

Agrochemical changes under deficit irrigation of cotton on meadow-alluvial soils of Karakalpakstan

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ABSTRACT

Efficient irrigation management is crucial for maintaining soil fertility and reducing secondary salinization in arid regions irrigated with mineralized water. This study evaluated the effects of soil-moisture-based deficit irrigation on the agrochemical properties and salt distribution of moderately saline meadow-alluvial soils under cotton (*Gossypium hirsutum* L., cv. Chimboy-5018) during 2016–2018. Six treatments were established by combining three water-supply levels ($\approx 40\%$, 60% and 80%) with two pre-irrigation moisture thresholds ($70\text{--}70\text{--}60\%$ and $80\text{--}80\text{--}60\%$ HB). Soil samples from 0–30, 30–50 and 50–100 cm layers were analyzed for humus, total NPK, mobile $\text{NO}_3\text{-N}$, P_2O_5 , K_2O , and water-soluble salts. Total NPK contents showed little variation among treatments, whereas mobile nutrient forms displayed pronounced vertical redistribution depending on the irrigation regime. Lower water supply ($\approx 40\%$) resulted in nutrient accumulation in the topsoil together with increased concentrations of Na^+ and Mg^{2+} salts. Higher irrigation levels ($\approx 80\%$) enhanced leaching, reducing salt accumulation in the root zone but also decreasing available K_2O by 35–45%. The intermediate 60% regime provided the most balanced conditions, maintaining moderate salt leaching, stable nutrient distribution, and the lowest risk of secondary salinization. ANOVA revealed significant differences in cotton yield, with the highest yield (30.4 c/ha) obtained under the 80% water-supply regime, while the 60% regime demonstrated comparable productivity with lower water use. Overall, moderate deficit irrigation ($\approx 60\%$) represents the optimal strategy for sustaining soil quality and crop productivity under saline irrigation conditions in arid environments.

Keywords: deficit irrigation, soil salinity, agrochemical properties, meadow-alluvial soils, cotton, arid conditions, Karakalpakstan.

INTRODUCTION

Irrigated agriculture in arid and semi-arid regions depends significantly on soil fertility, determined by a combination of agrochemical parameters, including organic matter content, available

nutrients, and other properties that characterize soil salinity. These parameters control the productivity of agroecosystems under water stress and the stability of soil fertility over time. Cation exchange capacity and the availability of mobile forms of phosphorus and potassium are closely

linked to crop yields in dryland conditions (Sainju and Liptzin, 2022). In arid climates, low organic matter content, insufficient amounts of available nitrogen and phosphorus, high alkalinity, and low water storage increase soil sensitivity to secondary salinization, structural deterioration, and lower soil functionality (Hag Husein et al., 2021; Díaz et al., 2021; Soltani-Gerdefaramarzi et al., 2023).

In Central Asia, including Karakalpakstan, a combination of natural and anthropogenic factors exacerbates arable land degradation. Traditional high irrigation rates coupled with low water-use efficiency have contributed to widespread salinization of irrigation systems and deterioration of soil structure (Jabbarov et al., 2025; Ruziyev et al., 2022; Dauletmuratov et al., 2024; Mirzaqobulov et al., 2025). It is estimated that up to 50% of the region's arable land is already susceptible to secondary salinization (Measho et al., 2022; Koriyev et al., 2025). Long-term excess moisture destroys aggregates and reduces soil permeability, while moisture deficit increases compaction of the upper horizon and increases salt concentrations in the root zone (Abdullaev et al., 2010; Qadir et al., 2014). With insufficiently developed drainage infrastructure, the accumulation of Na^+ and Cl^- causes dispersion of clay particles, increases pH, and limits nutrient availability (Hamidov et al., 2022; Dauletmuratov et al., 2024).

Global research highlights that irrigation regime and quality are key factors in transforming the agrochemical status of soils. Irrigation water salinity, irrigation frequency, and rates determine the accumulation or leaching of salts, organic matter dynamics, and nutrient availability, shaping the salt and nutrient regimes of the profile (Soltani-Gerdefaramarzi et al., 2023; Alsanad, 2024; Yan et al., 2025; Rafik et al., 2023; Meiramkulova et al., 2024). It was shown that the use of treated wastewater, in contrast to freshwater, can alter cumulative infiltration, aggregate stability, and nutrient availability; and the effect depends on the crop and irrigation process parameters (Gharaibeh and Eltaif, 2014; Meiramkulova et al., 2024). This is especially important in regions with highly mineralized irrigation waters, such as Karakalpakstan, where the chemical composition of irrigation water can both reduce and enhance salinization processes.

Long-term irrigation leads to restructuring of soil formation processes and changes in the organic carbon stocks, total nitrogen, and carbonate profile relative to rainfed areas (Sousa et al., 2021; Weldewahid et al., 2023). Using waters with

different chemical compositions has been shown to alter the soil's salt balance and the suitability of groundwater for agricultural use (Yan et al., 2025; Alsanad, 2024). Salt-affected and solonchic soils of Central Asia are particularly sensitive to irrigation regimes. A meta-analysis showed that deficit irrigation at a level of 0.85–0.90 of the full rate reduces salt accumulation in the root zone and increases water productivity (Lu et al., 2025). Field observations confirm that a decrease in water supply is accompanied by measurable changes in pH, EC, and the concentration of major ions in the arable layer (Hasani et al., 2024; Al-Khuzai et al., 2022). In Central Asia, the transition to economic irrigation regimes is considered an important tool for stabilizing the agrochemical status of soils when using saline irrigation water (Jabbarov et al., 2025; Hamidov et al., 2022; Hasani et al., 2024).

The combination of water delivery method and water deficit level determines the mineralogical and salt profiles. Changes in pH, EC, organic matter, available NPK forms, and enzymatic activity were shown for different irrigation systems under arid conditions (Teklu, 2017; Soltani-Gerdefaramarzi et al., 2023; Díaz et al., 2021; Boru et al., 2024). The use of regulated deficit irrigation (RDI) and partial root zone drying (PRD) improves water use efficiency and manages moisture and salt distribution with the correct selection of the deficit level (Zeineldin and Al-Molhim, 2021; Barbagallo et al., 2021; Hashem and El-Abedin, 2019). Studies with grain crops have shown that spatially and temporally differentiated water supply affects vertical salt transport, nitrate accumulation, and water productivity (Chen et al., 2022; Lu et al., 2025).

Thus, available data indicate that the agrochemical properties of irrigated soils in arid regions are determined not only by natural and climatic conditions but also by the quality, method, and regime of irrigation. However, for Karakalpakstan, characterized by high salinity of irrigation water and widespread secondary salinization, there is insufficient information on the dynamics of key agrochemical parameters and the salt regime of soils under various levels of deficit irrigation. Therefore, a comprehensive assessment of the impact of water supply regimes on the content of essential nutrients and salinization ions is needed to stabilize fertility and limit degradation processes.

The study aims to identify patterns of change in the agrochemical properties of meadow-alluvial soils of Karakalpakstan under various deficit

irrigation regimes and to substantiate the parameters of the irrigation regime that minimize the risk of secondary salinization while maintaining or increasing soil fertility.

MATERIALS AND METHODS

Research area

The study area is located in the northwestern part of the Republic of Uzbekistan, within its autonomous Republic of Karakalpakstan (40°58′–45°39′N and 56°00′–62°33′E). This region borders Kazakhstan to the west, north and northeast, and the Bukhara and Khorezm regions of Uzbekistan to the east and southeast. In the context of recent studies on the soil cover of Uzbekistan (Gafurova et al., 2024), the territory of Karakalpakstan represents an important area for analysing the structure and transformation of soil cover under arid and irrigated conditions. The region's climate is characterized by hot, dry summers and cold winters, high solar radiation, intense evaporation, and a deficit of precipitation during the warm season. The climatic conditions of the experimental site are characterized by hot and dry summers. Freezing of the arable layer is observed in winter. The average daily air temperature in summer is 24–31 °C, with a maximum of 44 °C; and in winter, drops to -14...-21 °C are possible. Average daily temperatures exceed 10 °C in spring in late March – early April, and in autumn in late September–October. The sum of effective temperatures (≥ 10 °C) for April–October is 2410–2470 °C, which makes cotton cultivation possible. However, the risk of water stress increases from late spring onward. Annual precipitation is low (74–170 mm), mostly falling during the cold season. Summer precipitation is often absent, and relative humidity is low, enhancing evaporation and transpiration. In terms of soil and geography, the experiment was conducted on meadow-alluvial soils, which correspond to *Fluvisols* in the international WRB classification, with a low to moderate degree of sulfate-chloride salinity.

Field experiment design

The field experiment was based on regulating the pre-irrigation soil moisture, which served as the main indicator of the crop water-supply level. Three water-supply regimes were

established—approximately 40%, 60% and 80% of the crop's estimated water requirement. These values did not represent fractions of the seasonal irrigation rate; instead, they corresponded to soil-moisture thresholds expressed as a percentage of field capacity (HB). Two pre-irrigation moisture regimes were used in the 0–30, 30–50 and 50–100 cm layers: 70–70–60% HB and 80–80–60% HB. Maintaining higher HB levels required more frequent irrigations, whereas lower HB thresholds resulted in fewer irrigations. Therefore, the actual irrigation volumes (m³/ha) differed between treatments, although the water-supply level itself was defined by the soil-moisture regime rather than by the total water applied. Irrigation schedules were encoded by three-digit schemes (e.g., 0–1–0, 1–1–0, 1–2–0), indicating the number of irrigations in the early growth phase, flowering, and boll-formation/ripening phases. The combination of moisture thresholds and irrigation schedules produced six experimental treatments (Table 1). Variants with 70–70–60% HB generally required fewer irrigations (800–2000 m³/ha), while variants with 80–80–60% HB required more frequent irrigations (1500–3000 m³/ha). Thus, the irrigation volume reflected the frequency and depth of irrigations required to maintain the specified HB levels.

The experiment was arranged as a randomized block design with four replications. Each plot covered 360 m², including 180 m² for measurements.

All experimental treatments used the same mineral nutrient background in order to isolate the effect of irrigation regimes. The main dose of phosphorus–potassium fertilizers ($\approx 60\%$ of the total rate) was applied during autumn plowing. Before sowing, N-30, P-100, and K-50 kg/ha were applied and incorporated. Organic fertilizers were not used. Cotton (*Gossypium hirsutum* L., variety Chimboy-5018) was sown at the standard time for the region. Weed control, inter-row cultivation, and plant protection measures were identical across treatments.

Irrigation was carried out using water from the local canal system hydraulically connected to saline groundwater. The salinity of the irrigation water ranged from 3.7 to 5.1 g/L, dominated by sodium, magnesium, and calcium sulfate–chloride salts, which increases the risk of secondary salinization.

Laboratory soil analysis

Soil samples were analyzed using established methods to determine soil properties. Organic

Table 1. Experimental treatments

Variant	Water-supply level*	Pre-irrigation soil moisture (HB, %)	Irrigation schedule	Total irrigation water (m ³ /ha)**)
1	40%	70–70–60	0–1–0	800
2	40%	80–80–60	0–2–0	1500
3	60%	70–70–60	1–1–0	2000
4	60%	80–80–60	1–2–0	2500
5	80%	70–70–60	1–2–0	3000
6	80%	80–80–60	1–3–0	3000

Note: * Water-supply level refers to the soil-moisture regime (HB), not to the seasonal irrigation rate.

** The irrigation volume reflects the number and depth of irrigations required to maintain the specified HB levels.

matter content was determined using the modified Tyurin method (CINAO), based on the oxidation of organic carbon with potassium dichromate, in accordance with state standards GOST 26213–91 (Committee for Standardization and Metrology of the USSR, 1991). Total phosphorus and potassium content were determined by acid digestion in accordance with GOST 26261–84 (Ministry of Agriculture of the USSR, 1984a), followed by measurement using spectrophotometry and flame photometric analysis. Total nitrogen was determined using the Kjeldahl method described in GOST 26107–84 (Ministry of Agriculture of the USSR, 1984b); the method included decomposition with concentrated sulfuric acid. In this study, soil salinity was evaluated using the total content and ionic composition of water-soluble salts in accordance with the classification developed by Pankova et al. (1996). Electrical conductivity (EC) was not measured instrumentally, so EC-based salinity classes (dS/m) were not used in the interpretation. The analysis relied on gravimetrically determined concentrations of water-soluble salts (% g/kg) and their ionic composition (Ca²⁺, Mg²⁺, Na⁺, Cl⁻, SO₄²⁻), which allowed characterization of salinity type (chloride-sulfate, sulfate-chloride) and degree (weak, moderate, strong). Although soil electrical conductivity (EC) is widely used in salinity studies, the applied approach based on the total content and ionic composition of water-soluble salts remains methodologically justified for sulfate–chloride meadow-alluvial soils of arid Central Asia. Under conditions of mineralized irrigation water, ion composition and redistribution of physiologically harmful salts (Na⁺ and Mg²⁺) within the soil profile provide more detailed information on salinization processes than integral EC values. The classification of salts as “physiologically harmless” (mainly Ca²⁺ salts) or “harmful” (Na⁺ and

Mg²⁺ chlorides and sulfates) follows the widely accepted approach for sulfate-chloride soils in Central Asia described by Pankova et al. (1996).

This approach provides a quantitative assessment of salinity in cases where EC measurements are unavailable, which is acceptable for irrigated meadow-alluvial soils where the primary concern is the redistribution of harmful ions within the 0–100 cm profile.

Statistical data processing

Cotton yield data (raw cotton yield) were subjected to a single-factor analysis of variance with the “irrigation treatment” factor. Means were compared using the LSD₀₋₀₅ ratio; differences were considered statistically significant at $p < 0.05$. Soil agrochemical parameters (humus, total and mobile forms of NPK, water-soluble salts) were analyzed using descriptive statistics (means and ranges) without formal analysis of variance. This approach was applied because the primary objective was to identify consistent trends and vertical redistribution patterns of nutrients and salts within the soil profile rather than to compare treatment means statistically. Depth-stratified and multi-year soil sampling further limits the applicability of classical single-factor ANOVA for soil parameters. Statistical processing was performed according to method of B.A. Dospikhov (Dospikhov, 1985).

RESULTS AND DISCUSSION

The initial agrochemical state of the meadow-alluvial soils of the experimental plot was characterized by average organic matter content and moderate macronutrient availability. Humus content in the 0–100 cm profile ranged from 0.48

to 0.69%, reaching a maximum in the 0–30 cm layer and decreasing to 0.48% in the 70–100 cm horizon, reflecting the typical stratification of organic matter in alluvial soils. Total nitrogen, phosphorus, and potassium also decreased with depth: from 0.06–0.146% in the 0–30 cm layer to 0.03–0.102% in the 70–100 cm horizon (Table 2).

Concentrations of mobile nutrient forms were highest in the arable layer and decreased with increasing profile depth. According to data from the first year, with a 40% water supply, the nitrate nitrogen ($\text{NO}_3\text{-N}$) content in the 0–30 cm layer was 3.38 mg/kg, at 60%, it was 3.02 mg/kg, and decreased to 2.329 mg/kg at 80%. In the 70–100 cm horizon, values decreased from 2.01 mg/kg (40%) to 1.581 mg/kg (80%). In the second year, a similar trend was observed: in the 0–30 cm layer, the $\text{NO}_3\text{-N}$ content varied from 3.41 to 2.322 mg/kg with an increase in water supply from 40 to 80%, and in the 70–100 cm horizon, from 2.02 to 1.623 mg/kg (Figure 1).

The content of mobile phosphorus (P_2O_5) also decreased with increasing water supply and depth. In the first year, in the 0–30 cm layer, the concentrations were 4.01, 3.18, and 3.04 mg/kg at 40, 60, and 80%, respectively. In the 70–100 cm horizon, the values varied from 1.02 to 2.11 mg/kg. In the second year, the ranges were 4.03–3.20 mg/kg in the 0–30 cm layer and 1.01–2.13 mg/kg in the 70–100 cm layer at 40–60% water supply, decreasing to 2.02 mg/kg at 80% (Figure 2).

The most pronounced changes were observed for mobile potassium (K_2O). In the first year, in the upper layer (0–30 cm), K_2O concentrations were 302.10 mg/kg at 40%, 244.11 mg/kg at 60%, and 204.29 mg/kg at 80%. In the 70–100 cm horizon, values increased from 115.08 mg/kg at 40% to 201.02 mg/kg at 60% and decreased to 161.11 mg/kg at 80%, indicating a redistribution of potassium to the lower part of the profile with higher irrigation rates. In the second year, similar

dynamics were maintained: concentrations decreased from 301.25 to 202.17 mg/kg in the 0–30 cm layer and increased from 113.20 to 159.89 mg/kg in the 70–100 cm horizon with an increase in water supply from 40 to 80% (Figure 3).

Averaging the data over the soil profile confirms the stability of the identified trends. In the first year, in the 0–100 cm layer, the average $\text{NO}_3\text{-N}$ content decreased from 2.36 mg/kg at 40% to 1.909 mg/kg at 80%, the P_2O_5 content decreased from 2.53 to 2.47 mg/kg, and K_2O decreased from 235.13 to 180.47 mg/kg. In the second year, a similar range was 2.367–1.946 mg/kg for $\text{NO}_3\text{-N}$, 2.517–2.465 mg/kg for P_2O_5 , and 234.33–180.04 mg/kg for K_2O . Thus, across all layers of the soil profile and in both study years, a consistent trend toward a decrease in the content of mobile forms of nitrogen, phosphorus, and potassium in the upper arable layer with increasing water availability and a partial redistribution of nutrients to the lower part of the profile was observed. The most pronounced changes were observed for nitrate nitrogen and potassium, while variations in phosphorus were less significant.

The observed difference in the vertical distribution of mobile forms of macronutrients is explained by differences in their soil mobility and migration mechanisms. Phosphate ions (P_2O_5) are quickly fixed in the upper horizons due to interaction with calcium and magnesium in carbonate soils, so their content varies little with depth, even with higher irrigation rates. Nitrate nitrogen (NO_3^-) is highly mobile, but a significant portion of it is consumed by plants and lost through denitrification, which reduces its accumulation in the deeper layers. In contrast, potassium (K^+) has intermediate mobility: it is partially washed down the profile with increasing water supply, which leads to a decrease in concentration in the upper layer and a simultaneous increase in content in the 70–100 cm horizon, especially at 60% water supply.

Table 2. Initial agrochemical properties of the soil profile

Depth, cm	Humus, %	Total content, %			Mobile forms, mg/kg		
		N	P	K	NO_3	P_2O_5	K_2O
0–30	0.69	0.06	0.146	1.87	3.74	3.95	310.00
30–50	0.64	0.05	0.139	1.13	2.34	3.68	306.12
50–70	0.54	0.03	0.103	1.07	2.54	2.43	258.07
70–100	0.48	0.03	0.102	1.05	1.12	1.02	194.31
0–50	0.66	0.05	0.142	1.50	3.04	3.81	308.06
0–100	0.58	0.04	0.122	1.28	2.43	2.77	267.12

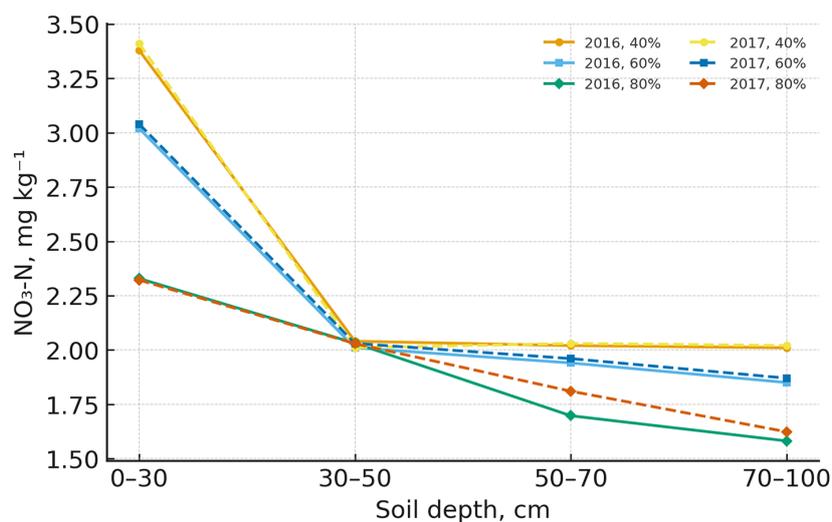


Figure 1. Depth-wise distribution of mobile NO₃-N at different irrigation water supply levels (40, 60 and 80%) in 2016 and 2017

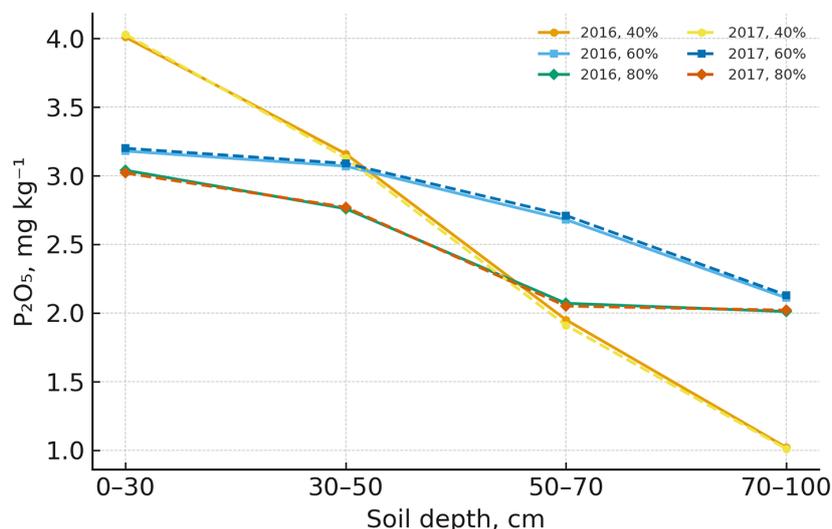


Figure 2. Depth-wise distribution of mobile P₂O₅ at different irrigation water supply levels (40, 60 and 80%) in 2016 and 2017

A comparison of the obtained data with the literature shows that the identified patterns are consistent with those of other studies. Teklu (2017) observed a decrease in the content of available phosphorus and potassium in the surface soil horizon with increased irrigation rates due to leaching. Hasani et al. (2024) reported a similar effect when corn was cultivated under drip irrigation with mineralized water, with a decrease in available potassium content of 30–40% compared to a deficit regime. This confirms that the decrease in K₂O concentration at 80% water availability under our conditions is consistent with the general pattern of nutrient removal with higher irrigation rates. Other researchers have noted similar differences between

macronutrients in terms of vertical migration. Field experiments on carbonate soils (De Paz et al., 2017; Kumar et al., 2020) found that phosphorus is almost entirely fixed in the upper horizon, while potassium tends to shift to deeper horizons under regular irrigation. This confirms that the increased sensitivity of K₂O to water availability observed in our study is typical for irrigated agricultural landscapes in the arid zone.

Since electrical conductivity (EC) was not measured instrumentally, the assessment of salinity dynamics in this study was based entirely on the total content and ionic composition of water-soluble salts. This approach is widely applied in studies of sulfate–chloride salinization in arid

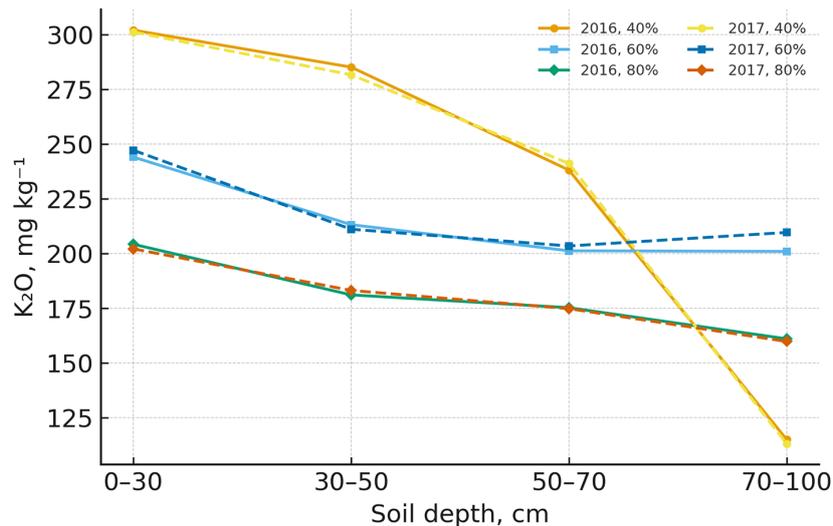


Figure 3. Depth-wise distribution of mobile K_2O at different irrigation water supply levels (40, 60 and 80%) in 2016 and 2017

regions, where the ecological impact of salinity is determined primarily by the redistribution of specific ions (Na^+ , Mg^{2+} , Ca^{2+} , Cl^- , SO_4^{2-}) rather than by integral EC values. Salinity levels in the 0–30, 30–50 and 50–100 cm soil layers were therefore interpreted according to the classification of Pankova et al. (1996), in which weak salinity corresponds to 0.20–0.40% total soluble salts and moderate salinity to 0.40–0.70%. This method provides a reliable basis for comparing irrigation treatments and characterizing salinity profiles under conditions where EC measurements are unavailable.

At the beginning of the growing seasons in both years of the experiment, the meadow-alluvial soils of the study site exhibited predominantly weak sulfate–chloride salinity with clear vertical differentiation (Figures 4 and 5). The upper 0–30 cm layer was characterized by a higher proportion of physiologically low-impact calcium salts, whereas the deeper 50–100 cm horizons contained an increased share of magnesium and sodium chlorides and sulfates. This vertical pattern served as the baseline for evaluating how different irrigation water-supply levels influenced salt redistribution within the soil profile.

In the second year, low-impact calcium salts ($Ca(HCO_3)_2$, $CaSO_4$) predominated in the 0–30 cm layer: their content reached 0.186% (77.8% of the total salts), with the proportion of high-impact sodium and magnesium salts being 0.053% (22.1%) and total mineralization being 0.239%. The proportion of high-impact salts increased

with depth, reaching ~50.4% in the 50–100 cm horizon, while the total salt content in the 0–50, 0–70, and 0–100 cm sections remained within the limits of weak salinization (0.192–0.212%). In 2018, the general patterns persisted, with a slight increase in mineralization in the upper horizons (up to 0.242% in the 0–30 cm layer) and an almost equal ratio of low-impact salts and high-impact salts (approximately 49–51%) in the 50–100 cm layer, indicating the accumulation of sulfates and chlorides of Na^+ and Mg^{2+} in the lower part of the profile. Even based on average values of water-soluble salt content in the 0–30 cm layer, with an increase in water supply from 40 to 80%, total mineralization decreased from 0.46 to 0.36%. The same trend was observed throughout the 0–100 cm profile: mineralization decreased from 0.50 to 0.39%, confirming the leaching effect of higher irrigation rates and reflecting the differences between the options in the degree of salinization of the arable layer.

The results of salinization analysis at different water supply levels (40, 60, and 80%) showed a clear trend of the nature and intensity of salt accumulation on the irrigation regime. With minimum water supply (40%), the upper soil layer (0–30 cm) contained 0.133% of low-impact salts $Ca(HCO_3)_2$ and $CaSO_4$ and 0.330% of harmful salts $MgSO_4$, Na_2SO_4 and $NaCl$, and the average mineralization in the 0–100 cm layer reached 0.504%, which corresponds to the transition to average sulfate-chloride salinization. At 60% water supply, the proportion of low-impact

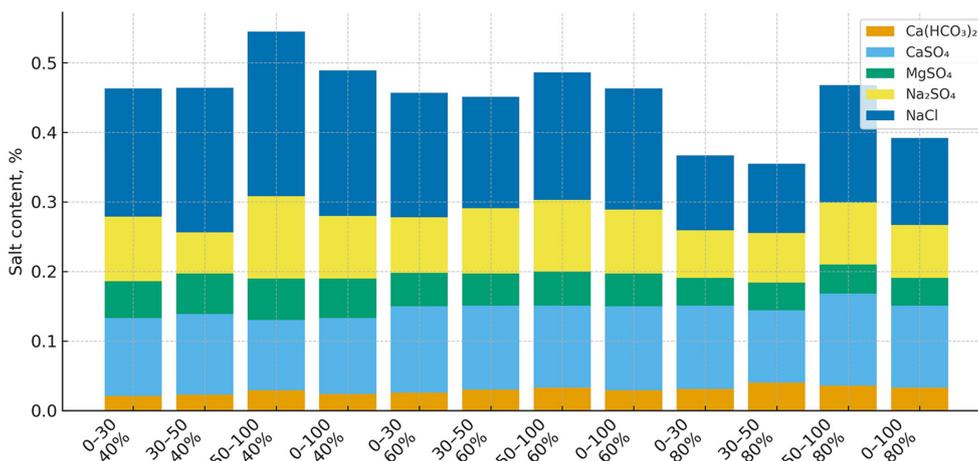


Figure 4. Ionic composition of water-soluble salts in meadow-alluvial soils at different depths and irrigation water supply levels at the end of the 2016 growing season

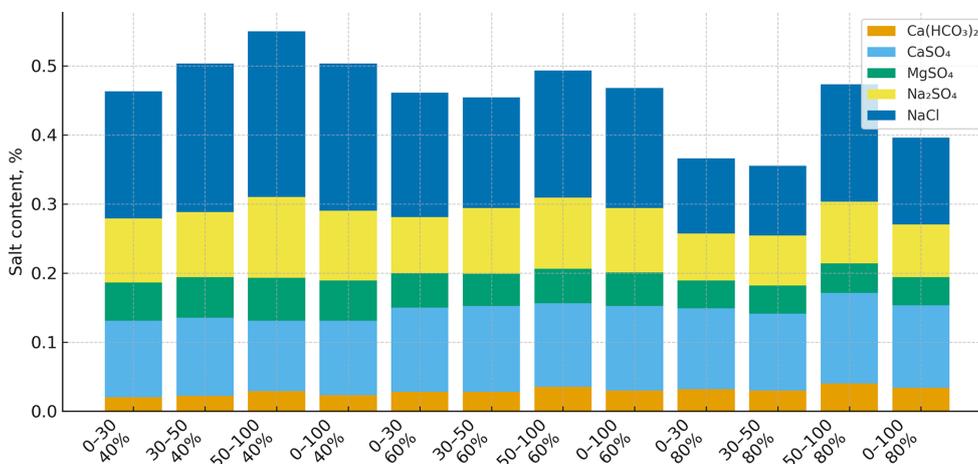


Figure 5. Ionic composition of water-soluble salts in meadow-alluvial soils at different depths and irrigation water supply levels at the end of the 2017 growing season

salts in the arable layer increased to 0.151%, and the proportion of high-impact salts decreased to 67.0%. In the 30–50 cm layer, the content of $\text{Ca}(\text{HCO}_3)_2$ and CaSO_4 increased to 0.201%, reflecting a partial leveling of the salt profile, although in the 50–100 cm layer the proportion of harmful salts remained high. The greatest decrease in the concentration of harmful salts in the upper layer was observed at 80% water supply: in the 0–30 cm layer, the content of low-impact salts was 0.151%, high-impact salts – 0.210%, while in the 50–100 cm layer, the proportion of harmful salts remained high, and the total mineralization reached 0.469%. The average total mineralization in the 0–100 cm layer decreased from 0.504% to 0.394% with increased water supply, indicating greater salt migration down the profile at higher irrigation rates. A similar pattern of

seasonal downward shift of the salt front under the influence of high irrigation rates was observed in experiments with winter wheat (Chen et al., 2022) and alfalfa on saline soils (Yang et al., 2019). In both cases, the authors noted that high water consumption leads to the accumulation of Na^+ and Mg^{2+} in the subsurface horizons (50–100 cm), which is consistent with our data for the meadow-alluvial soils of Karakalpakstan. This confirms that the efficiency of salt leaching into the lower layers at 80% water availability is a natural process characteristic of arid regions.

Irrigation with 40%, 60%, and 80% water-supply levels resulted in significant differences in cotton yield. The highest yield (30.4 c/ha) was obtained under the 80% water-supply regime (1–3–0 scheme). A three-year analysis of variance (ANOVA) confirmed statistically significant

differences among treatments ($F_{\text{fact}} = 21.63 > F_{0.05} = 3.33$, $p < 0.05$), and the least significant difference ($LSD_{0.05} = 1.08 \text{ c/ha}$) verified the reliability of these differences. However, the 80% regime was also associated with the greatest leaching losses of available K_2O and enhanced downward migration of high-impact Na^+ and Mg^{2+} salts. In contrast, the 60% regime produced only slightly lower yields but maintained a more balanced nutrient status in the root zone, reduced total mineralization in the upper soil layer, and lowered the risk of secondary salinization. Therefore, considering agrochemical stability, water-use efficiency, and ecological safety, the 60% water-supply level represents a more optimal long-term irrigation strategy than the high-input 80% regime.

These results are generally consistent with data from other researchers studying deficit irrigation in saline and semi-saline conditions, including studies on the impact of irrigation water quality and brackish irrigation on soil salinity and crop yield (Dinh et al., 2021; Rafik et al., 2023; Meiramkulova et al., 2024). It is emphasized that the optimal deficiency level depends on the degree of mineralization of the irrigation water and the depth of the groundwater table: with relatively low-salinity water, some experiments recommend regimes close to full water supply, while with higher salt concentrations, more stringent irrigation rate restrictions are required to prevent secondary salinization (Liu et al., 2024).

Our data fits well with this concept. Under Karakalpakstan conditions, using mineralized irrigation water and shallow saline groundwater, a 40% deficiency regime led to the concentration of mobile forms of NPK and salts in the upper horizons due to increased capillary rise and insufficient leaching effect of irrigation. However, at 80%, intensive leaching of high-impact salts from the arable layer and their accumulation in the deeper profile were observed, as well as a significant decrease in the content of available potassium. A similar trend in vertical salt redistribution under the influence of increased irrigation rates and the use of saline irrigation water was observed in field experiments with maize and other crops in arid regions (Lor Mohammad Hasani et al., 2024; Yuan et al., 2019). For cotton crop under drip irrigation with brackish water, it was shown that a combination of moderate moisture deficit and optimal doses of nitrogen and potassium allows for the maintenance of an acceptable soil salt regime

with high efficiency of water and fertilizer use (Min et al., 2014; Zhang et al., 2025).

Against this background, an intermediate irrigation regime of approximately 60% can be considered a hydrological and agrochemical compromise. It provides sufficient moisture content to limit capillary rise and prevent excessive concentrations of salts and mobile forms of NPK in the surface layer (as with 40% irrigation regime), but does not lead to pronounced potassium removal and other nutrient losses characteristic of the 80% regime. Similar conclusions about the advantages of moderate deficit irrigation compared to both severe deficit and excess water supply are presented in several publications on cotton and other crops under conditions of water deficit and secondary salinization (Lu et al., 2025; Min et al., 2014; Zhang et al., 2025).

These results demonstrate that maintaining a moderate deficit irrigation level of approximately 60% of the estimated water requirement ensures a balance between the leaching of harmful salts and the retention of essential nutrients in the root zone. Under saline irrigation conditions (3.7–5.1 g/L), this level reduced the total salt mineralization in the topsoil, prevented the intensive removal of available potassium into the soil profile, and ensured higher cotton productivity compared to the 40% and 80% water supply options.

CONCLUSIONS

A consistent relationship was established between water supply levels, the vertical distribution of available nutrients, and soil salinity parameters when using saline irrigation water. Increasing irrigation from 40% to 80% of the estimated water requirement led to a decrease in the content of mobile forms of NO_3-N , P_2O_5 , and K_2O in the 0–30 cm layer, while their concentration simultaneously increased in the 70–100 cm horizons. A stable vertical gradient in the availability of potassium was observed with increasing water supply. Changes in nitrate nitrogen and phosphorus were less pronounced.

Although the maximum cotton yield was achieved under the 80% water-supply regime, this treatment also intensified the leaching of available potassium from the arable layer and promoted the downward migration of high-impact salts. The 60% regime resulted in only a slight reduction in yield but maintained a more

balanced distribution of nutrients in the root zone, decreased total mineralization in the upper soil layer, and reduced the risk of secondary salinization. Therefore, from the standpoint of soil fertility preservation, water-use efficiency, and ecological sustainability, the 60% water-supply level can be considered the most optimal irrigation regime under saline water conditions.

From a long-term sustainability perspective, the accumulation of Na⁺ and Mg²⁺ ions in the 50–100 cm layer under the 80% regime may pose risks for subsoil properties, whereas the 60% water-supply level provides a more balanced compromise between salt leaching and nutrient retention in the root zone.

REFERENCES

- Abdullaev, I. (2010). Aral Sea Crisis: large-scale irrigation and its impact on drinking water quality and human health. *Asian Journal of Water, Environment and Pollution* 7(1), 63–69. https://doi.org/10.3233/AJW-2010-7_1_09
- Al-Khuzai M.M., Abdul Maulud K.N., Taib A.M. (2022). Soil salinity monitoring and quantification using modern techniques. *Journal of Ecological Engineering*, 23(11), 57–67. <https://doi.org/10.12911/22998993/152542>
- Alsanad, M.A. (2024). The environmental assessment of soil chemical properties irrigated with treated wastewater under arid ecosystem of Al-Ahsa, Saudi Arabia. *Arab Gulf Journal of Scientific Research*, 42(3), 976–990. <https://doi.org/10.1108/AGJSR-01-2023-0020>
- Barbagallo, M.G., Vesco, G., Di Lorenzo, R., Lo Bianco, R., Pisciotta, A. (2021). Soil and regulated deficit irrigation affect growth, yield and quality of ‘nero d’avola’ grapes in a semi-arid environment. *Plants (Basel)*, 28(10/4), 641. <https://doi:10.3390/plants10040641>
- Boru, G.W., Birhan, T.S., Beyene, T.L. (2024). Integrated effects of furrow irrigation systems and irrigation regimes on water productivity of onion (*Allium cepa* L.) crop in a semi-arid area. *Heliyon*, 10(21):e40098. <https://doi:10.1016/j.heliyon.2024.e40098>
- Chen, H., Ren, A., Hu, Z., Jia, C., Wang, J. (2022). Effects of irrigation and fertilization on soil salt migration, yield, and water use efficiency of winter wheat in the Yellow River Delta. *Crop Science*, 62(4), 1584–1602. <https://doi.org/10.1002/csc2.20753>
- Gafurova, L.A., Savin, I. Yu., Djalilova, G.T. (2024). Updating of soil map of mountainous regions of Uzbekistan. *Dokuchaev Soil Bulletin*, 118, 21–47. <https://doi.org/10.19047/0136-1694-2024-118-21-47>
- Dauletmuratov, M., Gafurova, L., Djalilova, G., Ergasheva, O., Xalmuratova, B., Umarov, M. (2024). Study on agrochemical information and analytical systems in irrigated agriculture. *E3S Web of Conferences*, 563, 03083. <https://doi.org/10.1051/e3sconf/202456303083>
- Díaz, F. J., et al. (2021). Effects of irrigation management on arid soils enzyme activities. *Journal of Arid Environments*, 185, 104330. <https://doi.org/10.1016/j.jaridenv.2020.104330>
- Dospekhov, B.A. (1985). Methods of field experiments (in Russian). Moscow: Agropromizdat. 351.
- Gharaibeh, M.A., Eltaif, N.I. (2014). Impact of water quality, cultivation, and cropping systems on infiltration and physical properties of an arid clay soil. *Soil and Water Research*, 9(3), 127–134. <https://doi.org/10.17221/20/2013-SWR>
- Hag Husein, H., Lucke, B., Bäumler, R., Sahwan, W. (2021). A contribution to soil fertility assessment for arid and semi-arid lands. *Soil Systems*, 5(3), 42. <https://doi: 10.3390/soilsystems5030042>
- Hamidov, A., Kasymov, U., Djumaboev, K., Pau, I.C. (2022). Rebound effects in irrigated agriculture in Uzbekistan: a stakeholder-based assessment. *Sustainability*, 14(14), 8375. <https://doi.org/10.3390/su14148375>
- Hasani, M. L., Talebnejad, R., Noshadi, M. (2024). Effect of deficit irrigation and irrigation water salinity on soil chemical properties in grain maize cultivation under tape drip irrigation system. *Iranian Journal of Soil and Water Research*, 55(3), 415–429. <https://doi.org/10.22059/ijswr.2023.363923.669562>
- Hashem, M.S., El-Abedin, T.Z. (2019). Rational water use by applying regulated deficit and partial root-zone drying irrigation techniques in tomato under arid conditions. *Chilean Journal of Agricultural Research*, 79(1), 75–86. <http://dx.doi.org/10.4067/S0718-58392019000100075>
- Jabbarov, Z., Kholdorov, Sh., Nomozov, U., Makhmadiyev, S., Djalilova, G., Abdullaev, Sh. (2025). The drying of the Aral Sea: Soil formation and restoration potential on the seabed. *Soil Science Annual* 76(2), 207727. <https://doi.org/10.37501/soilsa/207727>
- Koriyev, M., Mirzahmedov, I., Boymirzaev, K., Juraev, Z. (2025). Effects of mulching, terracing, and efficient irrigation on soil salinity reduction in Uzbekistan’s Fergana Valley. *Cogent Food & Agriculture*, 11(1). <https://doi.org/10.1080/23311932.2024.2449201>
- Lu, D., Liu, L., Bai, Y. An, Q., Cheng Y., Huang, G. (2025). Deficit irrigation alleviates the increase in soil salinity content in saline-alkali regions of China and improves irrigation water productivity: A meta-analysis. *Agricultural Water Management Volume*, 320, 109872. <https://doi.org/10.1016/j.agwat.2025.109872>

19. Measho, S., Li, F., Pellikka, P., Tian, C., Hirwa, H., Xu, N., Qiao, Y., Khasanov, S., Kulmatov, R., Chen G. (2022). Soil Salinity Variations and Associated Implications for Agriculture and Land Resources Development Using Remote Sensing Datasets in Central Asia. *Remote Sensing*, 14(10), 2501. <https://doi.org/10.3390/rs14102501>
20. Meiramkulova, K., Kydyrbekova, A., Kydyrbekova, A., Daldabayeva, G., Bauyrzhan, O., Shegenbayev, A., Khalkhabay, B., Baikenzheyeva, A., Bulanbayeva, P., Mkilima, T. (2024). Evaluating the long-term effects of recycled wastewater irrigation on soil health, crop yield, and ecological sustainability in arid regions. *Journal of Ecological Engineering*, 25(12), 10–25. <https://doi.org/10.12911/22998993/193079>
21. Ministry of Agriculture of the USSR. (1984a). Soils. Methods for determining total phosphorus and total potassium. Moscow.
22. Ministry of Agriculture of the USSR. (1984b). Soils. Methods for determination of total nitrogen. Moscow.
23. Mirzaqobulov, J., Mehta, K., Ilyas, S., Salokhiddinov, A. (2025). The role of collector–drainage water in sustainable irrigation for agriculture in the developing world: an experimental study. *World* 6(1), 1. <https://doi.org/10.3390/world6010001>
24. Qadir, M., Quillérou, E., Nangia, V., Murtaza, G., Singh, M. Thomas, R., Drechsler, P., Noble, A. (2014). Economics of salt-induced land degradation and restoration. *Natural Resources Forum*, 38(4), 282–295. <https://doi.org/10.1111/1477-8947.12054>
25. Rafik, F., Saber, N., Iben Halima, O., Douaik, A. (2023). The effects of the quality of irrigation water used on agricultural soils in coastal Chaouia, Morocco. *Journal of Ecological Engineering*, 24(2), 50–60. <https://doi.org/10.12911/22998993/156691>
26. Ruziyev, I.M., Yusupov, G.U., Djalilova, G.T., Igamberdiyeva, D.A., Kodirova, D.A. (2022). Development of geographic information system (gis) to change the level of soil salinity in Syrdarya region. *AIP Conference Proceedings*, 2432, 040041. <https://doi.org/10.1063/5.0097347>
27. Sainju, U.M., Liptzin, D. 2022. Relating soil chemical properties to other soil properties and dryland crop production. *Frontiers in Environmental Science*, 10(07). <https://doi.org/10.3389/fenvs.2022.1005114>
28. Soltani-Gerdefaramarzi, S., Alemzadeh, A., Yarami, N. et al. (2023). The effects of irrigation methods and water quality on soil chemical properties and leaf nutrient uptake of lavender (*lavandula angustifolia* L.) in an arid region. *Journal of Plant Growth Regulation*, 42, 1256–1265. <https://doi.org/10.1007/s00344-022-10627-z>
29. Sousa, M. G., Araujo, J. K. S., Ferreira, T. O., Andrade, G. R. P., Araújo Filho, J. C., Fracetto, G. G. M., et al. (2021). Long-term effects of irrigated agriculture on Luvisol pedogenesis in semi-arid region, northeastern Brazil. *Catena*, 206, 1–14. <https://doi.org/10.1016/j.catena.2021.105529>
30. Teklu, L. (2017). Effect of furrow irrigation methods and deficit levels on soil properties and yield of tomato (*Solanum lycopersicum* L.) at Dugda District, Central Rift Valley, Ethiopia. *International Journal of Engineering Research & Technology (IJERT)* 6/ 4. <https://doi.org/10.17577/IJERTV6IS040706>
31. Weldewahid, Y., Habtu, S., Taye, G., Teka, K., Gesesse, T.A. (2023). Effects of long-term irrigation practice on soil quality, organic carbon and total nitrogen stocks in the drylands of Ethiopia. *Journal of Arid Environments*, 214, 104982. <https://doi.org/10.1016/j.jaridenv.2023.104982>
32. Yan, Y., Shi, H., Miao, Q. et al. (2025). Evolution of chemical characteristics and irrigation suitability of groundwater in arid and semi-arid regions. *Agricultural Water Management*, 311, 109361. <https://doi.org/10.1016/j.agwat.2025.109361>
33. Yang H, An F, Yang F, Wang Z. (2019). The impact of irrigation on yield of alfalfa and soil chemical properties of saline-sodic soils. *PeerJ* 7:e7148. <https://doi.org/10.7717/peerj.7148>
34. Zeineldin, F.I., Al-Molhim, Y. (2021). Polymer and deficit irrigation influence on water use efficiency and yield of muskmelon under surface and subsurface drip irrigation. *Soil and Water Research*, 16(3), 191–203. <https://doi.org/10.17221/94/2020-SWR>