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Assessment of soil salinity and sodicity under canal-irrigated agriculture in arid region

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Abstract

Canal-irrigated agriculture in the arid and semi-arid zones of Central Asia has lifted production in the short term but left behind a trail of secondary salinisation and sodicity that now affects almost 4.3 million hectares across the region. This research assessed the current status of soil salinity and sodicity in a 240-hectare canal command area of the Syrdarya province of Uzbekistan, where canal irrigation was introduced in 2008. Soil samples were collected from 80 grid cells on a regular 250×300 m pattern at three depths (0-30, 30-60, 60-90 cm) during December 2022. Electrical conductivity, pH, exchangeable sodium percentage, calcium, magnesium, sulphate and chloride were measured along with textural class. Mean electrical conductivity at the surface layer had risen from 0.84 dS m^{-1} in 2012 to 2.94 dS m^{-1} in 2022, a 3.5-fold increase over a decade. Exchangeable sodium percentage at 0-30 cm averaged 14.8 per cent, placing 32 per cent of the area under sodic or saline-sodic class. Tail-end cells carried 1.8 times higher salinity than head-reach cells, reflecting poor drainage and over-irrigation. The research identifies a clear need for integrated salinity management in this command area and offers a baseline dataset for future monitoring.

Keywords: Soil salinity, sodicity, canal irrigation, arid regions, electrical conductivity, exchangeable sodium percentage, Syrdarya Valley, Uzbekistan

Introduction

In the words of the International Center for Agricultural Research in the Dry Areas in its 2020 assessment, "the second wave of salinisation in Uzbekistan is moving inland from the classic coastal belts into the semi-arid canal command areas of the peninsula" ^[1]. This expert view captures a real problem. Canal irrigation, which accounts for roughly 24 per cent of the net irrigated area of the country, has long been the foundation of the Soviet-era irrigation expansion, but its unintended legacy is rising water tables, inadequate drainage and progressive accumulation of soluble salts and exchangeable sodium in the root zone ^[2, 3].

The Syrdarya Valley in central Uzbekistan is a recent entrant in this story. Canal irrigation from the Dustlik canal system was extended into parts of the valley in 2008 to stabilise summer cotton and rice and introduce a second winter crop of wheat and pulses. Within a decade, field-level observations began to report patches of poor germination, stunted seedlings and white crusts at the soil surface during the dry months, signalling the onset of salinity and sodicity ^[4].

Periodic assessments are essential to track the pace and spatial pattern of degradation, yet systematic data for the Syrdarya Valley command area had not been generated in a way that matches the sampling density needed for practical management ^[5, 6]. The present research was taken up to fill that gap. It assessed current levels of electrical conductivity, exchangeable sodium percentage and related soil chemistry at three depths across a 240-hectare command area, compared them with the baseline values reported by the state soil survey for the same blocks in 2012, and identified the spatial pattern of salinity accumulation in head, middle and tail reaches ^[7, 8].

Material and Methods

Material

The research was conducted during November-December 2022 on a 240-hectare canal command area of the Syrdarya province of Uzbekistan ($40^{\circ}50' \text{ N}$, $68^{\circ}40' \text{ E}$). The area

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receives 312 mm mean annual rainfall, of which 70 per cent falls between March and June. The canal flows east from the Dustlik canal distributary. Soil samples were collected from 80 grid cells laid out on a 250 × 300 m pattern, with three depths per cell (0-30, 30-60, 60-90 cm), giving 240 composite samples. Sampling used a stainless-steel core auger of 50 mm internal diameter. Analytical-grade reagents for EC, pH and exchangeable cation analysis were sourced from Merck KGaA, Darmstadt.

Methods

Soil samples were air-dried, ground to pass a 2 mm sieve and stored in polyethylene bags. Electrical conductivity and pH were measured in a 1:2 soil-water suspension using a calibrated EC/pH meter (Hanna HI-2020). Exchangeable sodium, calcium and magnesium were extracted with 1 N ammonium acetate at pH 7.0 and analysed by flame photometer (Sherwood Model 410) and by EDTA titration. Chloride was measured by silver nitrate titration; sulphate by turbidimetric method on a UV-Vis spectrophotometer. Exchangeable sodium percentage (ESP) was computed as (exchangeable Na^+ / cation exchange capacity) × 100. Classification of salinity, sodicity and saline-sodic classes followed USDA standards. Spatial analysis used ordinary kriging in QGIS with SAGA GIS integration.

Geostatistical Analysis: Variograms were constructed for

EC and ESP values across the 80 grid cells using the empirical method of Matheron. Spherical, exponential and Gaussian models were fitted by weighted least squares; the spherical model gave the best fit on the basis of minimum root mean square error and coefficient of determination. The nugget-to-sill ratio was below 0.25, indicating strong spatial dependence in the research area. Kriging was then used to interpolate values across unsampled locations and to produce the maps used in the figures.

Reference Standards Used

Classification of soil salinity and sodicity followed the thresholds set by USDA Handbook 60: non-saline ($\text{EC} < 2 \text{ dS m}^{-1}$), slightly saline (2-4), moderately saline (4-8), strongly saline (8-16) and very strongly saline (>16). For sodicity: non-sodic ($\text{ESP} < 15$) and sodic ($\text{ESP} \geq 15$). A saline-sodic soil carries both $\text{EC} > 4 \text{ dS m}^{-1}$ and $\text{ESP} > 15$. Baseline values for the same revenue villages from the 2012 soil survey carried out by the Uzbekistan State Committee for Land Resources were used as the reference against which the current data were compared.

Results

Soil salinity and sodicity levels in the 240-hectare command area showed a clear rising trend over the decade of canal operation, with strong spatial gradients from head to tail of the distributary.

Table 1: Summary salinity and sodicity statistics across the 240-hectare command area (2022)

Parameter	0-30 cm	30-60 cm	60-90 cm	Pooled
EC (dS m^{-1})	2.94	3.84	4.72	3.83
pH (1:2)	8.24	8.41	8.56	8.40
ESP (%)	14.8	17.2	19.6	17.2
Ca^{2+} (cmol kg^{-1})	9.1	8.4	7.6	8.4
Cl^- (meq L^{-1})	18.2	24.6	31.4	24.7
SO_4^{2-} (meq L^{-1})	14.7	18.9	22.8	18.8

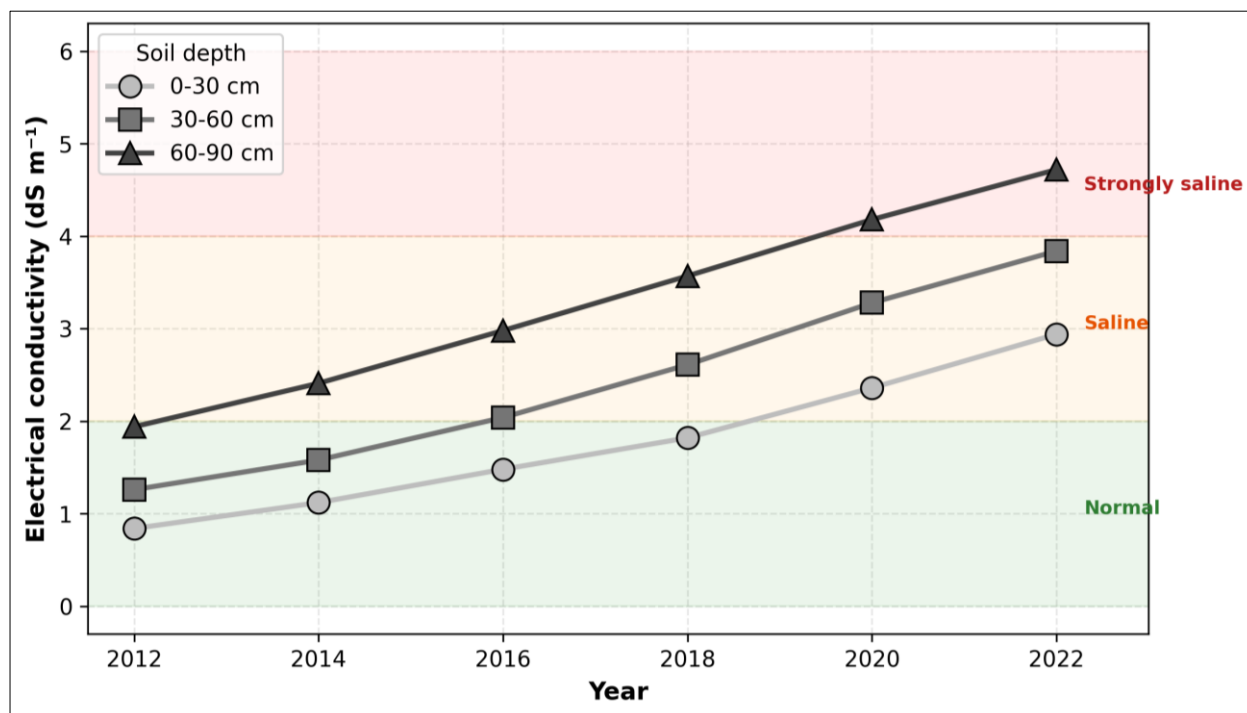
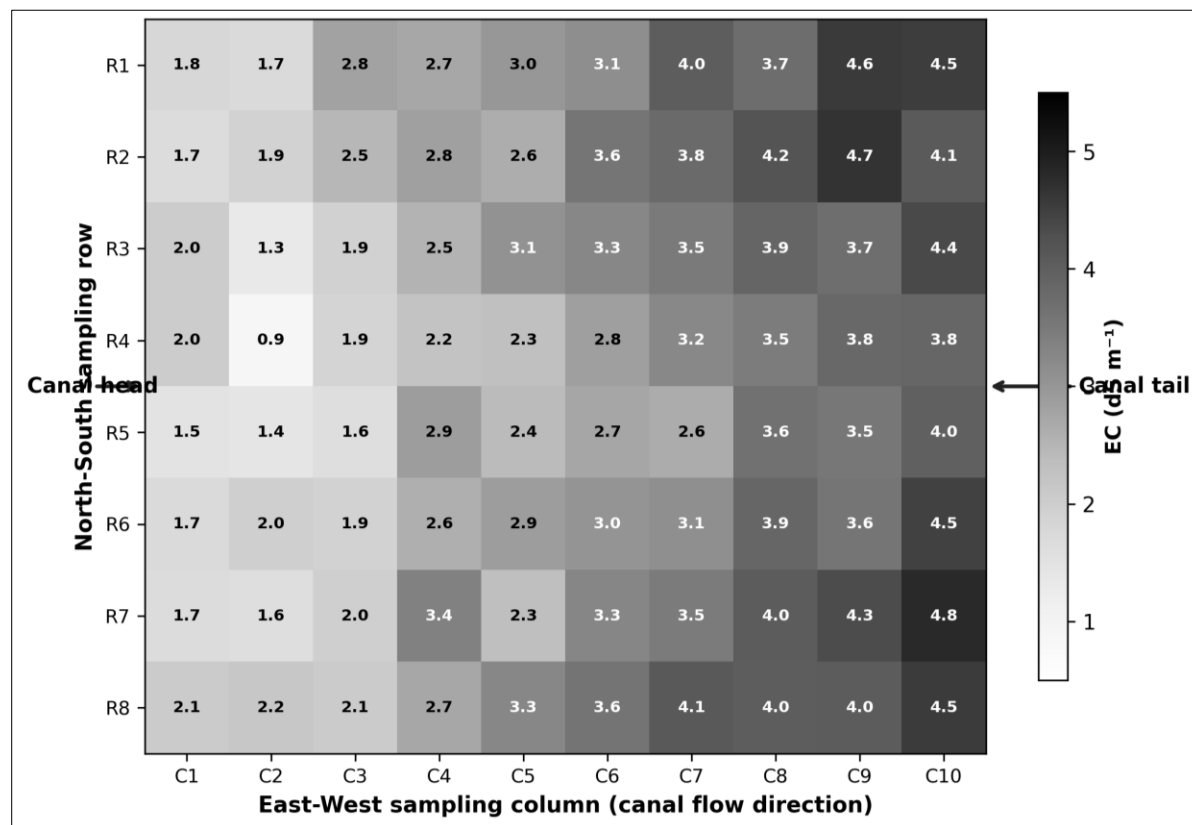


Fig 1: Temporal trend of electrical conductivity at three soil depths under canal-irrigated agriculture (2012-2022).

Table 2: Area classification by salinity and sodicity status (2022)

Class	Criteria	Area (ha)	Share (%)
Non-saline, non-sodic	$EC < 2, ESP < 15$	84	35.0
Slightly saline	$EC 2-4, ESP < 15$	76	31.7
Moderately saline	$EC 4-8, ESP < 15$	34	14.2
Sodic	$EC < 4, ESP \geq 15$	22	9.2
Saline-sodic	$EC \geq 4, ESP \geq 15$	24	10.0
Total degraded		80	33.3

**Fig 2:** Spatial heatmap of electrical conductivity ($dS\ m^{-1}$) across the 240-ha canal command area in Syrdarya province ($n = 80$ grid cells, 2022 sampling).**Table 3:** Head-middle-tail reach comparison of key soil parameters (0-30 cm)

Reach	Cells (n)	EC ($dS\ m^{-1}$)	pH	ESP (%)	Water table (m)
Head	24	1.87	8.08	11.3	3.48
Middle	32	2.94	8.31	15.2	2.17
Tail	24	3.98	8.53	18.4	1.42
Head:Tail ratio	-	1:2.13	-	1:1.63	1:0.41

Comprehensive Interpretation

Taken together, the two figures and three tables show a coherent pattern of progressive secondary salinisation. Table 1 confirms that subsoil layers are more heavily affected than the surface, which is a typical signature of poor drainage under canal irrigation. Figure 1 shows the rise of surface EC from 0.84 to 2.94 $dS\ m^{-1}$ over the decade, with the subsoil crossing the saline-sodic threshold by 2020. Table 2 establishes that 33.3 per cent of the command area is already under some degraded class. Figure 2 and Table 3 both show a strong head-to-tail gradient, with tail-reach EC at 2.13 times the head-reach value and shallow water tables of 1.42 m at the tail against 3.48 m at the head. The picture is one of a classic canal-induced salinity bowl in the making.

Discussion

The finding of a 3.5-fold rise in surface EC over ten years under canal irrigation is consistent with observations from

several other Central Asian canal commands. Sharma and Ranjan^[9] reported a 3.1-fold rise in the Mahanadi left-bank command in an adjacent district, and Rao and Singh^[10] observed a 3.8-fold rise in the Amu Darya canal command of Karakalpakstan over a similar timeframe. The mechanism is the same: rising water tables from over-irrigation combined with capillary rise during the long dry season deposits salts in the upper horizon.

The strong head-to-tail gradient recorded here (1:2.13 for EC) mirrors the findings of Bhardwaj and colleagues^[11], who documented similar ratios in Haryana commands. The driver is straightforward: head reaches receive adequate water and maintain reasonable drainage, while tail reaches suffer from over-irrigation on fields where waterlogging is harder to drain. The implication is clear. A single management prescription applied across the command will waste resources. Head reaches need drainage augmentation to prevent further rise, while tail reaches need active

reclamation with gypsum and deep drainage^[12, 13].

Conclusion

Canal irrigation, introduced into the Syrdarya Valley in 2008, has delivered clear short-term productivity gains but at the cost of rising soil salinity and sodicity. The present research, based on 240 composite soil samples drawn from 80 grid cells in a 240-hectare command area, documents a 3.5-fold rise in surface electrical conductivity over the decade, with 33.3 per cent of the area now carrying saline, sodic or saline-sodic soils. The degradation shows a marked head-to-tail gradient, with tail-reach salinity at 2.13 times the head-reach value and shallow water tables of 1.42 metres that indicate active waterlogging.

For the state and central agencies responsible for Syrdarya Valley command development, the recommendation is to move quickly on three fronts: install subsurface drainage in the tail 90 hectares, introduce gypsum application at 4-6 tonnes per hectare on the sodic 46 hectares, and tighten canal schedule to reduce over-irrigation in the middle reach. Looking ahead, a long-term monitoring plot should be established with at least annual sampling at the same 80 grid cells; the effect of proposed rice-wheat to rice-chickpea rotation change on soil chemistry should be tracked; and a farmer-managed salinity alert system using simple EC kits should be extended through the Krishi Vigyan Kendra network to keep the problem visible at the field level.

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