Challenges for the sustainable use of water and land resources under a changing climate and increasing salinization in the Jizzakh irrigation zone of Uzbekistan (Postprint)

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Abstract

Jizzakh Province in Uzbekistan is one of the largest irrigated areas in Central Asia without natural drainage. In combination with aridity, climate change and extensive irrigation practices, this has led to the widespread salinization of agricultural land. The aim of this study was to identify opportunities to improve the reclamation status of the irrigated area and how best to effectively use the water resources in Jizzakh Province based on investigations conducted between 1995 and 2016. A database of field measurements of groundwater levels, mineralization and soil salinity conducted by the provincial Hydro-Geological Reclamation Expeditions was used in the study. The total groundwater mineralization was determined using a portable electric conductometer (Progress 1T) and the chloride concentration was determined using the Mohr method. The soil salinity analyses were conducted by applying two different methods: (1) the extraction and assessment of the soluble salt content, and (2) using an SM-138 conductivity sensor applied to a 1:1 mixture of soil sample and water. The analyses of the monitoring results and the salt balance in the "irrigation water-soil-drainage water" system clearly demonstrated that the condition of the irrigated land in the province was not significantly improved. Under these conditions, the stability of crop yields is achieved mainly through the use of large volumes of fertilizer. However, excess amounts of mineral fertilizers can also cause the salinization of soils. The average groundwater salinization value in most of the irrigated land (75.3%) fluctuated between 1.1 and 5.0 g/L, while the values were less than 1.0 g/L in 13.1% of the land and in the range of 5.1-10.0 g/L in 10.5% of the land. During the period of 1995-2016 the salinization level of the irrigated land in Jizzakh Province increased slightly and the area could be divided into the following classes: no salinity (17.7% of the total area), low salinity (51.3%), moderate salinity (29.0%), and high salinity (2.0%). Detailed studies of the salt balance in irrigated land, the impact of climate change, increased fertilizer use, and repeated remediation leaching on the groundwater level and mineralization should be conducted in the future, due to the possibility of accelerated salinization, fertility decline, and reduced yields of agricultural crops.

Full Text

Preamble

Challenges for the Sustainable Use of Water and Land Resources under a Changing Climate and Increasing Salinization in the Jizzakh Irrigation Zone of Uzbekistan

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Abstract: Jizzakh Province in Uzbekistan is one of the largest irrigated areas in Central Asia without natural drainage. In combination with aridity, climate change, and extensive irrigation practices, this has led to widespread salinization of agricultural land. The aim of this study was to identify opportunities to improve the reclamation status of the irrigated area and determine how to effectively use water resources in Jizzakh Province based on investigations conducted between 1995 and 2016. A database of field measurements of groundwater levels, mineralization, and soil salinity conducted by the provincial Hydro-Geological Reclamation Expeditions was used in the study. Total groundwater mineralization was determined using a portable electric conductometer (Progress 1T) and chloride concentration was determined using the Mohr method. Soil salinity analyses were conducted using two different methods: (1) extraction and assessment of soluble salt content, and (2) an SM-138 conductivity sensor applied to a 1:1 mixture of soil sample and water. Analyses of monitoring results and the salt balance in the "irrigation water-soil-drainage water" system clearly demonstrated that the condition of irrigated land in the province has not significantly improved. Under these conditions, stable crop yields are achieved mainly through the application of large volumes of fertilizer. However, excessive mineral fertilizers can also cause soil salinization. The average groundwater salinization value in most irrigated land (75.3%) fluctuated between 1.1 and 5.0 g/L, while values were less than 1.0 g/L in 13.1% of the land and in the range of 5.1-10.0 g/L in 10.5% of the land. During 1995-2016, the salinization level of irrigated land in Jizzakh Province increased slightly, with the area divided into the following classes: no salinity (17.7% of total area), low salinity (51.3%), moderate salinity (29.0%), and high salinity (2.0%). Detailed studies of the salt balance in irrigated land, the impact of climate change, increased fertilizer use, and repeated remediation leaching on groundwater level and mineralization should be conducted in the future due to the possibility of accelerated salinization, fertility decline, and reduced agricultural crop yields.

Keywords: irrigation; groundwater level; salinity; soil salinization; salt balance; Uzbekistan

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1 Introduction

Agriculture is an important economic sector in Uzbekistan, accounting for about 23% of GDP and 27% of total employment (Kulmatov, 2014). Irrigated farming produces more than 90% of agricultural yield and consumes over 90% of the nation’ s available water resources annually (Uzbekistan N C, 2009; Dyhovniy and Schutter, 2011; Opp et al., 2016). However, due to the flat topography of many irrigated areas in the Aral Sea Basin (ASB) countries, particularly the Republic of Uzbekistan, which has low natural drainage and extensive flood irrigation with poor-quality water, soil salinization and degradation of irrigated land has occurred (Panin, 1958; Pankova et al., 1996; Gafurova et al., 2005; SCNP, 2008; Kulmatov, 2018).

Currently, more than 60% of all irrigated areas in Uzbekistan are affected by salinization, resulting in reduced crop yields (e.g., 20%–30% for cotton). In most farms, these losses are usually overcome through increased reclamation of leached water and application of large quantities of mineral fertilizers (SCNP, 2008; Kulmatov, 2014, 2018). Agricultural, industrial, and urban development have all contributed to increased salinity in streams and rivers, but the likely effects of future development and climate change remain unknown. Most change is related to the extent of human land uses, with climate change accounting for only 12% of the increase (Olson, 2019). However, land salinization and degradation are aggravated by the vulnerability of sensitive arid lowlands to climate change.

Uzbekistan is located in an arid plain and the semi-arid foothill areas of the endorheic (closed) ASB. As the main water consumer in the ASB, it receives about 80%–85% of its water resources from neighboring upstream countries, primarily through three transboundary rivers: the Syrdarya, Amudarya, and Zarafshan (FAO, 2017). For these and many other rivers in the ASB, water from snowmelt and glaciers in the Pamir and Tian Shan mountains is the main source of river discharge, and therefore runoff is strongly dependent on changes in precipitation patterns and seasonal snow water storage capacity. Precipitation amounts have decreased across the entire region in recent years, especially in the western parts of Turkmenistan, Uzbekistan, and Kazakhstan (Bai et al., 2011; Lioubimtseva et al., 2018). Endorheic basins are known to be sensitive to various changes in ambient conditions, making them vulnerable to climate change and other human-induced pressures, including agricultural intensification (Karthe et al., 2017). Water abstraction for irrigation is the main cause of reduced river flows in downstream areas, but climate change also leads to decreased water discharges in river catchments. Temperature increases followed by spreading aridity have been observed throughout Central Asia during the last century and are predicted to continue in the future at a rate above the global average (Lioubimtseva and Henebry, 2009; Mannig et al., 2013). Clear evidence of negative consequences of climate change already exists, including decreased available water resources and declining agricultural productivity. Between the 1960s and 2010s, glacier area decreased by 23%–49% in various river catchment basins of the ASB (Semakova et al., 2015). During 2001–2010, the estimated volume of total glacier runoff in the Amudarya and Syrdarya river basins was reduced from 19.0 and 3.4 km^3 to 18.0 and 3.2 km^3, respectively (Savoskul and Smakhtin, 2013).

In the future, upstream countries plan to construct facilities to accumulate additional water volumes in existing reservoirs for hydropower energy production, which may present another potential threat to land use sustainability. Combined with high population growth rates in the ASB, this is likely to lead to decreased river water availability and increased water consumption (Uzbekistan N C, 2009; Dukhovny and Schutter, 2011; Groll et al., 2015). These trends are likely to be exacerbated until coordinated mitigation and adaptation activities are implemented (Dukhovny and Schutter, 2011; Groll et al., 2015; Canedo-Arguelles et al., 2016).

Furthermore, extensive unsustainable land use and insufficient maintenance of irrigation and drainage networks have caused increased groundwater levels and mineralization, resulting in dramatic deterioration of irrigated area conditions in recent decades (SCNP, 2013; Kulmatov, 2014, 2018).

A comparative analysis of climatic characteristics of desert and arid lands in Central Asia (Turan Depression, Gobi Desert, and deserts of the Dzungar and Tarim depressions) revealed that the degree of aridity, continentality, and precipitation amount and regime differ among these areas (Pankova and Konyushkova, 2013). Moisture deficit in the modern climate results in preservation of salt accumulations at their point of origin. The importance of specific regional climate features has been noted, including the precipitation regime and its effect on redistribution of salts in the profiles of automorphic salt-affected soils (Pankova and Konyushkova, 2013).

In recent years, quality has deteriorated and quantity decreased for surface water resources and reclamation conditions in irrigated lands of provinces located in mid- and downstream areas of the Amudarya River (Ibrakhimov et al., 2007). Only in Navoi Province in Uzbekistan between 2000 and 2015 has groundwater level and soil salinity shown slight improvement (Kulmatov et al., 2018; Kulmatov et al., 2015).

In irrigated land in Jizzakh Province (Syrdarya River Basin), humus content and absorption capacity have declined in recent years, while simultaneously the mechanical composition and fertility of soils have decreased (Sherimbetov, 2015; Rakhmatov and Abdullaev, 2016). Some studies have shown that long-term irrigation significantly impacts absorption capacity and physical and chemical properties of soils. When agricultural activities are conducted in irrigated soils for extended periods, varying degrees of change occur in soil layers.

It has been revealed that among the four soil components (humus, carbonates, gypsum, and water-soluble salts), water-soluble salts play the dominant role in spectral reflectance from saline soils (Karavanova et al., 2001; Sherimbetov, 2015).

Previous studies have attempted to investigate relationships between soil productivity and salinization to ensure sustainable use of water and land resources in the study area. Unfortunately, most of these studies were conducted within short periods, and the ionic composition and mineralization of irrigation water over long periods were not sufficiently considered. The salt balance in the "irrigation water-soil-drainage water" system has not been studied. Pathways of salt migration in natural and agricultural land are important to understand for long-term monitoring and prevention of soil and water salinization; however, they have still not been quantitatively determined in Jizzakh Province.

The objective of this study was to determine long-term changes (1995-2016) in irrigation water quality, groundwater level and mineralization, amelioration requirements in irrigated land, and the salt balance in the "irrigation water-soil-drainage water" system, as well as to develop recommendations for sustainable use of water and land resources, with specific focus on the Jizzakh irrigation zone.

2 Study Area

Jizzakh Province is located in the center of the Republic of Uzbekistan, bordered by Syrdarya Province to the east, the Republic of Kazakhstan to the north, and the Republic of Tajikistan to the south, and enclosed by the Syrdarya River, the Turkestan border, and the Kizil-Kum Desert. The total area of irrigated land (39°57 -41°24 N, 66°66 -68°57 E) in the province is 3.0×10 hm^2, with main agricultural crops including cotton, wheat, berries, fruit, grapes, melons, and gourds.

The province is situated in a continental area characterized by dry, hot summers and moderately cold winters. Precipitation occurs mainly in winter and spring, with average annual rainfall of 308 mm. The highest recorded air temperature was 36.4°C, observed in July. The average annual air temperature is 15.6°C, with humidity levels of 70%–80% in winter. The vegetation growth period is 210–240 days (State Department of Statistics of Uzbekistan, 2017).

Soils of Jizzakh Province are classified as light gray meadow-brown, dark-brown, typical and light-brown grass, meadow-grass, grassland and swampy-grass, sandy desert, sand, and sandy-saline soil (SCNP, 2016). Soils in the irrigation zone are classified as typical dark-brown and light-brown, meadow-grassy, grass-grassland, and meadow and wetland-grass soils.

The water supply in Jizzakh Province is transboundary and largely dependent on water quantity from upstream countries, primarily Kyrgyzstan and Tajikistan. There are three main sources of irrigation water in the province with average annual diverted volumes of 1.89 km³ (62.2% of total) from the Syrdarya River, 1.05 km³ (34.5%) from the Zarafshan River, and 0.10 km³ (3.3%) from the Sangzor River. Total water volume used in the province is 3.04 km³, of which 2.85 km³ (93%) is used for agricultural purposes and the remaining 0.19 km³ (7%) for industry and drinking water supply.

Organic matter concentration in water from the Syrdarya and Zarafshan rivers is very low; however, both rivers have elevated concentrations of inorganic substances, mainly sulfate, chloride, and carbonate ions (Table 1), which causes secondary salinization of agricultural land (Yakubov et al., 2011; Karimov et al., 2014; Karimov et al., 2019).

Table 1 Mineralization of river water used for irrigation in Jizzakh Province during 2000–2016

River	Hydropost	River water mineralization (g/L)
		Min
Syrdarya	Nadejdinskiy	
Zarafshan	Pervomayskiy	

Note: Min, minimum; Max, maximum; Ave, average. Hydropost –measuring infrastructure within the main canal.

3 Materials and Methods

The study utilized a database of field measurements of groundwater, mineralization, and soil salinity levels conducted by the provincial Hydro-Geological Reclamation Expeditions (HGRE) under the Uzbek Basin Irrigation System

Administration of the Ministry of Agriculture and Water Resources of the Republic of Uzbekistan. The HGRE conducts a monitoring program throughout Uzbekistan.

Indicators of spatial and temporal changes in groundwater levels and mineralization in irrigated areas of Jizzakh Province were determined by HGRE specialists through 2255 continuous monitoring wells. The Ministry of Agriculture and Water Resources also maintains a detailed database of long-term inorganic fertilizer use in all irrigated land in Uzbekistan, including Jizzakh Province, which has been processed statistically and can be used to study fertilizer use dynamics. This existing extensive database was complemented by additional data regarding soil characteristics, soil salinity, and cropping patterns based on results from a soil-sampling exercise conducted by the authors.

Groundwater samples were taken by on-farm technicians, enabling swift collection and analysis of more than 12,600 groundwater samples per year. Groundwater level monitoring stations were equipped with tubes (inner diameter 90-110 mm, length 3-6 m) filled with sand-gravel filters. Groundwater samples from monitoring wells at depths of 0.0–1.0, 1.0–1.5, 1.5–2.0, 2.0–3.0, 3.0–5.0, and 10.0 m were taken and sent to the laboratory for analysis.

Groundwater level and mineralization were determined three times annually on April 1, July 1, and October 1. Total mineralization of groundwater was determined using a portable electric conductometer (Progress 1T, Central Asian Scientific Research Institute of Irrigation (SANIIRI), Uzbekistan) and chloride concentration was determined using the Mohr method (argentometric titration). During the first sampling period (April), effects of extensive salt leaching occurring just before the irrigation season could be detected. The second sampling period (July) covered peak irrigation activity, and the third sampling period (October) took place immediately after the growing season ended, enabling analysis of phreatic surface lowering without groundwater recharge. Analysis of groundwater level dynamics outside the growing season is important because seasonal salinity restoration might occur when upward flux prevails over lateral outflow.

During 2000–2016, 111,634 groundwater samples were analyzed. Groundwater mineralization was assessed and classified following the approach of Priklonsky (1970) (Table 2).

Table 2 Classification of groundwater (GW) based on total mineralization (Priklonsky, 1970)

Category	Total dissolved solids (TDS; g/L)
Fresh	
Low mineralization	
Medium mineralization	
High mineralization	

A total of 17,500 soil samples were taken annually by HGRE staff at the end of the growing season in November during 2000–2016. Each soil sample consisted of three subsamples collected at depths of 0–30, 30–70, and 70–100 cm. More than 116,000 soil samples were collected from these depths in irrigated areas to determine soil salinity. Each sample was considered representative of an area of 10–20 hm^2, resulting in a much denser soil data grid than groundwater data.

Mineral fertilizers (mainly nitrogen-containing) can cause salinization of irrigated soils. In calculating the salt balance, the contribution of mineral fertilizers was included in the total salt balance because their residues enter the collector-drainage network; therefore, their contribution was not accounted for separately. Effects of side flows, such as unsaturated groundwater from irrigated land, were not considered when calculating the salt balance.

Soil salinity level of irrigated land was measured twice annually on April 1 and October 1. For each soil sample, electric conductivity was measured at the four corners of a 1.5×2.0 m^2 area surrounding the soil-sampling site. Soil samples were dried naturally in locations without direct sunlight, then passed through a special sieve with mesh size of 0.1 cm, and three solution samples were prepared with 50 g of soil in distilled water for analysis. Soil salinity analyses were conducted using two methods: first through extraction and assessment of soluble salt content, and then through a conductometer (IKS Express 1T, SANIIRI, Uzbekistan) applied to a 1:1 mixture of soil sample and water (Shirokova and Chernyshev, 1999).

Measured soil salinity (total mineralization) was categorized as low (0.3–1.0 g/L), moderate (1.0–2.0 g/L), high (2.0–3.0 g/L), or very high (>3.0 g/L). This classification was assigned to the area represented by each soil sample to obtain spatial and temporal information about soil salinity distribution and dynamics. Based on groundwater and soil data, the overall extent of salinization in irrigated areas was assessed using the salinity classification system developed by Bazilevich and Pankova (1970) (Table 3).

Table 3 Classification of soil salinity, based on TDS and chloride (Cl) concentration (modified after Bazilevich and Pankova (1970))

Level of salinization	TDS (g/L)	Chloride Cl (g/L)	Sulfate-chloride TDS (g/L)	Cl (g/L)	Sulfate TDS (g/L)	Chloride-sulfate TDS (g/L)	Cl (g/L)
No salinity	<0.01	<0.01					
Low salinity	>0.30	<0.01					
Moderate salinity							
High salinity							

Level of salinization	TDS (g/L)	Chloride Cl (g/L)	Sulfate-chloride TDS (g/L)	Cl (g/L)	Sulfate TDS (g/L)	Chloride-sulfate TDS (g/L)	Cl (g/L)
Very high salinity							

4.1 Groundwater Level and Its Influence on the Characteristics of Irrigated Land

In arid areas, factors affecting the efficiency and sustainability of irrigated agriculture are closely linked with groundwater level. Improper irrigation and inefficient drainage networks can lead to soil salinization (Eshchanov, 2008; Martin and Sauerborn, 2013; Kulmatov, 2018). To ensure sustainable long-term irrigation and crop yields, it is necessary to determine the reasons for temporal and spatial changes in GW level and mineralization. High groundwater salinity combined with shallow groundwater levels leads to salinization of irrigated land and waterlogging of crop root systems, resulting in yield losses (Gafurova et al., 2005; Eshchanov, 2008).

Table 4 shows admissible levels of groundwater salinity for different groundwater depths. A groundwater level of less than 1.0 m is especially critical because even salt concentrations below 1.0 g/L can lead to land salinization, while groundwater at depths of 3.0 m or more could have salinity up to 5.0 g/L before full salinization effects occur (Gafurova et al., 2005; Kulmatov et al., 2018).

These "critical depths" were used to assess the level of amelioration required for irrigated land and to implement practical measures against salinization. If groundwater was located above the "critical depth," upward movement of salts from lower layers would increase and soils would be exposed to salinization. However, if groundwater was located below the critical depth, salt would not rise from lower layers into the topsoil and soil salinization would not occur.

Table 4 The critical groundwater (GW) depth and related admissible level of groundwater salinity in irrigated soils (Gafurova et al., 2005)

Critical GW depth (m)	Admissible level of GW salinity (g/L)	Maximum concentration of chlorine in GW (%)
About 1.0	>0.69	

The critical groundwater depth also depends on soil properties, particularly capillary structure, water retention potential, and percolation characteristics (e.g., amount of macropores or soil density) (Childs, 1969; Nielsen et al., 1973; Bowles, 1979; Heath, 2004; Gafurova et al., 2005; Kulmatov, 2018). To account for these parameters, Table 5 shows critical groundwater depth in relation to water retention and percolation capability of irrigated land. This integration of several important soil hydrological parameters makes critical groundwater depth a crucial concept for sustainable use of irrigated land resources.

Table 5 Critical GW depth related to water retention and percolation capability of irrigated soils (Gafurova et al., 2005)

Water retention and percolation capability of irrigated soils	GW salinity (g/L)	Critical GW depth (m)	Admissible GW level (m)
Average			
Strong			
Strong			

To ensure long-term sustainable irrigation and stable crop yields, it is necessary to determine the reasons for temporary changes in groundwater level, with special consideration given to critical groundwater level and salinity. Analysis of groundwater level dynamics in Jizzakh Province (Fig. 1 [Figure 1: see original paper]) revealed no irrigated fields with very shallow (0.0-1.0 m) groundwater levels. The largest area of irrigated land in the province (200.0×10³ hm²; 66.96% of total irrigated land) had a groundwater table at 2.1-3.0 m depth, followed by 63.93×10³ hm² (21.41%) at 3.1-5.0 m, 2.71×10³ hm² (9.27%) at >5.0 m, 6.23×10³ hm² (2.09%) at 1.5-2.0 m, and 0.80×10³ hm² (0.27%) at 1.0-1.5 m. During 1995-2016, groundwater level in a large area of the province' s irrigated land (291.00×10³ hm²) remained generally stable, varying only 5%-10%.

Groundwater level in Jizzakh Province has also been elevated by anthropogenic activities that have led to additional water inputs into the groundwater zone. Extensive leaching during spring, high-intensity irrigation during the vegetative season, leakage from irrigation canals and drainage water collectors, and waterlogging due to damaged or blocked drainage networks are the main reasons for raised groundwater levels.

Fig. 1 Dynamics of groundwater (GW) level changes in irrigated land in Jizzakh Province

This can be problematic for crop growth because shallow saline groundwater levels can reduce water uptake (e.g., in cotton), thus causing crop losses (Hutmacher et al., 1996; SANIIRI, 2005). Studies conducted by the Central Asian Research Institute of Irrigation (SANIIRI) have shown that cotton productivity decreases by 15%-20% in slightly saline soils, 35%-40% in moderately saline soils, and 70%-80% in highly saline soils. In addition to reduced yields (from 2.10 to 0.90-1.25 t/hm²), salinity has also been shown to influence the quality of raw cotton fibers (SANIIRI, 2005).

4.2 Dynamics of Groundwater Mineralization Fluctuations in the Province

Groundwater observations for 1995-2016 indicated that average groundwater mineralization in most irrigated land of the province fluctuated between 1.1-5.0 g/L (75.3% of all irrigated land), with averages below 1.0 g/L in 13.1% of irrigated land and in the range of 5.1-10.0 g/L in 10.5% of irrigated land (Table 6).

Table 6 Dynamics of long-term (1995-2016) average GW mineralization in Jizzakh Province

Mineralization (g/L)	Irrigated land area (×10^3 hm^2)	Percentage (%)
10.0		
Total		

In 1995, the irrigated area with groundwater mineralization of 0.0-3.0 g/L was 73.65×10^3 hm^2, while in 2016 the corresponding figure was 152.76×10^3 hm^2—an increase of 79.11×10^3 hm^2 (25.30% of all irrigated land). The area with average mineralization (3.1-5.0 g/L) also increased from 86.11×10^3 hm^2 in 1995 to 133.33×10^3 hm^2 in 2016—an increase of 47.22×10^3 hm^2 (14.57%).

In contrast, in 1995 the irrigated area with high groundwater mineralization (5.0-10.0 g/L) was 118.93×10^3 hm^2, while in 2016 it was 13.75×10^3 hm^2—a considerable decrease of 105.18×10^3 hm^2 (36.58%). Similarly, irrigated area with groundwater mineralization 10.0 g/L was reduced from 10.32×10^3 hm^2 in 1995 to 0.70×10^3 hm^2 in 2016 (97.00% reduction, Fig. 2 [Figure 2: see original paper]). In most irrigated land area of the province (75.33%), groundwater mineralization was in the range of 1.1 to 3.0-5.0 g/L.

During 1995-2016, the area with relatively low groundwater mineralization increased from 58.70×10^3 to 91.00×10^3 hm^2, indicating slight improvement in the state of irrigated land in the province. During the same period, the area of irrigated land with average groundwater mineralization (3.1-5.0 g/L) decreased from 44.90×10^3 to 16.50×10^3 hm^2 (20.80%), indicating positive changes in groundwater mineralization dynamics in irrigated areas of the province.

Thus, based on these analyses it can be concluded that groundwater quality in Jizzakh Province has considerably improved in recent years. One of the main causes of enhanced groundwater outflow in the province is improvement of the drainage network in the Jizzakh irrigation area, which has diverted drainage water toward the Aydar-Arnasay and Tuzkan lakes in the Mirzachul Desert in the southern part of the province.

Fig. 2 Long-term (1995-2016) dynamics of groundwater (GW) mineralization of irrigated land in Jizzakh Province

4.3 Salinization Level of Irrigated Soils in the Province

As shown in Figure 1, the majority of irrigated area in Jizzakh Province was characterized by groundwater levels deeper than 2.0 m. Additionally, most irrigated area in the province had low groundwater mineralization (Fig. 2). However, because availability of low-mineralized deep groundwater is limited, additional water needed for crop growth in irrigated areas is provided by diversion from the Syrdarya and Zarafshan rivers. Mineralization levels in both rivers have increased (Table 2), with the result that extensive irrigation has led not only to rising groundwater levels but also increased groundwater mineralization.

An efficient drainage network would prevent salt accumulation, but the technical infrastructure used in the drainage system in Jizzakh Province is outdated and not always well maintained; therefore, salt removal is incomplete.

Results of this study indicated that most irrigated land in Jizzakh Province is slightly saline, with an average of 51.3% of irrigated area falling into this category (Fig. 3 [Figure 3: see original paper]). Another 17.7% showed no sign of salinization. However, 29.0% of irrigated area was moderately saline and 2.0% was highly saline. Overall, salinization in Jizzakh Province was much lower than in neighboring Bukhara Province, where 27.6% of irrigated area is classified as moderately saline and 7.8% as highly saline (Kulmatov et al., 2015).

Fig. 3 Temporal soil salinization dynamics of irrigated area in Jizzakh Province from 1995 to 2016

All relevant parameters (irrigation water mineralization, groundwater level, and groundwater salinity) are subject to considerable temporal dynamics (Table 2; Figs. 1 and 2), meaning their influence on soil salinity is also dynamic. Therefore, managing salinization of irrigated land is a complex process requiring flexible agrotechnical practices. In recent years, this paradigm has been increasingly incorporated into the agrarian sector, explaining observed improvements in salinity conditions in Jizzakh Province.

Salinization of agricultural land negatively affects soil structure and biological activity of soil microorganisms. This can lead to reduced mineral fertilizer use by plants and may cause various plant diseases (SCNP, 2013). Cotton productivity in Uzbekistan has decreased by 15%-20% in low-salinity soils, 35%-40% in moderately saline soils, and 70%-80% in highly saline soils (SANIIRI, 2005). Therefore, monitoring and assessment of salinization levels in irrigated soils is very important for agriculture. Based on results obtained, programs to control effects of salt leaching on the following year' s crop can be initiated.

In Jizzakh Province in 1995, the area of irrigated land not affected by salinization was 50.57×10^3 hm^2 (17.50% of total irrigated land area), which increased to 67.64×10^3 hm^2 (22.50%; Fig. 3) in 2016. This indicates that in recent years, irrigated area not affected by salinization increased by 17.07×10^3 hm^2 (5.00%). The area of low-salinity irrigated land was 159.81×10^3 hm^2 (55.30%) in 1995, decreasing slightly to 158.67×10^3 hm^2 (52.80%) in 2016—a decrease of 1.15×10^3

hm^2 (0.50%). The area of moderate-salinity irrigated land was 74.59×10^3 hm^2 (25.80%) in 1995, decreasing to 68.62×10^3 hm^2 (22.80%) in 2016—a decrease of 5.97×10^3 hm^2 (3.00%). High-salinity irrigated land area increased slightly from 4.04×10^3 hm^2 (1.40%) in 1995 to 5.62×10^3 hm^2 (2.00%) in 2016.

In general, it can be concluded that during 1995-2016, the salinization level of irrigated lands in the province increased slightly. Based on average soil salinization level, the province' s irrigated areas can be classified as follows: no salinity (17.7%), low salinity (51.3%), moderate salinity (29.0%), and high salinity (2.0%) (Fig. 3). The observed slight increase in salinity in irrigated land in Jizzakh Province occurred due to use of outdated irrigation technology and inefficient drainage systems. Because of relatively high amounts of mineralized salts in irrigated land and proximity of groundwater, reclamation leaching of irrigated land is required each winter.

4.4 "Irrigation Water-Soil-Drainage Water" Salt Balance

Climate change and frequently recurring droughts in Central Asia in recent years have diminished river water flows, with the result that more water resources are required for irrigation (SCNP, 2013). If the amount of water available for irrigation does not meet scientifically based crop needs, or if excessive amounts of water are used, salts accumulate in irrigated soils. Salt accumulation associated with irrigated agriculture is mainly caused by two factors: introduction of salts in irrigation water to the land, and extremely high levels of saline groundwater caused by excessive irrigation and poor drainage systems (Dukhovny, 1983; Kovda, 2008). Difficulty in natural outflow of excess water from irrigated areas leads to salinization and swamping, reducing soil fertility (Kulmatov et al., 2015, 2018). Increased salinity in water and soil has had serious negative impacts on agriculture, food security, and human health worldwide. Direct impacts of salinity on both soil microbial communities and crops can seriously affect crop production, yield, and cropping patterns (Yan et al., 2015; Rahaman et al., 2019).

It is therefore important to identify the total amount of salts entering irrigated land with irrigation water, the amount of salt remaining in irrigated areas, and the amount of salt leached out through the drainage system (reclamation leaching). Analysis of "irrigation water-soil-drainage water" salt balance dynamics in the irrigated area was conducted based on monitoring data for 2000-2016 (Table 7).

During 2000-2016, an average of 2690.9×10 m^3 of water was used for irrigation during the vegetation growth period, autumn crop irrigation, and winter salt leaching in the province. The highest irrigation water volume (3368.8×10 m^3) was used in 2005, from which 799.0×10 m^3 was diverted to drainage systems (Table 7).

The average annual irrigation water volume (2690.9×10 m^3) had a total salt content of 3271.4×10^3 t, with chlorides accounting for 974.9×10^3 t. The annual average drainage water outflow was 826.4×10 m³, containing a total salt content of 2878.0×10³ t, with chlorides accounting for 887.5×10³ t. Thus, the total amount of salts remaining in the irrigated area was 393.4×10³ t, with chlorides accounting for 87.4×10³ t.

On average for each hectare of irrigated land in the province, 1.21 t of salts entered the soil with irrigation water and 1.06 t of salts were leached out by drainage water. Thus, 12.0% of salts and 8.9% of chlorides that entered the soil with irrigation water remained in irrigated areas. On average, 0.15 t of salt remained on each hectare of irrigated land (Table 7). The lowest irrigation water volume used was 2351.8×10 m³ in 2001 (an extreme drought year), with 980.6×10 m³ diverted to the drainage system. The remaining 1371.2×10 m³ was used during the vegetation growth season. In autumn-winter, 88.9×10 m³ of river water is used annually for reclamation leaching in irrigated soils, resulting in desalinization and improved reclamation status.

The average salt concentration in water used for irrigation in the province was 1.2 g/L during 2000-2016. The maximum amount of salts entering irrigated area soils (4099.2×10³ t) occurred in 2000, of which 4319.1×10³ t was leached out by drainage water. Thus, the amount of salt entering through irrigation water was less than that leached out, likely because salt leaching in autumn-winter 2000 was more effective than in other years.

In 2012, total salt entering soils through irrigation water was 2865.8×10³ t, of which 2209.1×10³ t was leached out by drainage water, leaving 656.7×10³ t of salts in the irrigated area. During 2000-2016, average salt content in irrigation water was 3271.4×10³ t, of which 2878.0×10³ t was leached out. Total residual salt in irrigated area was 393.4×10³ t. As a result, 1.3 t/hm² of salt accumulated on irrigated land during the 17-year study period. Thus, 11.7% of total incoming salts remained in irrigated areas (Table 7).

Table 7 "Irrigation water-soil-drainage water" salt balance of Jizzakh Province during 2000-2016

Parameter	Irrigation water input	Drainage water output	Salt balance
	(×10 m³)	(g/L)	(×10³ t)
Average			

Parameter	Irrigation water input	Drainage water output	Salt balance
Note: WV, water volume; M, mineralization; C, chlorine content; TS, total salt content; TC, total chlorine content; TSB, total salt balance; TCB, total chlorine balance.			

During 2000–2016, average chlorine concentration in irrigation water was 0.3 g/L. The lowest amount of chlorine entering irrigated fields (823.2×10^3 t) was observed in 2014, with 886.3×10^3 t leached out through drainage waters, implying that chlorine in irrigation water was less than that flowing out in drainage water, likely because soil leaching was more effectively conducted during autumn–winter 2014.

In 2013, total chlorine entering soils in irrigation water was 1364.3×10^3 t, of which 895.4×10^3 t was leached out, leaving 468.9×10^3 t of excess chlorine in irrigated areas.

In general, during 2000–2016, the average amount of chlorides in irrigation water was 974.9×10^3 t/a, of which 887.5×10^3 t/a was leached out through drainage water. Residual chlorides amounted to 87.4×10^3 t/a, with 0.29 t/a of chlorides per hectare accumulating during the 17-year study period. On average, 10.1% of total incoming chlorides accumulated in irrigated land (Table 7). Thus, analysis of the "irrigation water–soil–drainage water" salt balance indicated a low salinization level in irrigated soils of the region.

Most salt-affected land has experienced salinization due to natural causes, with salt accumulation over long periods in arid and semiarid zones (Rengasamy, 2002). More than 800×10 hm^2 of land worldwide are salt-affected, including 4.5×10 hm^2 (20%) of the current 2.3×10 hm^2 of irrigated land (FAO, 2008).

The average groundwater salinization value in most (75.3%) irrigated land of Jizzakh Province fluctuated between 1.1-5.0 g/L, with values <1.0 g/L in 13.1% and 5.1-10.0 g/L in 10.5% of irrigated land. High groundwater salinization can increase salt content in upper soil layers through capillary action, affecting crop root zones and reducing productivity. Salinization can be effectively controlled in irrigated land by reducing groundwater level, increasing efficiency of drainage networks that divert drainage water, and most importantly, using modern climate-smart water-saving irrigation techniques.

Low rainfall in dryland areas, high vegetation transpiration rates, and high summer evaporation rates cause salt accumulation in root zone layers (Rengasamy, 2002). Temperatures in the ASB are likely to increase by 2°C–3°C by 2050 and 3°C–5°C by 2080, predicted to be particularly high in summer and autumn (Lioubimtseva, 2015). Under elevated soil salinity, repeated remediation leaching reduces surface soil salinity, but because existing drainage systems do not cover all irrigated land area and are inefficient, permanent salinization, fertility decline, and reduced agricultural crop yields can occur.

During 1995–2016, the salinization level of irrigated lands in Jizzakh Province increased slightly, with the area divided into the following classes: no salinity (17.7% of total area), low salinity (51.3%), moderate salinity (29.0%), and high salinity (2.0%). Remediation leaching of soils with elevated salinity requires additional water resources, which increases groundwater level and mineralization and accelerates the salinization process in irrigated soils.

5 Conclusions

Under current conditions of low soil fertility, stable crop yields (e.g., 10%–15% for cotton and grain) in Jizzakh Province have been achieved mainly through use of large volumes of mineral fertilizers. However, permanent use of excessive mineral fertilizers (primarily nitrogen-containing) can also cause soil salinization.

The average groundwater salinization value in most (75.3%) irrigated land fluctuated between 1.1-5.0 g/L, with values <1.0 g/L in 13.1% and 5.1-10.0 g/L in 10.5% of irrigated land. The condition of irrigated land in the province has not significantly improved. High groundwater salinization levels can reduce crop productivity. The best way to effectively control salinization is to reduce groundwater level, increase drainage network efficiency, and most importantly, use modern climate-smart irrigation techniques.

The salt balance in the "irrigation water-soil-drainage water" system is extremely complex. It changes over time and requires monitoring and analysis of numerous parameters. Repeated remediation leaching reduces surface soil salinity, but because existing drainage systems do not fully cover irrigated land area and are ineffective, permanent salinization, fertility decline, and reduced agricultural crop yields are unavoidable. During 1995–2016, the salinization level of irrigated land in Jizzakh Province increased slightly, with the area divided into the following classes: no salinity (17.7% of total area), low salinity (51.3%), moderate salinity (29.0%), and high salinity (2.0%).

Analysis of long-term monitoring data for Jizzakh Province revealed the importance of sustainable use of available water resources, as well as the need to improve reclamation status of irrigated land, maintain groundwater level and mineralization at optimal levels, keep irrigated soil salinization at optimal levels, and maintain the drainage system to ensure effective operation. This would enable sustainable use of water and land resources under a changing climate. Detailed studies of salt balance in irrigated areas, and the impact of climate change, increased fertilizer use, and repeated remediation leaching on groundwater level and mineralization, should be conducted in the future to better understand processes leading to accelerated salinization, fertility declines, and reduced agricultural crop yields.

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Note: Figure translations are in progress. See original paper for figures.