

Article

Seasonal And Spatial Hydrochemistry of Agricultural Collector-Drainage Water in The Navoi–Bukhara Irrigation Zone (Uzbekistan): Salinity, Sodicity, Fluoride and Boron As Constraints on Reuse

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Abstract : Collector-drainage water (CDW) from irrigated agriculture is a large but under-used water source in the arid lower reaches of Central Asian river basins, yet its seasonal composition is rarely documented at the resolution needed for reuse planning. This study characterised the seasonal and spatial hydrochemistry of CDW in a collector of the Navoi–Bukhara irrigation zone (Uzbekistan). Samples were collected at three sites along the collector during four agronomic periods of 2025 (winter leaching, spring, summer vegetation irrigation and autumn) and analysed for more than 20 parameters. At the outlet site, total dissolved solids (TDS) ranged from 2.8 to 7.2 g L⁻¹ and specific conductance (κ_{25}) from 4.2 to 9.8 mS cm⁻¹. The water was of sulfate–chloride sodium type in all seasons (Na⁺ 62–68 % of cation equivalents; sodium adsorption ratio 9.2–18.2), with Na⁺/Cl⁻ equivalent ratios above unity. Salinity, hardness, fluoride (up to 4.8 mg L⁻¹) and boron (up to 3.5 mg L⁻¹) peaked during winter leaching, whereas summer irrigation diluted the salts but raised phosphate (4.5 mg L⁻¹) and chemical oxygen demand (COD, 110 mg O₂ L⁻¹). The nearly constant F⁻/TDS (0.67–0.75 mg g⁻¹) and B/TDS (0.43–0.49 mg g⁻¹) ratios point to a common geogenic origin of fluoride, boron and salts. Along the collector, salinity and fluoride increased downstream while phosphate, nitrate and COD decreased despite rising salinity, indicating in-channel attenuation. Heavy metals occurred at trace levels (≤ 0.045 mg L⁻¹). Salinity, chloride, sodium, fluoride and boron exceeded FAO irrigation guidelines in every season, and phosphate and COD exceeded national limits. κ_{25} was linearly related to TDS ($r = 0.999$), supporting low-cost conductivity monitoring as a real-time proxy for the salinity-, fluoride- and boron-dominated leaching regime. The governing constraint on reuse thus shifts from geogenic contaminants in winter–spring to agrochemical contaminants in summer, which must be reflected in any treatment or reuse scheme.

Keywords: collector-drainage water; seasonal variability; hydrochemical facies; sodium adsorption ratio; fluoride; boron; irrigation water quality; Aral Sea basin

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1. Introduction

Irrigated agriculture in the Aral Sea basin withdraws most of the available surface water of the Amu Darya and Syr Darya systems, and a large share of this water returns to the river network or to terminal depressions as collector-drainage water (CDW). In the lower reaches of Uzbekistan — the Bukhara, Navoi and Khorezm provinces and the Republic of Karakalpakstan — CDW is at the same time a major pollution source for rivers and lakes and a potentially important water reserve in a region facing chronic freshwater deficits [1][2][3][4]. Long-term monitoring shows rising groundwater and drainage-water mineralisation across the irrigated zones of the country, driven by shallow saline water tables, repeated leaching and intensive fertiliser use [5][6][7].

CDW combines geogenic contaminants mobilised from saline soils and aquifers — high TDS and hardness, fluoride, boron and dissolved silica — with agrochemical residues such as phosphate, nitrogen compounds and organic matter. Its safe reuse for irrigation is therefore limited not only by salinity but also by sodicity, by specific-ion toxicity (boron, chloride, fluoride) and by nutrient and organic loads that affect receiving waters [8],[9].

Existing assessments of CDW in Uzbekistan are largely based on annual means of mineralisation or on a small number of routinely monitored parameters. What remains poorly quantified is how the full composition of CDW varies over the agricultural year and along a collector. Leaching, fertilisation and vegetation irrigation are expected to change not only the salinity of CDW but also the identity of the contaminants that limit its reuse, and these changes determine whether a treatment scheme — from membrane desalination [10] to electrocoagulation [11] — must be designed for a single dominant pollutant or for a seasonally shifting set. The implications of the present data for electrocoagulation treatment are analysed in a companion paper [12].

The objectives of this study were therefore (i) to characterise the seasonal hydrochemistry of CDW at the outlet of a representative collector of the Navoi–Bukhara irrigation zone over four agronomic periods; (ii) to describe the downstream evolution of salinity, fluoride and agrochemical indicators along the collector; (iii) to identify the hydrochemical facies, sodicity and likely origin of fluoride and boron; and (iv) to evaluate compliance with irrigation and discharge criteria and to assess whether conductivity can serve as a real-time monitoring proxy.[13]

2. Materials and Methods

The study was carried out on a collector-drainage network in the Navoi–Bukhara irrigation zone, Uzbekistan. The area has an arid continental climate in which potential evaporation greatly exceeds precipitation. Irrigated soils are moderately to strongly saline, and irrigation water is supplied from the Zarafshan River and, via canal transfer, from the Amu Darya. Three sampling sites, located by GPS, were selected to represent the downstream evolution of drainage water (Fig. 1): **D1**, the head of the collector, receiving fresh field drainage (40°12'34" N, 65°20'15" E); **D2**, the middle (transit) reach, where several laterals merge (40°08'45" N, 65°15'30" E); and **D3**, the outlet reach upstream of the discharge point, where drainage from the whole command area has accumulated (40°02'10" N, 65°08'50" E). The straight-line distance between D1 and D3 is about 25 km. D3 was used as the reference site because it integrates the drainage of the whole command area.[14]

Samples were collected in 2025 during four periods that correspond to the main agronomic operations of the region (Table 1). At each site, water was sampled from 20–30 cm below the surface of the flowing collector. Sampling, preservation and transport followed ISO 5667-3 [13]. Aliquots for metals were collected in 0.5 L polyethylene (PE) bottles and acidified to pH < 2 with high-purity HNO₃; aliquots for COD and ammonium were acidified to pH < 2 with H₂SO₄. Aliquots for fluoride and boron were collected in PE bottles, filled without headspace, to avoid contamination from borosilicate glass. All samples were transported in insulated containers with ice packs at about 4 °C and analysed within the recommended holding times.[15]

Table 1. Sampling campaigns and their agronomic context.

Period	Months	Agronomic operations and hydrological context	Sampling date
Winter / early spring	Feb–Mar	Pre-sowing capital leaching of saline soils; low water temperature	15 Feb 2025
Spring	Apr–May	Sowing; first light irrigations	12 May 2025

Period	Months	Agronomic operations and hydrological context	Sampling date
Summer	Jul–Aug	Peak vegetation irrigation and fertiliser application; maximum drainage discharge	18 Aug 2025
Autumn	Oct–Nov	Harvest and post-harvest period; irrigation discontinued	10 Nov 2025

Water temperature (T), pH, dissolved oxygen (DO) and electrical conductivity were measured in situ with a portable multiparameter meter (HQ40d, Hach, USA; The instrument was calibrated before each field campaign with standard buffers and conductivity standards. Conductivity is reported as specific conductance at 25 °C (κ_{25}), obtained with the instrument's linear temperature compensation ($\alpha = 0.02 \text{ }^{\circ}\text{C}^{-1}$) [14–15]. Note that $1 \text{ mS cm}^{-1} = 1 \text{ dS m}^{-1}$.

Laboratory analyses followed Standard Methods and the ISO methods listed in Table 2. Each sample was analysed in triplicate. TDS was determined gravimetrically after filtration through a $0.45 \mu\text{m}$ membrane filter and drying of the filtrate at $105 \text{ }^{\circ}\text{C}$ to constant mass. Sulfate was determined turbidimetrically as BaSO_4 at 420 nm, Na^+ and K^+ by flame photometry (PFP7, Jenway, UK), and HCO_3^- and CO_3^{2-} by titration with 0.05 N HCl to the phenolphthalein and methyl orange end-points. Samples with high concentrations were diluted into the linear range of each method. For COD, mercury(II) sulfate was added to suppress chloride interference, because chloride concentrations reached 1500 mg L^{-1} .

Table 2. Analytical methods and limits of detection (LOD).

Parameter	Method	Instrument	Reference	LOD (mg L^{-1})
T, pH, DO, κ_{25}	Electrometric / luminescent sensors, in situ	Hach HQ40d	APHA 4500-H ⁺ B; 2510 B	—
TDS	Gravimetric; $0.45 \mu\text{m}$ filtration, $105 \text{ }^{\circ}\text{C}$	Analytical balance	cf. APHA 2540 C ^a	—
Total hardness, Ca^{2+}	EDTA titration, Eriochrome Black T	—	APHA 2340 C; 3500-Ca B	—
Na^+ , K^+	Flame photometry	Jenway PFP7	APHA 3500-Na B	—
Cl^-	Argentometric (Mohr)	—	APHA 4500- Cl^- B	—
HCO_3^- , CO_3^{2-}	Titration, 0.05 N HCl; phenolphthalein / methyl orange	—	APHA 2320 B	—
SO_4^{2-}	Turbidimetric (BaSO_4), 420 nm	UV-Vis	APHA 4500- SO_4^{2-} E	—
F^-	SPADNS, 580 nm	UV-Vis	APHA 4500-F ⁻ D	0.02
B	Azomethine-H, 420 nm	UV-Vis	ISO 9390 [16]	0.05

Parameter	Method	Instrument	Reference	LOD (mg L ⁻¹)
PO ₄ ³⁻	Ascorbic acid– molybdenum blue, 880 nm	UV-Vis	APHA 4500-P E	0.01
NO ₃ ⁻	UV spectrophotometric, 220/275 nm	UV-Vis	APHA 4500-NO ₃ ⁻ B	—
SiO ₂	Heteropoly blue, 815 nm	UV-Vis	APHA 4500-SiO ₂ D	—
COD	Dichromate oxidation with HgSO ₄ , closed reflux, colorimetric	UV-Vis	APHA 5220 D	—
Cu, Zn, Ni, Cr, Pb	AAS, graphite furnace	Shimadzu 7000	AA- APHA 3113 B	0.001– 0.005

^a APHA 2540 C specifies drying at 180 °C; at 105 °C gypsum-rich residues retain water of crystallisation, so TDS may be slightly overestimated.

Reagent blanks, calibration standards and certified reference materials were analysed with each batch, and calibration curves had coefficients of determination ≥ 0.995 . The accuracy of the major-ion analyses was checked by the charge balance error (CBE):

$$\text{CBE (\%)} = (\Sigma \text{cations} - \Sigma \text{anions}) / (\Sigma \text{cations} + \Sigma \text{anions}) \times 100 \quad (1)$$

where the ion sums are expressed in meq L⁻¹. Analyses were accepted when $|\text{CBE}| < 5 \%$.

Measured concentrations were compared with the FAO guidelines for irrigation water quality [16] for salinity (κ , TDS), specific-ion toxicity (chloride, boron) and trace elements (fluoride, heavy metals), and with the national limits [17] for sulfate, phosphate, COD and hardness. The degree of non-compliance was expressed as an exceedance factor, $\text{EF} = \text{C}/\text{C}_{\text{lim}}$. Sodium hazard was assessed with the sodium adsorption ratio:

$$\text{SAR} = \text{Na}^+ / [(\text{Ca}^{2+} + \text{Mg}^{2+})/2]^{1/2} \quad (2)$$

with concentrations in meq L⁻¹. SAR was interpreted jointly with the electrical conductivity of the water (EC_w) for infiltration hazard, and separately for sodium toxicity under surface irrigation.

To discriminate between sources, the equivalent ratio Na^+/Cl^- and the mass ratios F/TDS and B/TDS were calculated for each season. Results are reported as mean $\pm$ standard deviation of triplicate analyses. Differences among seasons were tested by one-way ANOVA followed by Tukey's HSD test ($\alpha = 0.05$), and linear relationships were assessed by Pearson correlation and least-squares regression. Hydrochemical facies were identified from the equivalent proportions of the major ions; a Piper diagram and mineral saturation indices calculated with PHREEQC [19] will be added once Ca^{2+} and Mg^{2+} are reported separately (both are available from the EDTA titrations).

3. Results

The composition of CDW at the outlet site D3 changed markedly over the agricultural year (Table 3; Fig. 2). All parameters in Table 3 differed significantly among the four periods (one-way ANOVA, $F(3, 8)$ between 10.7 for pH and 238 for TDS; $p < 0.01$). The highest salinity occurred during winter leaching: TDS reached $7.2 \pm 0.3 \text{ g L}^{-1}$ and κ_{25} $9.8 \pm 0.4 \text{ mS cm}^{-1}$, i.e. 2.6 and 2.3 times the summer minima (2.8 g L^{-1} and 4.2 mS cm^{-1}). Total hardness ($32.5 \rightarrow 14.2 \text{ meq L}^{-1}$), sulfate ($2800 \rightarrow 1100 \text{ mg L}^{-1}$), chloride ($1500 \rightarrow 358 \text{ mg L}^{-1}$) and dissolved silica ($48.5 \rightarrow 22.1 \text{ mg L}^{-1}$) followed the same winter-maximum, summer-minimum pattern, with spring and autumn intermediate.

Fluoride and boron were likewise highest during leaching (4.8 ± 0.3 and $3.5 \pm 0.2 \text{ mg L}^{-1}$) and lowest in summer (2.1 and 1.2 mg L^{-1}). The agrochemical indicators behaved in

the opposite way: phosphate rose from 1.2–2.0 mg L⁻¹ in the other periods to 4.5 ± 0.3 mg L⁻¹ in summer, and COD from 45–60 to 110 ± 8 mg O₂ L⁻¹. pH remained slightly alkaline throughout (7.6–8.2), with its maximum in summer.[16]

Table 3. Seasonal physicochemical composition of collector-drainage water at the outlet site D3 (mean ± SD, n = 3) and water-quality criteria.

Parameter (unit)	Winter (leaching)	Spring	Summer	Autumn	FAO irrigation [8]	National limit ^a [17]
T (°C)	8.5 ± 1.2	18.4 ± 1.5	28.6 ± 1.8	14.2 ± 1.1	—	—
pH	7.6 ± 0.1	7.8 ± 0.1	8.2 ± 0.2	7.9 ± 0.1	6.5–8.4	6.5–8.5
κ ₂₅ (mS cm ⁻¹)	9.8 ± 0.4	7.5 ± 0.3	4.2 ± 0.2	5.8 ± 0.2	> 3.0 severe	—
TDS (g L ⁻¹)	7.2 ± 0.3	5.2 ± 0.2	2.8 ± 0.1	3.9 ± 0.2	> 2.0 severe	1.0–1.5
Total hardness (meq L ⁻¹)	32.5 ± 1.5	25.0 ± 1.1	14.2 ± 0.8	18.6 ± 1.0	—	≤ 10.0
SO ₄ ²⁻ (mg L ⁻¹)	2800 ± 120	1750 ± 90	1100 ± 60	1450 ± 85	—	500
Cl ⁻ (mg L ⁻¹)	1500 ± 85	980 ± 55	358 ± 21	820 ± 45	> 355 severe ^b	350
F ⁻ (mg L ⁻¹)	4.8 ± 0.3	3.8 ± 0.2	2.1 ± 0.1	2.9 ± 0.1	1.0	1.5 ^c
B (mg L ⁻¹)	3.5 ± 0.2	2.4 ± 0.1	1.2 ± 0.1	1.8 ± 0.1	0.7 ^d	0.5–1.0
SiO ₂ (mg L ⁻¹)	48.5 ± 3.2	35.4 ± 2.5	22.1 ± 1.8	31.0 ± 2.1	—	—
PO ₄ ³⁻ (mg L ⁻¹)	1.2 ± 0.1	1.5 ± 0.1	4.5 ± 0.3	2.0 ± 0.2	—	0.2
COD (mg O ₂ L ⁻¹)	45 ± 4	60 ± 5	110 ± 8	55 ± 5	—	30

^aLimits of the national standard for water quality. ^b Surface irrigation, 10 meq L⁻¹. ^c Equal to the WHO drinking-water guideline value. ^d Threshold above which injury to sensitive crops is expected; > 3.0 mg L⁻¹ = severe restriction. ^e Spatial data for D1 and D2 are given in Table S1.

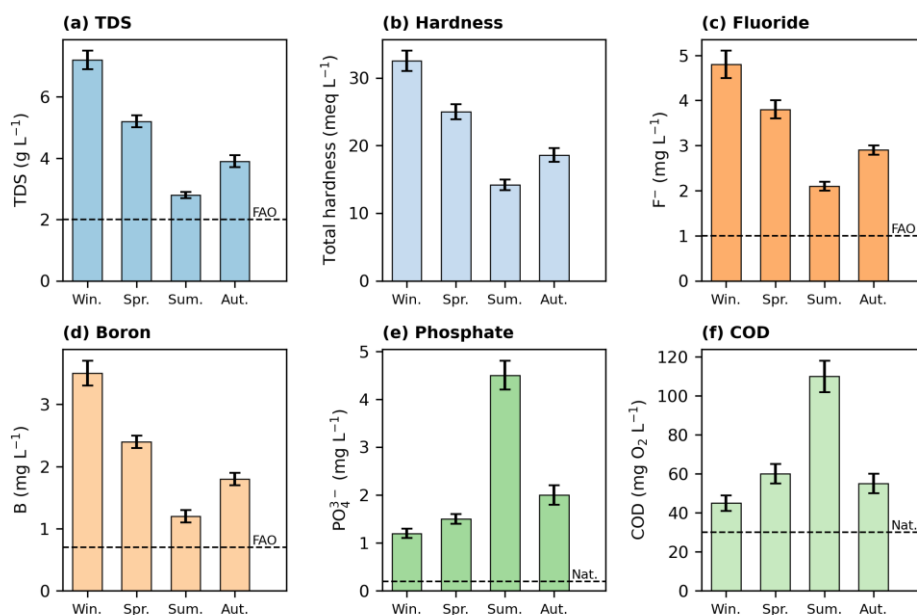


Figure 2. Seasonal variation of (a) TDS, (b) total hardness, (c) fluoride, (d) boron, (e) phosphate and (f) COD at the outlet site D3 (mean $\pm$ SD, $n = 3$). Dashed lines: FAO irrigation guideline (a, c, d; for boron, the threshold for sensitive crops) or national limit (e, f). Win. = winter leaching; Spr. = spring; Sum. = summer; Aut. = autumn.

The full major-ion composition at D3 is given in Table 4 and Fig. 3a. The charge balance error was 0.46–1.34 % in all periods, well within the 5 % acceptance limit. Sodium was the dominant cation throughout, contributing 62–68 % of the cation equivalents, while $\text{Ca}^{2+} + \text{Mg}^{2+}$ accounted for 30–36 % and K^{+} for about 2 %. Sulfate was the dominant anion (47–59 %), followed by chloride; bicarbonate was a minor anion except in spring, when it reached 12.8 meq L^{-1} (17 % of anions). The water is therefore of a sulfate–chloride sodium type in all seasons, with the total ion concentration changing by a factor of about 2.7 between winter and summer while the ionic proportions remain broadly similar.[17]

SAR followed salinity, from 9.2 in summer to 18.2 during leaching (Table 4). Because EC_w was also high, all samples fall in the "no reduction in infiltration" field of the FAO SAR– EC_w diagram (Fig. 3b): the high electrolyte concentration counteracts the dispersive effect of sodium. However, SAR exceeded 9 in every season, which places the water in the severe class for sodium toxicity to sensitive crops under surface irrigation, and the infiltration hazard would re-emerge if the water were partly desalinated or diluted without a matching reduction in SAR.

Table 4. Major-ion balance and sodium adsorption ratio at site D3 (meq L^{-1} ; mean $\pm$ SD, $n = 3$).

Parameter	Winter (leaching)	Spring	Summer	Autumn
Na^{+}	73.5 ± 3.2	52.4 ± 2.1	24.5 ± 1.5	38.2 ± 2.0
K^{+}	2.1 ± 0.1	1.5 ± 0.1	0.8 ± 0.05	1.2 ± 0.1
$\text{Ca}^{2+} + \text{Mg}^{2+}$	32.5 ± 1.5	25.0 ± 1.1	14.2 ± 0.8	18.6 ± 1.0
Σ cations	108.1	78.9	39.5	58.0
SO_4^{2-}	58.3 ± 2.5	36.4 ± 1.8	22.9 ± 1.2	30.2 ± 1.5
Cl^{-}	42.3 ± 2.0	27.6 ± 1.5	10.1 ± 0.6	23.1 ± 1.2
HCO_3^{-}	6.5 ± 0.3	12.8 ± 0.5	5.5 ± 0.2	3.8 ± 0.2
Σ anions	107.1	76.8	38.5	57.1

Parameter	Winter (leaching)	Spring	Summer	Autumn
CBE (%)	0.46	1.34	1.28	0.78
Na ⁺ share of cations (%)	68.0	66.4	62.0	65.9
SAR	18.2	14.8	9.2	12.5

CO₃²⁻ was not detected (below the phenolphthalein end-point).

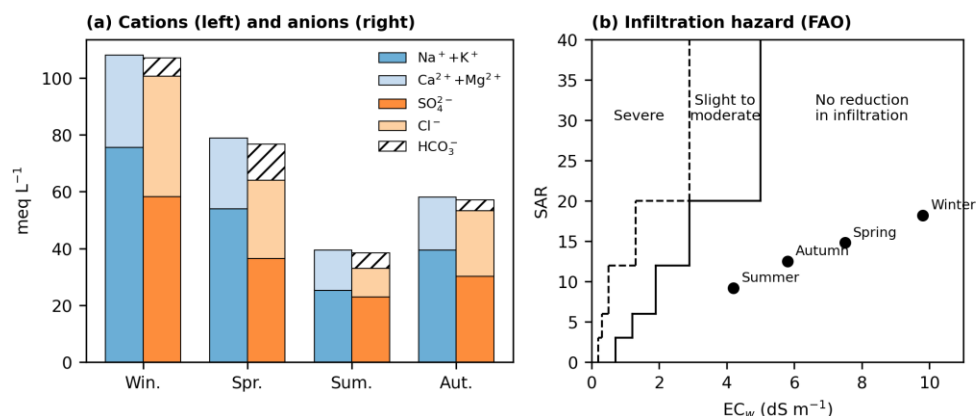


Figure 3. (a) Major cation and anion equivalents at site D3 by season. (b) Seasonal samples on the FAO diagram of infiltration hazard as a function of SAR and EC_w; solid line: upper limit of the slight-to-moderate field; dashed line: upper limit of the severe field.

The ratios in Table 5 describe how the proportions of the constituents changed while the total concentration varied 2.6-fold. The mass ratios F/TDS (0.67–0.75 mg g⁻¹) and B/TDS (0.43–0.49 mg g⁻¹) were nearly constant across seasons, and fluoride and boron were strongly correlated with TDS ($r = 0.996$, $p = 0.005$ and $r = 0.999$, $p < 0.001$, respectively; $n = 4$). The Na⁺/Cl⁻ equivalent ratio exceeded unity in every season (1.65–2.43), with the highest value in summer, indicating a sodium excess over chloride.

Table 5. Ionic ratios at site D3.

Ratio	Winter (leaching)	Spring	Summer	Autumn
F/TDS (mg g ⁻¹)	0.67	0.73	0.75	0.74
B/TDS (mg g ⁻¹)	0.49	0.46	0.43	0.46
Na ⁺ /Cl ⁻ (eq eq ⁻¹)	1.74	1.90	2.43	1.65
Cl ⁻ /SO ₄ ²⁻ (mol mol ⁻¹)	1.45	1.52	0.88	1.53

Calculated from Tables 3 and 4.

Heavy metals were detected in all seasons but at trace concentrations. Zinc and nickel were stable at 0.020–0.035 mg L⁻¹, and lead ranged from 0.005 to 0.012 mg L⁻¹. Copper increased from 0.015 mg L⁻¹ in spring to 0.045 mg L⁻¹ in summer, and chromium reached 0.025 mg L⁻¹ in summer. All values were one to three orders of magnitude below the FAO recommended maxima for irrigation water (Cu 0.20, Zn 2.0, Ni 0.20, Cr 0.10 and Pb 5.0 mg L⁻¹).

The summer survey along the collector (Table S1) revealed opposite trends for geogenic and agrochemical constituents. From D1 to D3, TDS increased from 1.9 to 2.8 g L⁻¹ and κ_{25} from 3.0 to 4.2 mS cm⁻¹, and fluoride rose from 1.2 to 2.1 mg L⁻¹, i.e. faster than TDS (F/TDS from 0.63 to 0.75 mg g⁻¹). Conversely, phosphate decreased from 7.2 to 4.5

mg L⁻¹ (-38 %), nitrate from 45.6 to 24.0 mg L⁻¹ (-47 %) and COD from 135 to 110 mg O₂ L⁻¹ (-19 %). Because salinity increased downstream, these decreases cannot be explained by dilution. Spatial sampling was carried out in the summer period only.

In all four periods κ_{25} exceeded 3.0 dS m⁻¹ and TDS exceeded 2000 mg L⁻¹, placing CDW in the "severe restriction" salinity class of the FAO guidelines [8]. Chloride was above the 10 meq L⁻¹ severe-toxicity threshold for surface irrigation throughout. Fluoride exceeded the FAO recommended maximum of 1.0 mg L⁻¹ by a factor of 2.1–4.8, and boron exceeded the 0.7 mg L⁻¹ threshold for sensitive crops by a factor of 1.7–5.0, reaching the severe class (> 3.0 mg L⁻¹) during leaching. SAR (9.2–18.2) exceeded the severe sodium-toxicity threshold for surface irrigation in every period, whereas trace metals were far below the FAO limits. Relative to the national limits, phosphate exceeded the criterion 6–23-fold and COD 1.5–3.7-fold, with the largest exceedances in summer. No period therefore produced water suitable for unrestricted reuse or direct discharge; the governing contaminants, however, changed from salinity, fluoride and boron in winter–spring to phosphate and COD in summer (Table 6).

Table 6. Exceedance factors (EF = C/C_{lim}) at site D3.

Constituent (criterion)	Winter (leaching)	Spring	Summer	Autumn
TDS (FAO severe, 2.0 g L ⁻¹)	3.6	2.6	1.4	2.0
F ⁻ (FAO, 1.0 mg L ⁻¹)	4.8	3.8	2.1	2.9
B (FAO sensitive crops, 0.7 mg L ⁻¹)	5.0	3.4	1.7	2.6
PO ₄ ³⁻ (national, 0.2 mg L ⁻¹)	6.0	7.5	22.5	10.0
COD (national, 30 mg O ₂ L ⁻¹)	1.5	2.0	3.7	1.8

κ_{25} and TDS were linearly related (Fig. 4):

$$\text{TDS (g L}^{-1}\text{)} = 0.788 \kappa_{25} \text{ (mS cm}^{-1}\text{)} - 0.60, \quad r = 0.999, \quad p = 0.0015, \quad n = 4 \quad (3)$$

with TDS/ κ_{25} ratios of 0.67–0.73, in the upper part of the range typical of natural waters, as expected for sulfate-dominated water. κ_{25} was equally closely correlated with total hardness ($r = 0.999$), fluoride ($r = 0.999$), boron ($r = 0.997$) and silica ($r = 0.991$; all $p < 0.01$), whereas its relationships with phosphate ($r = -0.86$, $p = 0.14$) and COD ($r = -0.82$, $p = 0.18$) were negative and not significant. Total hardness was also closely correlated with sulfate ($r = 0.974$, $p = 0.026$), consistent with the dissolution of calcium and magnesium sulfates (gypsum) during leaching. Because these coefficients are based on the four seasonal means at D3, they should be regarded as indicative.

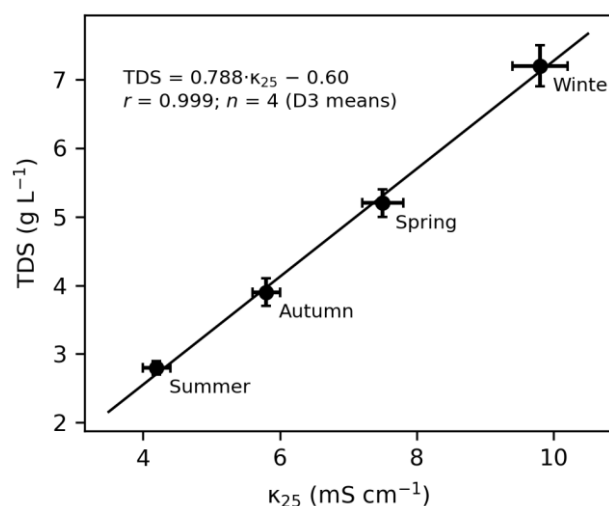


Figure 4. Relationship between specific conductance (κ_{25}) and TDS at the outlet site D3 (seasonal means $\pm$ SD).

4. Discussion

The pronounced seasonal variation in collector-drainage water (CDW) chemistry demonstrates that the agricultural calendar is a major control on water quality in the Navoi–Bukhara irrigation zone. The highest TDS, electrical conductivity, hardness, sulfate, chloride, fluoride, and boron concentrations occurred during winter leaching, whereas their lowest concentrations were generally observed during the summer irrigation period. This pattern is consistent with the mobilisation of salts accumulated in saline soils and shallow groundwater during intensive pre-sowing leaching. In arid irrigated regions, repeated evaporation and limited natural drainage promote salt accumulation within the soil profile, which can subsequently be flushed into collector systems during leaching events. Similar salinity problems have been reported for irrigated areas of Uzbekistan and the wider Aral Sea Basin [5], [6], [7]. The approximately 2.6-fold seasonal variation in TDS therefore reflects not merely changes in water volume but the interaction between irrigation management, soil salinity, groundwater conditions, and seasonal drainage processes.

Despite these large seasonal changes in total dissolved-ion concentration, the ionic composition remained relatively stable, with sodium contributing 62–68% of cation equivalents and sulfate remaining the dominant anion. Consequently, the CDW retained a sulfate–chloride sodium hydrochemical character throughout the year. This stability suggests that the same underlying geochemical processes continue to control the major-ion composition even when dilution and concentration vary seasonally. The Na^+/Cl^- equivalent ratio was consistently greater than unity (1.65–2.43), indicating an excess of sodium that cannot be explained solely by chloride-associated salts. Such behaviour may reflect contributions from sodium-bearing mineral weathering, ion exchange, or dissolution of salts stored in the soil–groundwater system. The close relationship between hardness and sulfate ($r = 0.974$, $p = 0.026$) further supports the contribution of calcium- and magnesium-sulfate minerals, including gypsum, to the mineralisation of the drainage water.

Fluoride and boron provide additional evidence that geogenic processes are important controls on CDW quality. Their concentrations closely followed TDS across seasons, while F^-/TDS and B/TDS ratios remained within narrow ranges of 0.67–0.75 mg g^{-1} and 0.43–0.49 mg g^{-1} , respectively. Moreover, fluoride and boron were strongly correlated with TDS ($r = 0.996$ and $r = 0.999$, respectively). These relationships indicate that both constituents are mobilised together with the dissolved mineral load rather than being primarily associated with seasonal agricultural inputs. The downstream increase in fluoride from 1.2 to 2.1 mg L^{-1} during summer, accompanied by an increase in TDS from 1.9 to 2.8 g L^{-1} , further supports progressive geogenic enrichment along the collector. This

finding is important for reuse planning because reducing nutrient inputs alone would not eliminate fluoride and boron constraints; treatment or blending strategies must also address the mineralised component of the drainage water.

In contrast to the geogenic constituents, phosphate and COD displayed a clear summer maximum, reaching 4.5 mg L^{-1} and $110 \text{ mg O}_2 \text{ L}^{-1}$, respectively. This opposite seasonal pattern is consistent with the period of peak vegetation irrigation and fertiliser application identified in the sampling design. The simultaneous reduction of phosphate, nitrate, and COD from D1 to D3, despite increasing salinity downstream, is particularly significant because it excludes simple dilution as the main explanation. Instead, the pattern indicates in-channel attenuation through processes that may include sediment adsorption, biological uptake, microbial transformation, and degradation of organic matter. Phosphate declined by approximately 38%, nitrate by 47%, and COD by 19% between D1 and D3 during the summer survey. Nevertheless, because spatial sampling was conducted only in summer, the persistence and magnitude of these attenuation processes during other seasons remain uncertain and should be tested through year-round longitudinal monitoring. 17071_Naskah_Utama

The irrigation implications are substantial because no sampled season produced CDW suitable for unrestricted reuse. TDS and conductivity remained within the FAO severe-restriction salinity category, while chloride, fluoride, boron, and SAR also exceeded relevant irrigation thresholds. SAR ranged from 9.2 to 18.2, indicating a considerable sodium-toxicity concern, even though the simultaneously high electrolyte concentrations placed the samples in the FAO field associated with little immediate reduction in infiltration. This distinction has practical importance: desalination or dilution could reduce salinity while potentially exposing soil-structure problems if SAR is not reduced proportionally. Therefore, treatment decisions should consider salinity and sodicity jointly rather than relying on TDS reduction alone. The very low heavy-metal concentrations, by comparison, indicate that trace metals are not currently the principal limitation to agricultural reuse.

Finally, the strong linear relationship between specific conductance and TDS ($r = 0.999$) provides a practical basis for low-cost, continuous monitoring of the collector system. Conductivity was also strongly associated with hardness, fluoride, boron, and silica, indicating that an online conductivity sensor could provide an effective operational proxy for the geogenic mineralisation regime. However, its negative and statistically non-significant relationships with phosphate and COD show that conductivity cannot adequately represent summer agrochemical and organic pollution. Accordingly, an effective monitoring system should combine continuous conductivity measurements with periodic or sensor-based monitoring of nutrient and organic-load indicators. The results therefore reveal a seasonally shifting management problem: winter–spring treatment should prioritise salinity, sodicity, fluoride, and boron, whereas summer management requires additional attention to phosphate and organic loads. This seasonal distinction provides a stronger basis for designing adaptive treatment, blending, and reuse strategies than management based solely on annual mean water-quality values.

5. Conclusion

The composition of collector-drainage water in the Navoi–Bukhara irrigation zone is governed by the agricultural calendar. Winter leaching produces the highest salinity (TDS 7.2 g L^{-1} , κ_{25} 9.8 mS cm^{-1}), hardness, fluoride (4.8 mg L^{-1}) and boron (3.5 mg L^{-1}), whereas summer irrigation dilutes the salts but raises phosphate (4.5 mg L^{-1}) and COD ($110 \text{ mg O}_2 \text{ L}^{-1}$). The water is of sulfate–chloride sodium type throughout (SAR 9.2–18.2), with a sodium excess over chloride.

Fluoride and boron are of geogenic origin: their ratios to TDS are nearly constant across seasons and both correlate with salinity rather than with agrochemical indicators. Along the collector, salinity and fluoride increase downstream while phosphate, nitrate and COD are attenuated, which makes the outlet reach the preferred abstraction point for treatment.

In every period, salinity, chloride, sodium, fluoride and boron exceeded FAO irrigation guidelines and phosphate and COD exceeded national limits, so CDW cannot be reused or discharged without treatment or blending; heavy metals were at trace levels. The governing contaminants shift from geogenic (winter–spring) to agrochemical (summer). Continuous conductivity logging can track the salinity-, fluoride- and boron-dominated regime in real time but must be complemented by an organic-load indicator in summer.

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