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GIS-Based Assessment of the Ecological Properties of Saline Soils in the Syrdarya Region, Uzbekistan

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Abstract: Secondary salinization is the principal form of land degradation in the irrigated lowlands of the middle Syrdarya basin, where shallow and mineralized groundwater, high evaporative demand and inefficient drainage combine to degrade soil quality. This study assesses the ecological properties of saline soils in the Syrdarya region of Uzbekistan by integrating field and laboratory soil analyses with remote sensing and geographic information system (GIS) techniques. A total of 120 georeferenced soil samples were collected from the eight rural districts of the region and analyzed for electrical conductivity of the saturation extract (EC_e), pH, chloride and sulfate content, sodium adsorption ratio (SAR) and humus. Four spectral indices (SI, NDSI, VSSI and NDVI) were derived from Sentinel-2 MSI imagery and combined with groundwater table (GWT) depth and groundwater mineralization in a multiple linear regression model; residuals were interpolated by ordinary kriging. The regression-kriging model achieved a validation coefficient of determination of $R^2 = 0.70$ and a root mean square error of 1.80 dS m^{-1} . Approximately 92.2% of the surveyed irrigated area was saline to some degree, with 35.4% moderately, 13.1% highly and 2.2% extremely saline. A Soil Ecological Condition Index (SECI), weighted by the analytic hierarchy process, ranged from 0.34 in Mirzaobod to 0.61 in Boyovut and revealed a clear north-east to south-west gradient of deterioration associated with shallow, mineralized groundwater in the Mirzachul (Hungry Steppe) part of the region. The proposed GIS framework provides a reproducible basis for district-level prioritization of drainage rehabilitation, leaching regimes and salt-tolerant cropping.

Keywords: soil salinity; geographic information system; remote sensing; Sentinel-2; regression-kriging; soil ecological condition index; Syrdarya region; Uzbekistan

INTRODUCTION

Soil salinization is among the most widespread and persistent threats to agricultural sustainability in arid and semi-arid regions. Salt accumulation in the root zone reduces osmotic availability of water, induces specific ion toxicity, disperses clay colloids where sodium dominates the exchange complex, and ultimately lowers crop yield and soil biological activity. Recent syntheses estimate that salt-affected soils occupy close to one billion hectares worldwide and emphasize that the knowledge gaps concern not only the extent of salinity but also its dynamics, its interaction with irrigation management and its consequences for soil functions [1]. Global-scale mapping based on remote sensing and machine learning has further shown that the area of salt-affected land has changed substantially over recent decades and that irrigated drylands of Central Asia belong to the most affected hotspots [2].

The economic dimension of the problem is equally significant. Salt-induced land degradation causes losses in crop production, depreciation of land value, abandonment of farmland and increased costs of water and drainage management; at the global level these losses have been estimated in the order of tens of billions of US dollars per year, which makes timely diagnosis and restoration economically justified [3]. In Uzbekistan, where irrigated agriculture provides most of the crop output and employs a large part of the rural population, salinity directly affects food security, export earnings and rural incomes.

The Syrdarya region (Sirdaryo viloyati) lies in the middle reaches of the Syrdarya River and includes a large part of the Mirzachul (Hungry Steppe), one of the oldest irrigation massifs of Central Asia. The region is characterized by flat topography, heavy-textured alluvial and proluvial deposits, a continental arid climate with potential evapotranspiration several times higher than precipitation, and a groundwater table that in many places lies within 1–3 m of the surface. Under these conditions, capillary rise of mineralized groundwater during the growing season is the main driver of secondary salinization. Studies in the neighbouring Jizzakh irrigation zone have demonstrated that climate change, deteriorating collector-drainage networks and excessive irrigation jointly increase the area and severity of saline land, creating challenges for the sustainable use of water and land resources [4]. For the Syrdarya region itself, long-term analysis of monitoring data from 2000–2019 combined with GIS interpolation showed that salinity is widespread, that its spatial pattern depends strongly on local terrain conditions and that integration of GIS technologies into traditional monitoring is urgently needed [5].

Conventional assessment of soil salinity relies on dense soil sampling and laboratory determination of electrical conductivity and ion composition. Although accurate, this approach is labour-intensive, expensive and provides only point information. Remote sensing offers spatially continuous observations: salts at the soil surface increase reflectance in the visible and near-infrared domains, while salinity stress reduces vegetation vigour and chlorophyll content. The potentials and constraints of such approaches have been critically reviewed, highlighting the influence of soil moisture, surface roughness, vegetation cover and the non-linear relation between surface spectral response and root-zone salinity [6]. A later review of applications in arid and semi-arid regions concluded that the most reliable results are obtained when spectral indices are combined with field measurements and auxiliary environmental variables in a GIS environment [7].

In the Syrdarya region, comparative testing of seven Landsat-derived salinity indices against the official soil salinity map showed that indices combining visible and near-infrared bands, in particular the vegetation soil salinity index (VSSI), achieved the highest classification accuracy [8]. Further work using a spatial database of spectral indices and machine learning classifiers reported overall accuracy above 90% for the random forest algorithm [9]. However, most previous studies focused on salinity classification alone and did not translate the results into an integrated assessment of the ecological condition of soils that simultaneously accounts for salinity, sodicity, organic matter and hydrogeological stressors. Moreover, the higher spatial resolution of Sentinel-2 imagery, which better resolves the small field units typical of post-reform farm structures, has rarely been exploited for the region.

The aim of this study is therefore to assess the ecological properties of saline soils in the Syrdarya region on the basis of GIS technology. The specific objectives are: (i) to characterize the physicochemical properties of saline soils from field and laboratory data; (ii) to evaluate the relationship between Sentinel-2 spectral indices, hydrogeological factors and soil salinity; (iii) to produce a regional soil salinity map by regression-kriging; and (iv) to develop and map a composite Soil Ecological Condition Index (SECI) at the district level to support land reclamation planning.

METHODS

A. Study Area

The Syrdarya region is located in the eastern part of Uzbekistan between approximately 40°15'–41°00' N and 68°00'–69°10' E, bordering Kazakhstan to the north-west and Tajikistan to the south-east. The total area of the region is about 4.3 thousand km², most of which is used for irrigated agriculture, mainly cotton, winter wheat, vegetables and fodder crops. Administratively, the study covered the eight rural districts: Boyovut, Guliston, Mirzaobod, Oqoltin, Sardoba, Sayxunobod, Sirdaryo and Xovos. The climate is sharply continental, with hot dry summers, mean annual precipitation of roughly 300–350 mm concentrated in winter and spring, and annual potential evapotranspiration exceeding 1,200 mm. Soils are predominantly irrigated meadow, meadow-sierozem and sierozem-meadow soils developed on loamy and clay-loam alluvium; the terrain declines gently from the Syrdarya River terraces in the north-east towards the closed depressions of the Mirzachul in the south-west.

B. Field Survey and Laboratory Analysis

Field sampling was carried out after harvest in September–October, when soils are relatively dry and surface salt crusts are most expressed, which is favourable for comparison with optical imagery. A stratified random design was applied: the irrigated area of each district was stratified by the official salinity classes and geomorphological units, and a total of 120 sampling points were allocated proportionally to the irrigated area, with a minimum of ten points per district. At each point, composite samples (five sub-samples within a 10 × 10 m plot corresponding to one Sentinel-2 pixel) were taken from the 0–30 cm and 30–60 cm layers and positioned with a handheld GNSS receiver (accuracy ±3 m). Depth to the groundwater table and groundwater mineralization were obtained from the nearest observation wells of the regional hydrogeological-ameliorative monitoring network and checked against field auger observations.

In the laboratory, samples were air-dried and sieved through a 2 mm mesh. Electrical conductivity was measured in a 1:5 soil–water extract and converted to the electrical conductivity of the saturation extract (ECe) using a texture-specific conversion factor calibrated on a subset of 24 saturated paste samples. Soil pH was determined potentiometrically in a 1:2.5 suspension; chloride by argentometric titration; sulfate gravimetrically; soluble sodium, calcium and magnesium by flame photometry and complexometric titration, from which the sodium adsorption ratio (SAR) was calculated; and humus content by the Tyurin wet oxidation method. Salinity classes were defined using the widely adopted ECe thresholds of the classic diagnostic handbook for saline and alkali soils: non-saline (< 2 dS m⁻¹), slightly saline (2–4), moderately saline (4–8), highly saline (8–16) and extremely saline (> 16 dS m⁻¹).

C. Remote Sensing Data and Spectral Indices

Cloud-free Sentinel-2 MSI Level-2A surface reflectance scenes acquired within ±10 days of the field campaign were mosaicked and clipped to the region boundary. Bands at 20 m resolution were resampled to 10 m. Landsat 8/9 thermal bands were used to derive land surface temperature as an auxiliary layer, and the SRTM digital elevation model (30 m) was used to derive elevation and slope. Four indices were calculated. The salinity index (SI), which exploits the brightness of salt-affected surfaces in the visible domain and has proved effective for detecting hydrosaline degradation in irrigated lands of Central Asia and Pakistan, is given by Eq. (1); the normalized difference salinity index (NDSI), the vegetation soil salinity index (VSSI) and the normalized difference vegetation index (NDVI) are given by Eqs. (2)–(4):

$$SI = \sqrt{(B \times R)} \quad (1)$$

$$NDSI = (R - NIR) / (R + NIR) \quad (2)$$

$$VSSI = 2G - 5(R + NIR) \quad (3)$$

$$NDVI = (NIR - R) / (NIR + R) \quad (4)$$

where B, G, R and NIR denote surface reflectance in the blue (B2), green (B3), red (B4) and near-infrared (B8) bands of Sentinel-2. The choice of Sentinel-2 rather than Landsat was motivated by comparative evidence from arid irrigated regions showing that Sentinel-2 MSI provides equal or better salinity detection owing to its higher spatial resolution and additional red-edge bands.

D. GIS Modelling and Ecological Assessment

All data were integrated in ArcGIS Pro and QGIS in the WGS 84 / UTM zone 42N projection. Pearson correlation analysis was used to screen predictors. Topsoil ECe (0–30 cm) was then modelled by multiple linear

regression (MLR) using the significant, non-collinear predictors (variance inflation factor < 3). The data set was randomly split into a calibration subset (70%, $n = 84$) and a validation subset (30%, $n = 36$). Regression residuals were tested for spatial autocorrelation (Moran's I) and interpolated by ordinary kriging with a spherical variogram; the final prediction surface was obtained as the sum of the regression trend and the kriged residuals (regression-kriging), Eq. (5):

$$ECe(s) = \beta_0 + \sum \beta_k \cdot X_k(s) + \varepsilon(s) \quad (5)$$

where $X_k(s)$ are the predictor values at location s , β_k the regression coefficients and $\varepsilon(s)$ the kriged residual. Model performance was evaluated by the coefficient of determination (R^2), root mean square error (RMSE) and mean absolute error (MAE).

To move beyond salinity mapping toward an ecological assessment, a Soil Ecological Condition Index (SECI) was constructed from six indicators: ECe, SAR, humus content, GWT depth, groundwater mineralization and NDVI. Each indicator was rescaled to the 0–1 interval with min–max normalization, using an inverse transformation for indicators whose increase worsens soil condition (ECe, SAR, groundwater mineralization). Weights were derived by the analytic hierarchy process (AHP) from pairwise comparisons made by a panel of five soil scientists and land reclamation specialists; the consistency ratio was 0.06 (< 0.10). The resulting weights were 0.32 for ECe, 0.20 for GWT depth, 0.16 for groundwater mineralization, 0.14 for SAR, 0.10 for humus and 0.08 for NDVI. The index was computed by weighted overlay, Eq. (6):

$$SECI = \sum w_i \cdot x_i, \quad \sum w_i = 1 \quad (6)$$

where w_i is the weight and x_i the normalized value of the i -th indicator. SECI values were classified as critical (0–0.20), poor (0.20–0.40), moderate (0.40–0.60), good (0.60–0.80) and favourable (0.80–1.00), and aggregated by district using zonal statistics. The overall workflow is shown in Fig. 1.

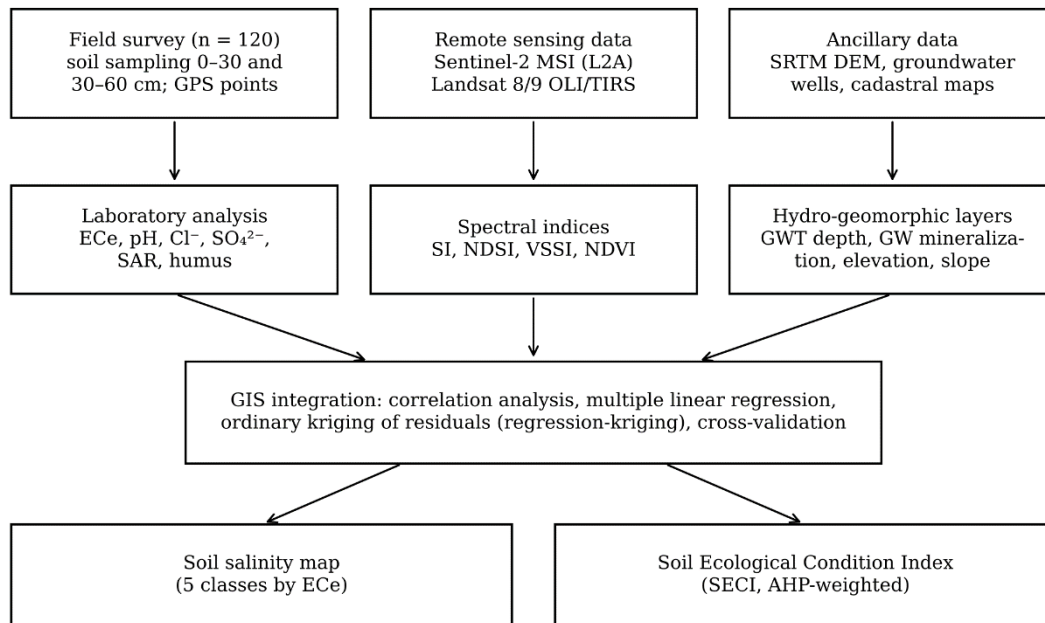


Fig. 1. Methodological framework of the GIS-based ecological assessment of saline soils.

RESULTS

A. Physicochemical Properties of Saline Soils

Descriptive statistics of the topsoil properties are summarized in Table I. ECe varied from 1.12 to 21.6 dS m⁻¹ with a mean of 6.84 dS m⁻¹, indicating that the average irrigated soil of the region falls within the moderately saline class. The high coefficient of variation (57.3%) and positive skewness show a strongly heterogeneous distribution with a long tail of highly and extremely saline sites. Sulfate dominated over chloride in most samples (mean Cl⁻/SO₄²⁻ ratio 0.22), corresponding to the chloride-sulfate and sulfate salinity types typical of the Mirzachul. Soil reaction was moderately alkaline (pH 7.6–8.6) with low variability. The mean SAR of 7.4 suggests an incipient sodicity risk on part of the territory, while humus content was low (mean 0.86%),

reflecting the long history of intensive cotton monoculture and limited organic inputs. Groundwater lay on average 1.92 m below the surface with a mean mineralization of 3.4 g L⁻¹, i.e. above the critical depth for capillary salinization under the prevailing climatic conditions [10].

TABLE I. DESCRIPTIVE STATISTICS OF TOPSOIL (0–30 cm) PROPERTIES AND GROUNDWATER INDICATORS (n = 120)

Indicator	Unit	Min	Max	Mean	SD	CV, %	Skewness
ECe	dS m ⁻¹	1.12	21.60	6.84	3.92	57.3	1.18
pH (1:2.5)	–	7.61	8.58	8.02	0.21	2.6	0.24
Cl ⁻	%	0.004	0.142	0.031	0.026	83.9	1.64
SO ₄ ²⁻	%	0.021	0.486	0.142	0.097	68.3	1.21
SAR	(mmol L ⁻¹) ^{0.5}	1.8	18.9	7.4	3.6	48.6	0.97
Humus	%	0.41	1.38	0.86	0.21	24.4	0.18
GWT depth	m	0.9	3.4	1.92	0.51	26.6	0.42
GW mineralization	g L ⁻¹	1.1	8.7	3.4	1.5	44.1	1.06

The subsoil layer (30–60 cm) had a slightly lower mean ECe (5.97 dS m⁻¹) than the topsoil, and the topsoil-to-subsoil ratio exceeded 1.0 at 71% of the sampling points. This upward-increasing salt profile is characteristic of evaporative accumulation driven by capillary rise, as opposed to the downward-increasing profile expected under effective leaching [11].

B. Relationships between Spectral Indices, Hydrogeological Factors and Salinity

Correlation coefficients between topsoil ECe and the candidate predictors in the calibration subset are presented in Table II. All indices were significantly correlated with ECe ($p < 0.01$). VSSI showed the strongest relationship ($r = -0.71$), followed by SI ($r = 0.64$) and NDVI ($r = -0.62$). Among the hydrogeological factors, GWT depth was strongly and negatively related to ECe ($r = -0.68$), confirming that shallower groundwater is associated with higher salinity, while groundwater mineralization had a moderate positive correlation ($r = 0.59$). Because SI and NDSI were highly collinear with VSSI ($|r| > 0.8$), they were excluded from the final regression model.

TABLE II. PEARSON CORRELATION OF PREDICTORS WITH TOPSOIL ECe (CALIBRATION SUBSET, n = 84)

Predictor	Type	r	R ²	p-value	Retained in MLR
VSSI	Spectral index	-0.71	0.50	< 0.001	Yes
SI	Spectral index	0.64	0.41	< 0.001	No (collinear)
NDSI	Spectral index	0.57	0.32	< 0.001	No (collinear)
NDVI	Spectral index	-0.62	0.38	< 0.001	Yes
GWT depth	Hydrogeological	-0.68	0.46	< 0.001	Yes
GW mineralization	Hydrogeological	0.59	0.35	< 0.001	Yes
Elevation	Topographic	-0.33	0.11	0.002	No (weak)

The final MLR model included VSSI, GWT depth, NDVI and groundwater mineralization and explained 74% of the variance of ECe in the calibration subset (adjusted $R^2 = 0.73$). Standardized coefficients indicated that VSSI ($\beta = -0.38$) and GWT depth ($\beta = -0.31$) were the dominant predictors, followed by NDVI ($\beta = -0.19$) and groundwater mineralization ($\beta = 0.17$). The regression residuals exhibited significant positive spatial autocorrelation (Moran's I = 0.27, $p < 0.01$), which justified the kriging step. On the independent validation subset, regression-kriging yielded $R^2 = 0.70$, RMSE = 1.80 dS m⁻¹ and MAE = 1.49 dS m⁻¹ (Fig. 2). The fitted trend line (slope 0.76) indicates a slight overestimation of low and underestimation of very high ECe values, a smoothing effect typical of interpolation-based models [12].

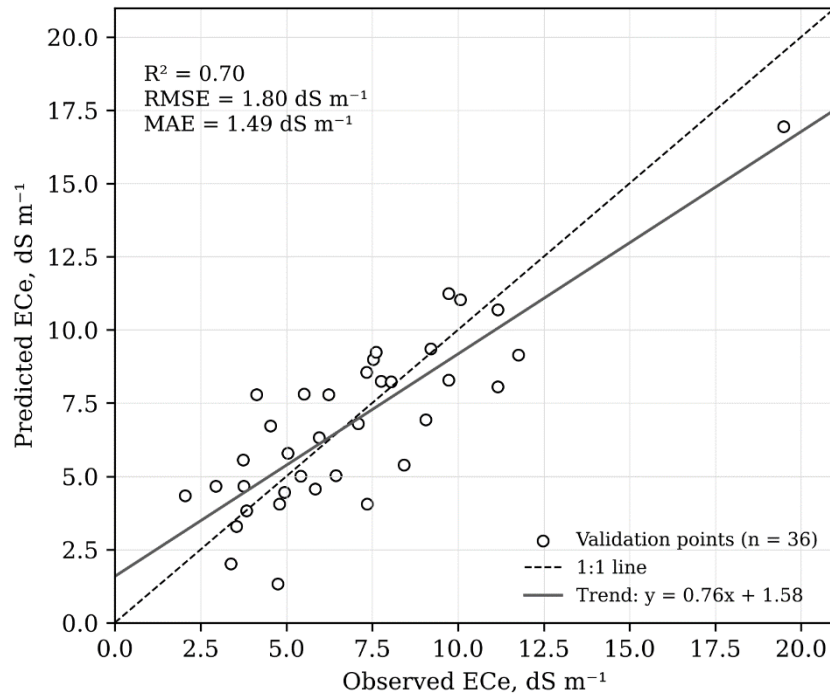


Fig. 2. Observed versus predicted topsoil EC_e for the validation subset (regression-kriging model).

C. Spatial Distribution of Soil Salinity

The regression-kriging map classified 7.8% of the surveyed irrigated area as non-saline, 41.5% as slightly saline, 35.4% as moderately saline, 13.1% as highly saline and 2.2% as extremely saline. Thus, more than half of the irrigated land (50.8%) is affected by at least moderate salinity, a level at which yield reduction of cotton and especially winter wheat becomes significant. The district-level distribution (Fig. 3) reveals a distinct spatial gradient. The north-eastern districts adjoining the Syrdarya River (Boyovut, Guliston and Sirdaryo) have the largest shares of non-saline and slightly saline land (60–66%), whereas the south-western Mirzachul districts (Mirzaobod, Sardoba and Oqoltin) have 62–67% of their irrigated area in the moderate-to-extreme classes. Hotspots of highly and extremely saline soils are concentrated in closed micro-depressions, along poorly functioning inter-farm collectors and at the tail ends of irrigation canals.

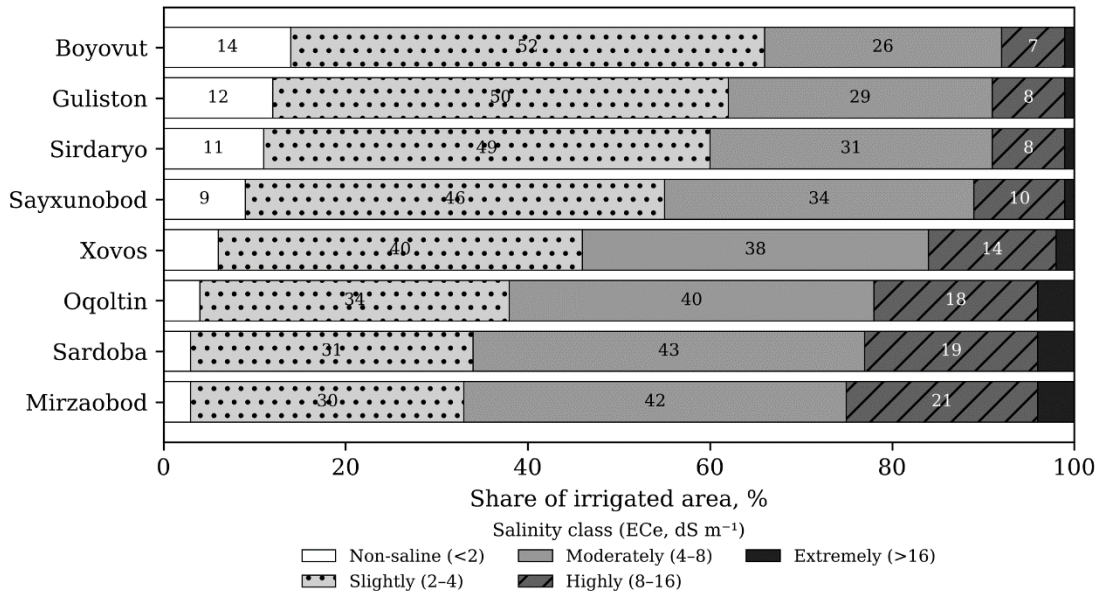


Fig. 3. Distribution of irrigated land by soil salinity class in the districts of the Syrdarya region, %.

D. Soil Ecological Condition Index

District-level SECI values and their principal drivers are given in Table III. The regional mean SECI was 0.48, placing the irrigated soils of the Syrdarya region as a whole in the moderate ecological condition class. Only Boyovut reached the good class (0.61), while Guliston, Sirdaryo, Sayxunobod and Xovos fell into the moderate class (0.46–0.58). Oqoltin, Sardoba and Mirzaobod were classified as poor (0.34–0.39). The ranking of districts by SECI closely followed the gradient of GWT depth (Spearman $\rho = 0.98$) and groundwater mineralization ($\rho = -0.98$), demonstrating that the hydrogeological regime is the key factor of soil ecological condition in the region. Within districts, pixel-level SECI maps revealed that 9.6% of the irrigated area falls into the critical class (< 0.20); these lands coincide with extremely saline, sodic patches with humus content below 0.6% and represent first-priority targets for reclamation or conversion to salt-tolerant land uses.

TABLE III. MEAN SOIL AND GROUNDWATER INDICATORS AND SECI BY DISTRICT

District	ECe, dS m ⁻¹	GWT depth, m	GW mineral., g L ⁻¹	SECI	Condition class
Boyovut	4.9	2.31	2.6	0.61	Good
Guliston	5.3	2.18	2.8	0.58	Moderate
Sirdaryo	5.6	2.12	2.9	0.56	Moderate
Sayxunobod	6.1	2.02	3.1	0.52	Moderate
Xovos	7.2	1.86	3.5	0.46	Moderate
Oqoltin	8.4	1.68	3.9	0.39	Poor
Sardoba	8.9	1.61	4.1	0.36	Poor
Mirzaobod	9.3	1.55	4.3	0.34	Poor
Region (mean)	7.0	1.92	3.4	0.48	Moderate

DISCUSSION

The results confirm that secondary salinization remains the dominant ecological constraint on irrigated soils of the Syrdarya region and that its spatial pattern is controlled primarily by the groundwater regime. The strong negative correlation between ECe and GWT depth and the near-perfect rank agreement between SECI and groundwater indicators are consistent with a multi-year analysis of about 3,800 soil sampling points and 1,500 observation wells in the same province, which identified shallow and mineralized groundwater as the main drivers of the expansion of saline irrigated areas between 2000 and 2019 [13]. The upward-increasing salt profiles observed at most sampling points further indicate that capillary rise during the hot season currently outweighs the leaching effect of irrigation and pre-season flushing.

The pronounced north-east to south-west gradient can be explained by geomorphology. The south-western districts occupy the lower, flatter parts of the Mirzachul with closed depressions, heavier soils and a lower natural drainage gradient, where collector-drainage networks built in the 1960s–1980s have partly silted up. Even small elevation differences on flat irrigated terrain are known to redistribute water and salts, so that micro-relief, groundwater depth and soil texture jointly determine the spatial distribution of salinity at field and farm scales [14]. The relatively weak direct correlation of ECe with elevation in this study ($r = -0.33$) therefore does not contradict the importance of terrain; rather, the topographic effect is mediated through groundwater depth, which was retained as a stronger predictor.

With respect to remote sensing, the superior performance of VSSI over SI and NDSI agrees with earlier comparisons of Landsat-based indices in the region and supports the view that indices combining visible and near-infrared information capture both the bright soil surface and the reduced vegetation vigour associated with salinity. Recent integrated work applying structural equation modelling to Landsat, MODIS and field data in the Sirdarya province likewise found that salinity can be predicted from a combination of spectral bands and hydrological variables, and emphasized the indirect role of surface water mineralization [15]. The present study extends this evidence in two ways. First, the use of 10 m Sentinel-2 data combined with regression-kriging achieved a validation R^2 of 0.70, which is competitive with previously reported accuracies while producing a continuous ECe surface rather than only a categorical map. Second, the SECI framework converts salinity information into a multi-criteria ecological assessment that accounts for sodicity, organic matter depletion and hydrogeological stress, which is more directly useful for land reclamation planning.

The practical implications are clear. Districts with poor SECI values (Mirzaobod, Sardoba and Oqoltin) should be prioritized for rehabilitation of the collector-drainage network and for lowering the groundwater

table below the critical depth of about 2.0–2.5 m. Leaching regimes should be adjusted to the actual distribution of salinity classes rather than applied uniformly, which would also save irrigation water. On critical patches, salt-tolerant crops and halophytic forage species, organic amendments to restore humus and gypsum application on sodic spots can improve soil condition at lower cost than conventional reclamation. Integrating the GIS-based salinity and SECI layers into the state land cadastre and the regional hydrogeological-ameliorative monitoring system would enable annual, low-cost updating of soil condition assessments.

Several limitations should be acknowledged. The analysis is based on a single post-harvest campaign; seasonal dynamics of salinity, which differ markedly between spring leaching and late summer, were not captured. Optical indices respond mainly to surface conditions, so prediction of subsoil salinity remains less reliable. The AHP weights reflect expert judgment and may be refined by sensitivity analysis or data-driven weighting. Future research should therefore incorporate multi-temporal Sentinel-2 and Sentinel-1 radar data, electromagnetic induction surveys for subsoil salinity and machine learning algorithms to improve predictive accuracy.

CONCLUSION

This study developed and applied a GIS-based framework to assess the ecological properties of saline soils in the Syrdarya region of Uzbekistan by integrating field and laboratory data, Sentinel-2 spectral indices and hydrogeological information. The main conclusions are as follows. (1) Irrigated soils of the region are predominantly moderately saline (mean EC_e 6.84 dS m^{-1}) with sulfate-dominated salinity, low humus content and an incipient sodicity risk. (2) VSSI and groundwater table depth are the strongest predictors of topsoil salinity; the regression-kriging model achieved a validation R^2 of 0.70 and RMSE of 1.80 dS m^{-1} . (3) About 50.8% of the irrigated area is at least moderately saline, with a clear deterioration gradient from the north-eastern riverine districts to the south-western Mirzachul districts. (4) The Soil Ecological Condition Index classifies the region overall as moderate (SECI = 0.48), with Mirzaobod, Sardoba and Oqoltin in poor condition and about 9.6% of the irrigated area in critical condition. The proposed approach is transferable to other irrigated provinces of the Aral Sea basin and can serve as a decision-support tool for targeted drainage rehabilitation, differentiated leaching and the adaptation of cropping systems to saline conditions.

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