETM+ canopy reflectance. *Remote Sensing of Environment*, 169, 335–343. <https://doi.org/10.1016/j.rse.2015.08.026>
- Smanov, Z., Duisenbayev, S., Zulpykharov, K., Laiskhanov, S., Turymtayev, Z., Kozhayev, Z., Atasoy, E., & Taukebayev, O. (2025). Soil salinization and its impact on the degradation of agricultural landscapes of the Talas district, Kazakhstan. *Journal of the Geographical Institute "Jovan Cvijić" SASA*, 75(2), 233–250. <https://doi.org/10.2298/IJGI2502233S>
- Tokbergenova, A. A., Zulpykharov, K. B., Kaliyeva, D. M., & Essanbekov, M. Y. (2023). Assessment of the current soil-reclamation state of the soils of Myrzashol in the Kazakhstan part (The Hungry Steppe). *Polish Journal of Environmental Studies*, 32(1), 789–805. <https://doi.org/10.15244/pjoes/155087>
- Tokbergenova, A. A., Zulpykharov, K. B., Taukebayev, O. Z., Essanbekov, M. Y., Kaliyeva, D. M., Alsherieva, D. Y., & Duanbekova, A. Y. (2023). Analysis of the problems of soil salinization in irrigated lands of the Turkestan region (Using the example of the Myrzasholsky irrigated massif). *Herald of Science of S. Seifullin Kazakh Agrotechnical Research University*, 116(1), 120–137.
- Vermeulen, D., & van Niekerk, A. (2016). Evaluation of a WorldView-2 image for soil salinity monitoring in a moderately affected irrigated area. *Journal of Applied Remote Sensing*, 10(2), Article 026025. <https://doi.org/10.1117/1.JRS.10.026025>
- Wu, W., Mhaimed, A. S., Al-Shafie, W. M., Ziadat, F., Dhehibi, B., Nangia, V., & De Pauw, E. (2014). Mapping soil salinity changes using remote sensing in Central Iraq. *Geoderma Regional*, 2–3, 21–31. <https://doi.org/10.1016/j.geodrs.2014.09.002>
- Yessymkhanova, Z., Niyazbekova, S., Dautletkhanova, Z., Satenova, D., Zhumasseitova, S., Kadyraliev, A. T., Supaeva, G., Dzholdosheva, T., & Dzholdoshev, N. (2021). Water resources management in Kazakhstan in conditions of their shortage. *IOP Conference Series: Earth and Environmental Science*, 937, Article 032012. <https://doi.org/10.1088/1755-1315/937/3/032012>

- Zhupankhan, A., Tussupova, K., & Berndtsson, R. (2018). Water in Kazakhstan: A key in Central Asian water management. *Hydrological Sciences Journal*, 63(5), 752–762. <https://doi.org/10.1080/02626667.2018.1447111>
- Zulpykharov, K. B. (2025). *Assessment of degradation processes on irrigated lands of Turkestan region based on remote sensing data* [Unpublished doctoral dissertation]. Al-Farabi Kazakh National University.