

Soil Salinization Characteristics and Multi-factor Risk Assessment in an Arid Lakeshore Zone: A Case Study of Chaiwopu Lake, Xinjiang, China

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Abstract

Drylands are highly vulnerable to salt accumulation, particularly near shrinking inland water bodies where strong evaporation, shallow groundwater, and terrain interact. To quantify this process, 39 surface samples (0–20 cm) were collected from a 94.18 km² belt surrounding Chaiwopu Lake, and nine indicators—ESP, pH, slope, aspect, distance to the lake, groundwater-level decline, Simpson's diversity index, vegetation coverage, and elevation—were integrated into a composite index. Correlation analysis, multiple linear regression, and GIS interpolation were used to map total dissolved salts and identify dominant controls. Shoreline soils were mainly moderately to severely affected, with saline and highly saline classes accounting for 45.56% of the area. High and very high classes occupied 33.47% and 45.97%, respectively, indicating basin-scale land degradation. The model explained 85.2% of the variance in total dissolved salts ($R^2 = 0.852$) and showed a strong positive relationship between the composite index and observed conditions ($r = 0.801$). Vegetation diversity, elevation, and vegetation coverage were the most influential factors. This framework provides a practical basis for zoning priorities for water regulation, amendment application, and ecological restoration in inland dryland basins.

Keywords: total dissolved salts; groundwater-level decline; vegetation diversity; elevation gradient; land rehabilitation

Introduction

Drylands—where potential evapotranspiration consistently exceeds precipitation—cover ~41% of Earth's land and support over two billion people, making them highly vulnerable socio-ecological systems. Recent global assessments indicate that salt-affected soils already extend across ~1.38 billion hectares (~10.7% of land), and about a tenth of both irrigated and rain-fed croplands are impacted, posing escalating risks to agricultural productivity and sustainable land management in arid and semi-arid regions. Recent multi-scale syntheses further emphasize that salinization emerges from coupled climate–hydrology–soil processes across scales from global patterns to pore-scale salt precipitation, underscoring the need for integrative assessment frameworks in drylands (Shokri et

al., 2024). In endorheic basins, lakeshore zones are hotspots of soil salinization because lake-level fluctuations, shallow and dynamic groundwater, and strong evaporative demand jointly concentrate salts in near-surface soils. This pattern has been documented across multiple saline lake systems (e.g., Lake Urmia) and is increasingly evident in north-western China, where terminal lakes have experienced pronounced shrinkage under climate change and intensive groundwater extraction. Against this backdrop, diagnosing and mapping salinization risk in arid lakeshores such as the Chaiwopu Lake lakeshore near Urumqi provides decision-relevant evidence for targeted land rehabilitation and water management.

The formation and evolution of soil salinization result from the interaction of various complex factors. The interplay between natural conditions and human activities promotes soil salinization, leading to the accumulation of soil salts and changes in soil structure, thereby jeopardizing the health and sustainable development of soil ecosystems (Mao et al., 2022; Marroquin et al., 2023). Natural factors such as climate, topography, and soil type play a crucial role in the process of soil salinization. Seasonal and long-term climatic variability, particularly changes in precipitation and evaporation, directly regulate hydrochemical conditions and the environmental setting that favors salt accumulation in dryland basins (Bouchareb et al., 2024; Bouchema et al., 2024). Uneven terrain and poor drainage conditions can exacerbate soil salinization. Similarly, the inherent properties of the soil, such as its structure, texture, and drainage capacity, also significantly influence the salinization process (Khosravichenar et al., 2023; King et al., 2022). Accordingly, reclamation and management of salt-affected soils in drylands increasingly rely on organic inputs and biochar-based soil management practices to improve soil quality, enhance nutrient availability, and support vegetation establishment (Murtaza et al., 2024; Kaur et al., 2024; Murtaza et al., 2025).

Prior research on Chaiwopu Lake and surrounding arid basins has mostly focused on lake shrinkage, aeolian dust/wind erosion, and sediment geochemistry/contamination, rather than on multi-factor lakeshore soil risk. Remote-sensing and deformation analyses document accelerated wind erosion around the exposed lakeshore as the lake receded (Lv et al., 2024). Remote sensing, GIS, geochemical analysis, and data-driven modelling have been widely used to map salt-affected soils, evaluate groundwater quality, assess irrigation suitability, and support environmental risk assessment in arid and data-scarce regions. In particular, Radhi et al. (2025) demonstrated the usefulness of integrating geochemical indicators with GIS-based spatial analysis for groundwater quality and irrigation suitability assessment in arid regions, providing a relevant methodological reference for linking hydrochemical conditions with spatial risk zoning. Awawdeh et al. (2025) further showed that downscaling GRACE data with artificial neural networks can improve groundwater forecasting, highlighting the value of combining large-scale hydrological observations with machine-learning methods for groundwater-resource assessment. In addition, He et al. (2025) proposed an integrated ecological governance model for analysing urban and rural water-pollution impacts, emphasizing that environmental assessment should be connected with governance-oriented zoning and management responses. Recent studies in *Global NEST Journal* also provide methodological precedents for the GIS-based salinity and risk mapping adopted in the present study (Radhi et al., 2025; Awawdeh et al., 2025; He et al., 2025; Kalphana et al., 2024; Tanneeru et al., 2022). Regional syntheses report pronounced changes in water quantity and quality across arid Xinjiang lakes, consistent with basin-scale hydrologic stress affecting Chaiwopu (Wu et al., 2014). Sediment-core geochemistry from Chaiwopu captures century-scale climatic and anthropogenic signals, and elemental patterns in lacustrine sediments and adjacent soils (Liu et al., 2016; Ma et al.,

2013). Little attention, however, has been paid to a quantitative, multi-indicator assessment of lakeshore soil salinization risk that explicitly links soil chemistry with topography, groundwater dynamics and vegetation diversity/coverage. To address this gap, we (i) develop a composite salinization risk index (CR) tailored to arid lakeshores; (ii) integrate Simpson's diversity index and vegetation coverage with terrain and groundwater indicators within the risk framework; and (iii) produce operational risk zoning to support targeted land rehabilitation and water management.

This study (i) maps and quantifies shoreline soil salinization/alkalinization in the Chaiwopu basin; and (ii) builds and validates a composite risk index (CR) that links soil chemistry with topography, groundwater dynamics, and vegetation to guide targeted land management. Chaiwopu Lake is a natural cold-water lake located about 45 km southeast of Urumqi City beneath Bogda Peak in the Chaiwopu Basin, a typical inland arid basin of the Mongolian–Xinjiang Plateau. The lake was once the largest freshwater body on the outskirts of Urumqi and formed an important ecological barrier to the east, but since the 1990s, construction and operation of water-supply projects to the northwest and southwest have progressively cut off its groundwater inflow. As a result, lake inflow has declined, the water surface has shrunk dramatically to about 0.18 km² by 2014, and pronounced soil salinization and land degradation have developed in the surrounding lakeshore zone under conditions of strong evaporation and shallow, fluctuating groundwater. Typically, the causes of soil salinization in drylands are complex, involving interacting climatic, hydrological, geomorphic, soil, and land-use factors, and they exhibit pronounced regional differences (Jiang et al., 2022; Li et al., 2023; Wang et al., 2023). In Xinjiang, severe primary and secondary salinization is widespread, yet relatively few studies have conducted multi-factor quantitative assessments of soil salinization risk in lakeshore zones that explicitly link soil chemistry with topography, groundwater dynamics, and vegetation characteristics, or that translate these assessments into operational tools for land management. Focusing on the lakeshore zone of Chaiwopu Lake, this study uses high-density soil sampling and multi-source environmental and ecological data to identify the main drivers of salinization, construct a composite salinization risk index and map its spatial pattern.

The aim is to diagnose salinization as a form of land degradation and to provide a practical framework for zoning management priorities and guiding soil and vegetation restoration in arid lakeshore environments, with potential transferability to other salinized dryland basins worldwide. From a management standpoint, the resulting risk zoning can guide where to prioritize soil amendment, organic-input management, and vegetation-based restoration to maximize effectiveness and resource efficiency in arid lakeshore settings (Kaur et al., 2024; Murtaza et al., 2025).

Study Area

Chaiwopu Lake is located in the Chaiwopu Basin beneath Bogda Peak, approximately 45 kilometers southeast of Urumqi City. It has geographic coordinates ranging from 87°51'E to 87°56'E and 43°28'N to 43°32'N, and it lies within the arid and semi-arid climatic characteristics of the Mongolian–Xinjiang Plateau. In this region, temperatures reach their lowest in January, around -20°C, with extreme lows down to -42.2°C; while in July, temperatures peak, averaging about 25°C, with extreme highs up to 43.5°C. The annual average precipitation in the Chaiwopu area is relatively low, varying between 70 and 500 millimeters. There is a noticeable vertical distribution difference in precipitation from the mountains to the basin's center, typically increasing with elevation.

The topography and geomorphology of the Chaiwopu Lake area are divided from top to bottom into four zones: the glacial belt at the basin's edge, desert canyons, piedmont alluvial fans, and the lake area at the basin center. Chaiwopu Lake and its surrounding areas are encircled by mountains, forming a semi-enclosed basin, bordered by the Yilianhabierga Mountain to the south and Bogda Mountain to the north. The region exhibits soil vertical distribution characteristics formed by variations in terrain, elevation, and hydrological conditions from the lake on the east side to the Xishan Farm's shallow river on the west side. Under conditions of low precipitation and high evaporation, the soil pH value is relatively high.

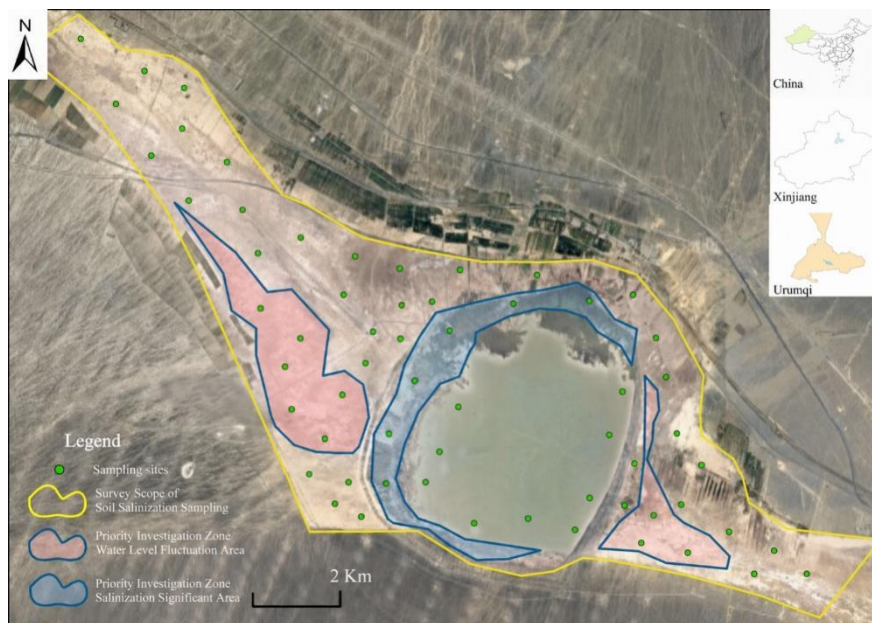


Fig. 1. Salt-affected investigation zones and sampling locations in the Chaiwopu Lake region.

Materials and methods

Sampling and analysis

In 2023, surface soil sampling was conducted in the 94.18 km² Chaiwopu lakeshore zone following China's "Technical Procedures and Standards for the Third National Soil Survey." To reflect the spatial heterogeneity of shoreline salinization, a stratified and gradient-oriented sampling scheme was adopted. Based on the salt-affected area investigation map, lake-shoreline conditions, field reconnaissance, vegetation cover, and visible salt accumulation, the study area was divided into a key investigation area and a general investigation area. The key investigation area covered 16.62 km² and included 19 sampling points at approximately 1 point km⁻², mainly distributed in near-shore belts, lake-level fluctuation/exposure zones, low-lying salt-accumulation areas, and sectors with more evident salinization. The general investigation area covered 77.56 km² and included 20 sampling points at approximately 1 point per 2 km², mainly representing the outer lakeshore belt, grassland-saline land transition zones, and western/northwestern peripheral areas with relatively weaker salinization. Thus, the 39 independent sampling locations represented the main landscape positions controlling lakeshore salinization, including near-lake, transitional, low-lying, vegetated, and peripheral zones, and captured the principal gradients in distance to the lake, elevation, groundwater-level decline, vegetation coverage, vegetation diversity, pH, and total dissolved salts.

Four duplicate samples were collected only for quality control and were not used as independent locations in descriptive statistics, spatial interpolation, or model fitting.

Surface soils (0–20 cm) were collected, air-dried, sieved, and analyzed in accredited local laboratories. Because the present dataset was based on 0–20 cm soil samples, the mapped salinity and CR patterns mainly describe the surface expression of salinization. Deeper soil layers may further influence the observed surface pattern by regulating upward salt supply under capillary rise, especially in low-lying lakeshore sectors affected by groundwater fluctuation. If salts are enriched in deeper layers, surface salinity may persist or reappear even after temporary leaching; conversely, if deeper layers contain lower salt contents, high surface salinity may mainly reflect recent evaporation-driven concentration or lake-level fluctuation/exposure processes (Perri et al., 2022; Ramos et al., 2023; Yin et al., 2022). Therefore, the strong surface salinity observed around the lake should be understood as the near-surface manifestation of a broader water–salt redistribution process. Further studies incorporating soil profile sampling and groundwater monitoring are needed to better distinguish short-term surface salt accumulation from longer-term vertical salt migration.

Monthly precipitation and station-observed evaporation data for 1993–2022 were obtained from the Dabancheng meteorological station located near Chaiwopu Lake. Monthly values were aggregated to annual totals, and the annual evaporation-to-precipitation ratio (E/P) was calculated by dividing annual evaporation by annual precipitation. Soil pH values were determined by the electrode method, while the ions of potassium, sodium, calcium, and magnesium in water-soluble salts were measured using plasma emission spectroscopy, and sulfate and chloride ions were analyzed using ion chromatography. All TDS values reported in this study are expressed on an oven-dry soil mass basis (g kg^{-1}) and represent the total soluble salts content of the soil. By contrast, the major ions (Cl^- , SO_4^{2-} , CO_3^{2-} , HCO_3^- , K^+ , Ca^{2+} , Na^+ , and Mg^{2+}) are reported as concentrations in the soil extract (mg L^{-1}) and are used to characterize ionic composition rather than as direct mass-based soil contents. DEM data were obtained from the 30-meter resolution ASTER GDEM, which was used to derive slope and aspect. The distance of sampling points from Chaiwopu Lake was precisely calibrated using field measurements and GIS remote sensing data. Vegetation coverage (VC) data were obtained through the inversion of optical remote sensing data and verified with field observations. Biodiversity was assessed using Simpson's Diversity Index (SDI). Alongside soil salinization sample collection, a 20 m x 20 m vegetation survey plot was established at each sample point; by aggregating the probabilities of all plant species in a community, the Simpson Index (SDI) can be calculated.

$$D = 1 - \sum_{i=1}^s p_i^2$$

The elevation (El) data for the research points was sourced from the Geospatial Data Cloud (www.gscloud.cn), and micro-topography of the points was recorded during field surveys. Groundwater-level decline (Gld) was derived from reconstructed groundwater-level surfaces for 1984 and 2023. Regional groundwater-level contour maps and hydrogeological data were georeferenced, digitized, and converted into continuous groundwater-level surfaces in GIS using a consistent contour-based surface reconstruction procedure. The groundwater-level decline was calculated as $\text{Gld} = H_{1984} - H_{2023}$, with positive values indicating groundwater-level decline. Gld

values at the 39 sampling sites ranged from 5.1 to 19.5 m.

Risk factors and data sources

We considered nine indicators capturing soil chemistry, topography, hydrology, and vegetation. To avoid ambiguity, symbols and definitions are standardized and used consistently: ESP (exchangeable sodium percentage), pH, Slo, Asp, El, DtC, Gld, SDI, and VC. Each variable is introduced at first mention by full name + symbol and retains the same symbol across text, figures, and tables; units are consistent (e.g., slope in degrees; TDS in g kg⁻¹).

Table 1. Definitions, symbols, units, and data sources of the salinization risk indicators used in this study

Symbol	Full name	Definition / physical meaning	Units	Data source (this study)
ESP	Exchangeable Sodium Percentage	Degree of soil sodicity; defined as $ESP = (Exchangeable\ Na / CEC) \times 100$. Used as an indicator of Na ⁺ dominance on the exchange complex.	%	As compiled for this study (see Section Sampling and analyses for analytical details)
pH	Soil pH (1:5 extract or as measured in this study)	Acidity/alkalinity of the soil extract used in this study; indicates alkalization tendency.	–	As compiled for this study
Slo	Slope	Local terrain steepness derived from DEM and reported in degrees .	°	DEM-derived
Asp	Aspect	Downhill-facing direction of the surface; 0–360° clockwise from north (flat areas may be assigned -1 by GIS tools).	°	DEM-derived
El	Elevation	Surface elevation at the sampling location (or raster cell).	m	DEM-derived
DtC	Distance to lakeshore	Euclidean distance from each sampling location to the mapped lake lakeshore for the sampling year (positive outward).	km	Lakeshore interpreted for this study
Gld	Groundwater level change (decline)	Difference between the reconstructed groundwater surface in 1984 and that in 2023; positive values indicate groundwater-level decline and represent the regional hydrological disturbance gradient.	m	Reconstructed from regional groundwater-level contour maps, hydrogeological materials, available groundwater-level records, and field investigation data for 1984 and 2023
SDI	Simpson's Diversity Index	Vegetation diversity index computed as $SDI = 1 - \sum p_i^2$ (Gini–Simpson form), where p_i is the	–	Vegetation composition data compiled for this study

		relative abundance of species <i>i</i> within the plot/area considered.		
VC	Vegetation coverage	Fractional vegetation cover in the lakeshore zone, aggregated to the analysis unit used in this study	%	as compiled for this study

To ensure unambiguous use, each variable is introduced at first mention by full name + symbol in parentheses (e.g., “Simpson’s Diversity Index, SDI”) and the same symbol is retained throughout the text, figures and tables. Units are kept consistent across all sections (e.g., slope in degrees everywhere, or percent everywhere). Where applicable, the year and mapping basis (e.g., lakeshore for the sampling year, DEM product) are specified in the corresponding data subsection.

Statistical analysis

We modeled surface-soil TDS (g kg^{-1}) as a function of nine indicators using standard multiple linear regression (ordinary least squares) with all predictors entered simultaneously. Before interpreting the standardized regression coefficients, potential multicollinearity among the nine predictors was evaluated using variance inflation factors (VIFs), tolerance values, and pairwise correlation analysis. VIF values below 5 were considered to indicate no substantial multicollinearity, whereas values between 5 and 10 were interpreted as moderate collinearity requiring cautious interpretation of regression coefficients. Model fit was assessed using R^2 , and standardized coefficients (β) were used to compare the relative explanatory contribution of each predictor within the combined model. Indicator weights were determined through a two-step data-driven procedure. First, the absolute Pearson correlation coefficient between each indicator and TDS was used to represent its bivariate association with surface soil salinity, and the correlation-based weight was calculated as $w_{r,i} = |r_i| / \sum |r_i|$. The absolute value was used because the sign of the correlation indicates the direction of influence, whereas the weight represents the relative contribution magnitude. Second, the absolute standardized regression coefficient of each indicator was used to represent its relative contribution within the multivariable regression model, and the regression-based weight was calculated as $w_{\beta,i} = |\beta_i| / \sum |\beta_i|$. The final composite weight was obtained by equally integrating the two components, $W_i = 0.5w_{r,i} + 0.5w_{\beta,i}$, so that both the single-factor association with TDS and the multivariable explanatory contribution were reflected in the CR index.

Salinization Assessment

Currently, there is no unified standard within the academic community for classifying the types and degrees of soil salinization. This is primarily because the formation mechanisms, processes, dominant conditions, and characteristics of soil salinization vary significantly across different countries and regions (Lin et al., 2022; Liu et al., 2023; Celleri et al., 2022). To enhance the regional applicability of the classification framework, this study adopted the salinity and alkalinity classification thresholds from *Improvement of Saline Soils in Xinjiang* (Xu, 1980), a regional reference specifically developed for salt-affected soils in Xinjiang. This standard was selected because salinization in Xinjiang is strongly controlled by arid climate, high evaporation, shallow and fluctuating groundwater, inland basin topography, and locally variable salt composition, which

differ from the mechanisms of coastal salinization or humid-region soil alkalization. Therefore, the thresholds used in this study are not intended as universal global criteria, but as regionally appropriate standards for interpreting soil salinization and alkalization in the Chaiwopu lakeshore zone.

The specific classification standards are presented in Tables 2-5.

Before classifying saline soils, it is necessary to grade them. Given the significant impact of saline soils on crop growth, their grading is primarily based on the salt tolerance of most crops, typically using the ratio of cations and anions as the criterion for determination (Perri et al., 2022).

Table 2. Classification Standards for Types of Salt Composition

Cl^-/SO_4^{2-}	>2	1-2	0.2-1	<0.2
Type of Salinization	Chloride	Sulfate-Chloride	Chloride-Sulfate	Sulfate

Note: The classification thresholds in Tables 2–5 are based on the regional saline-alkali soil classification framework proposed by Xu (1980) for Xinjiang soils.

The process of soil salinization involves the continuous accumulation of salts in the soil, for example, meadow soils not initially salinized being replaced by salinized meadow soils due to progressive salt accumulation, leading to a further deterioration of salinization (Mazhar et al., 2022; Ramos et al., 2023). Therefore, the grading of soil salinization levels was based on total dissolved salts (TDS) expressed on an oven-dry soil mass basis ($g\ kg^{-1}$), as shown in Table 3.

Table 3. Classification Standards for Degrees of Salinization in Chloride-Sulfate Soils

Degree of Salinization	Very Light	Light	Moderate	Severe	Saline Soil
TDS ($g\ kg^{-1}$)	6-8	8-10	10-15	15-20	>20
Growth of Salt-tolerant Crops	Normal growth, unaffected	Generally grows, slightly inhibited	Inhibited, significantly reduced yield	Severely inhibited, reduced yield due to missing plants	Death, no yield

Note: TDS thresholds are expressed on an oven-dry soil mass basis. The original percentage-based thresholds were converted to $g\ kg^{-1}$ using $1\% = 10\ g\ kg^{-1}$.

Table 4. Classification Standards for Alkaline Soils (pH)

Alkalinity Degree	Non-alkaline Soil	Weakly Alkaline	Moderately Alkaline	Strongly Alkaline	Alkaline Soil
pH	<8.5	8.5–9.0	9.0–9.5	9.5–10.0	≥ 10.0

Soil alkalization, commonly represented by exchangeable sodium percentage (ESP), is classified differently across regions. Some studies use 15% as the threshold for sodic or alkalized soils, whereas other standards adopt 20%. Considering the regional characteristics of Xinjiang soils, including the relatively low content of exchangeable cations, this study adopts 20% as the threshold for alkaline soils and further classifies ESP into continuous ranges for non-alkaline, weakly alkaline, moderately alkaline, strongly alkaline, and alkaline soils (Table 5).

$$ESP = \left(\frac{Na^+}{Ca^{2+} + Mg^{2+} + K^+ + Na^+} \right) \times 100\%$$

Table 5. Classification Standards for Alkaline Soils

Alkalinity Degree	Non-alkaline Soil	Weakly Alkaline	Moderately Alkaline	Strongly Alkaline	Alkaline Soil
Exchangeable Sodium as a % of Total Exchangeable Cations	<3	3–5	5–10	10–20	≥20

Salinization Risk Assessment

The assessment of soil salinization risk employs a multifactorial comprehensive index method, constructing a comprehensive score of soil salinization risk (CR). This approach allows for a quantifiable measure of salinization risk, taking into account various contributing factors. The CR is calculated as follows:

$$CR = \sum (K_i \times Q_i)$$

Where K_i is the final composite weight of indicator i , corresponding to W_i derived from the integrated correlation–regression weighting procedure, and Q_i is the standardized risk value of indicator i . For indicators positively related to salinization, higher standardized Q_i values indicate higher risk; for indicators negatively related to salinization, the standardization direction was reversed so that higher Q_i values consistently represented higher salinization risk. In this way, the sign of the correlation or regression coefficient was retained in the risk-direction standardization, while the absolute coefficient magnitude was used only to determine the relative contribution weight.

To ensure the reliability of the CR value, it is necessary to standardize the data:

$$CR' = \frac{(CR - CR_{min})}{(CR_{max} - CR_{min})}$$

In this formula, CR' refers to the normalized comprehensive evaluation index of soil salinization risk, with CR_{max} 、 CR_{min} representing the maximum and minimum values of the soil salinization risk comprehensive evaluation index, respectively.

After CR' values were obtained for the 39 sampling locations, the spatial distribution of salinization risk was mapped using inverse distance weighting (IDW) interpolation. IDW was selected as a deterministic local interpolation method to generate an intuitive risk-zoning map from point-based CR' values. The reliability of the generated map was assessed by comparing the spatial pattern of interpolated high-risk zones with the observed TDS distribution and by examining the correlation between CR' and measured TDS. Because no independent validation dataset was available, uncertainty was mainly considered in relation to sampling density, edge effects, and the spatial heterogeneity of soil salinity. Therefore, the IDW-derived risk map was interpreted as a relative vulnerability-zoning result rather than an exact cell-scale prediction of soil salinity.

The normalization process adjusts the range of the CR values, enabling comparison and aggregation across different datasets or study areas. By applying this standardized index, stakeholders can prioritize areas for intervention based on their relative risk levels. The inclusion of diverse factors into the CR calculation allows for a holistic understanding of salinization risk, incorporating climatic, hydrological, and human-induced variables that contribute to the salinization process.

This comprehensive assessment aids in identifying high-risk areas for soil salinization, guiding targeted management and remediation efforts. Moreover, by continually updating the CR with new data, it is possible to monitor changes in salinization risk over time, enabling dynamic management strategies to mitigate the impacts of soil salinization on agricultural productivity, water resources, and ecosystem health.

Results and Discussion

Assessment of Soil Salinization

Descriptive Characterization

The descriptive statistics provide a synoptic view of lakeshore salinization. The major chemical components and associated indicators of soil salinization in the Chaiwopu Lake lakeshore zone are presented in Table 6. Soil pH varies from 8.24 to 9.63, with a mean value of 8.86, indicating an overall alkaline environment. The principal ions measured in the soil extract include Cl^- , SO_4^{2-} , CO_3^{2-} , HCO_3^- , K^+ , Ca^{2+} , Na^+ , Mg^{2+} , while total dissolved solids (TDS) are expressed as soil total soluble salts content on a mass basis. These variables show the following observed ranges (Min–Max): 0.20 to 39.20 for Cl^- , 0.13 to 4.74 for SO_4^{2-} , 0.00 to 0.05 for CO_3^{2-} , 0.03 to 0.18 for HCO_3^- , 0.02 to 0.38 for K^+ , 0.12 to 3.34 for Ca^{2+} , 0.18 to 8.20 for Na^+ , and 0.04 to 0.61 for Mg^{2+} . The high CV of CO_3^{2-} (2.29) resulted mainly from its zero-inflated distribution: 28 of the 39 observations were recorded as zero, producing a very low mean concentration (0.0051) and a median of 0. Because CO_3^{2-} was used only for descriptive geochemical interpretation and was not included in the nine-predictor OLS model or CR calculation, its skewed distribution did not affect the assumptions or estimates of the core statistical model. Cl^- concentrations were substantially higher than SO_4^{2-} concentrations. Given the relatively high mobility and weak soil retention of Cl^- , this ionic pattern indicates that salts can be readily redistributed through lake-groundwater exchange and capillary rise and subsequently concentrated in near-surface soils by strong evaporation and limited leaching.

Table 6. Parameters related to the assessment and risk evaluation of salinization in the Chaiwopu Lake lakeshore zone.

Parameters	Sample size	Min	Max	Average	Variance	SD	CV	Data type
TDS (g kg^{-1})	39	1.69	55.50	16.67	162.66	12.75	0.77	+
ESP (%)	39	25.58	95.26	66.84	323.42	17.98	0.26	+
pH	39	8.24	9.63	8.86	0.14	0.37	0.04	+
Slo ($^\circ$)	39	0	2.390	0.64	0.42	0.65	1.01	+
Asp ($^\circ$)	39	0	351.86	120.63	14004.52	118.34	0.98	/
DtC (km)	39	0.11	11.08	2.91385	8.87307	2.97877	1.02	—
Gld (m)	39	5.10	19.50	13.68	14.43	3.80	0.28	+

SDI (-)	39	0.29	0.84	0.56	0.02	0.16	0.28	—
VC (%)	39	3.00	83.00	44.56	372.30	19.30	0.43	—
El (m)	39	1084.68	1116.89	1100.38	99.47	9.97	0.01	—
Cl ⁻ (mg L ⁻¹)	39	0.20	39.20	6.72	96.08	9.80	1.46	/
SO ₄ ²⁻ (mg L ⁻¹)	39	0.13	4.74	1.69	1.95	1.40	0.83	/
CO ₃ ²⁻ (mg L ⁻¹)	39	0.00	0.0474	0.0051	0.000135	0.0116	2.29	/
HCO ₃ ⁻ (mg L ⁻¹)	39	0.03	0.18	0.09	0.00	0.04	0.43	/
K ⁺ (mg L ⁻¹)	39	0.02	0.38	0.21	0.01	0.12	0.54	/
Ca ²⁺ (mg L ⁻¹)	39	0.12	3.34	1.65	0.86	0.93	0.56	/
Na ⁺ (mg L ⁻¹)	39	0.18	8.20	4.97	6.99	2.64	0.53	/
Mg ²⁺ (mg L ⁻¹)	39	0.04	0.61	0.14	0.01	0.09	0.65	/

Note: TDS is expressed as soil total soluble salts content (g kg⁻¹, oven-dry soil basis), whereas major ions are expressed as concentrations in the soil extract (mg L⁻¹). For CO₃²⁻, 28 of the 39 observations were recorded as zero. Its median and interquartile range were 0 and 0 – 0.00295, respectively. The CV was calculated using the unrounded mean and sample standard deviation.

Distribution of Soil Salinization and Alkalinization in the Study Area

Figure 2(a) maps TDS classes, showing the highest salinization around the lake—dominated by saline (20.95%) and severely salinized soils (24.61%). This near-lake concentration of high TDS is consistent with the climatic setting shown in Figs. 5 and 7, where strong evaporation and high E/P favor evaporative concentration in lake-margin and low-lying zones. Toward the northwest, salinization weakens to moderate, light (12.37%), and very light (5.25%) classes. Figure 2(b) shows the spatial distribution of soil pH. Overall, soil pH ranges from 8.24 to 9.63 (Table 6), indicating an overall alkaline environment. Based on the pH classification (Table 4), weakly alkaline soils (8.5–9.0) dominate (74.25%), moderately alkaline soils (9.0–9.5) account for 17.74%, strongly alkaline soils (9.5–10.0) occupy 5.67%, and non-alkaline soils (<8.5) represent 2.34%. Higher pH values are mainly concentrated on the south–southeast lakeshore, whereas the north–east and west–northwest sectors are dominated by weak alkalization. Because these proportions indicate a substantial extent of moderate to severe salinization, their interpretation requires comparison with the historical evolution of Chaiwopu Lake and with salinization processes reported in comparable arid-lake and arid-basin environments.

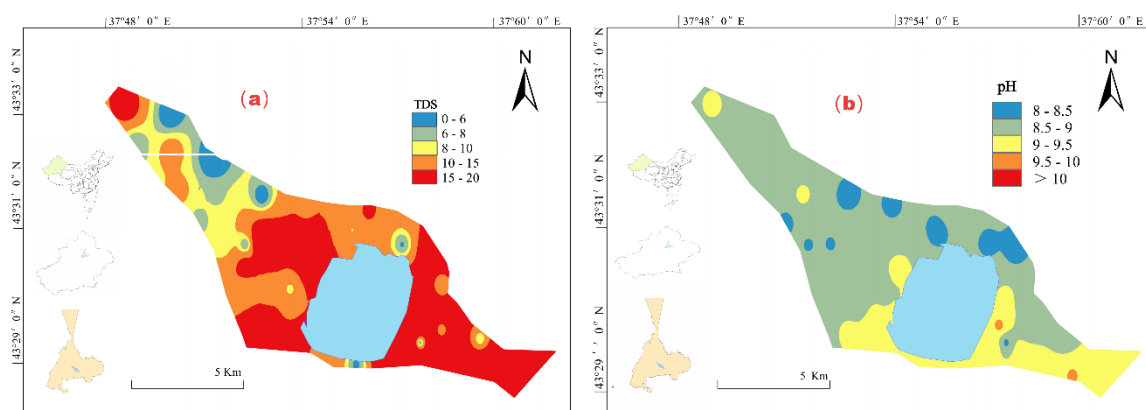


Fig. 2. Spatial distribution of (a) soil total dissolved salts (TDS, 0–20 cm) and (b) soil pH in the Chaiwopu lakeshore zone

Classification of Soil Chemical Ions Affecting Salinization

Consistent with Figure 3 and Table 6, the pronounced spatial variability of Cl^- and its co-occurrence with elevated Na^+ indicate active and spatially heterogeneous water – salt redistribution rather than merely a compositional classification. In this closed-basin lakeshore setting, relatively conservative and weakly retained Cl^- can be transported through lake – groundwater exchange and capillary rise and subsequently concentrated in near-surface soils by strong evaporation and limited leaching. As lake levels decline and former inundation zones are exposed, repeated mobilization and re-accumulation of soluble salts may increase the persistence of surface salinity and the likelihood of salt rebound after short-term leaching or superficial treatment (Hardie and Eugster, 1970; Eugster and Hardie, 1978; Warren, 2016).

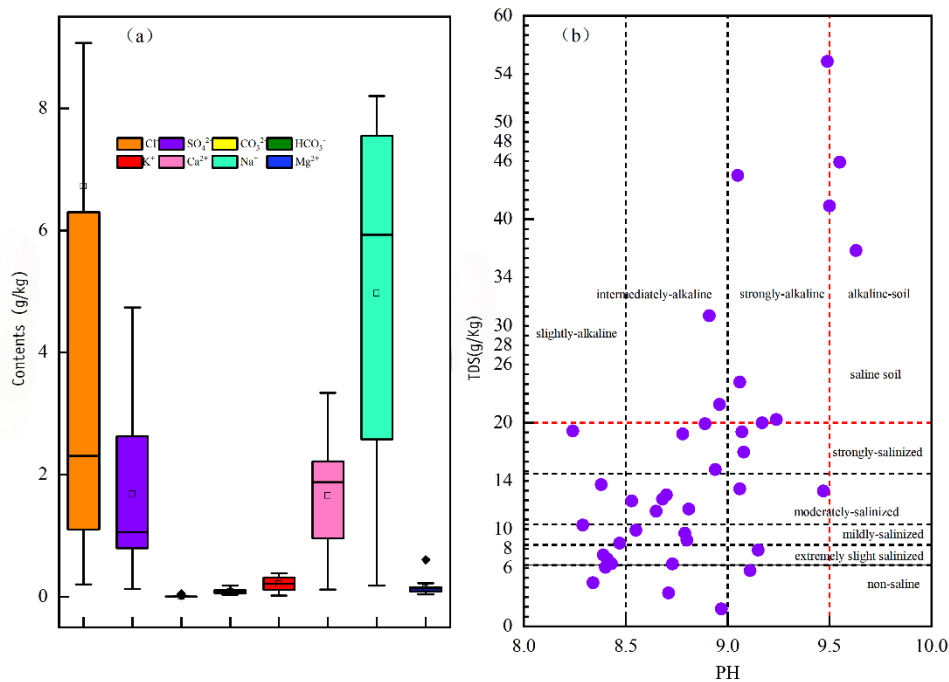


Fig. 3. Major-ion concentration box plots and TDS-pH classification of soil samples.

The high Na^+ and Cl^- concentrations in several near-lake and former inundation sampling points therefore reflect a combined geochemical process: evaporation-driven concentration of lake-derived salts, lake-groundwater exchange, and secondary accumulation after shoreline exposure. In comparison, carbonate and bicarbonate concentrations are relatively low, and Ca^{2+} and Mg^{2+} may be partly regulated by carbonate/sulfate precipitation, ion exchange, and dilution by local groundwater or surface runoff. This explains the stronger spatial variability of Cl^- and indicates that severe near-lake salinization is maintained by recurrent hydrological transport and evaporative reconcentration rather than by a static salt reservoir alone. The relatively weaker Na-Cl dominance in some northern and northwestern sectors suggests reduced direct influence from lake water, stronger background soil control, local vegetation buffering, or historical scouring and dilution near the old river channel.

Factors Influencing the Degree of Salinization and the Distribution of Chemical Ions in the Study Area

Shoreline salinization reflects the coupled effects of micro-topography, hydro-climatic forcing and groundwater dynamics, and vegetation structure, with human activities acting as multipliers.

Figure 4 provides a geochemical-facies comparison of the major ions and further supports the chloride-related salinization mechanism. In the saline soils on the south and southeast sides of Chaiwopu Lake, Na^+ , K^+ , and Cl^- are clearly higher than most other ions, indicating stronger influence from lake-level fluctuation, shoreline erosion/exposure, and lake-groundwater exchange. This ionic composition is consistent with an evaporation-concentration pathway in which soluble

chloride salts are repeatedly mobilized and re-concentrated in near-surface soils under strong evaporative demand. In contrast, the northern lakeshore, where reed beds are present, shows weaker Na–Cl dominance, suggesting lower direct lake-water influence and stronger modification by vegetation, shallow groundwater, and local soil background. The northwestern sector is more heterogeneous: with increasing distance from the lake, the influence of lake-derived salts weakens, while terrain, groundwater flow, and historical channel processes become more important. The old river channel connected to Chaiwopu Lake likely promoted local flushing and redistribution of salts, explaining why nearby soils are mainly moderately or lightly salinized and show lower concentrations of major ions.

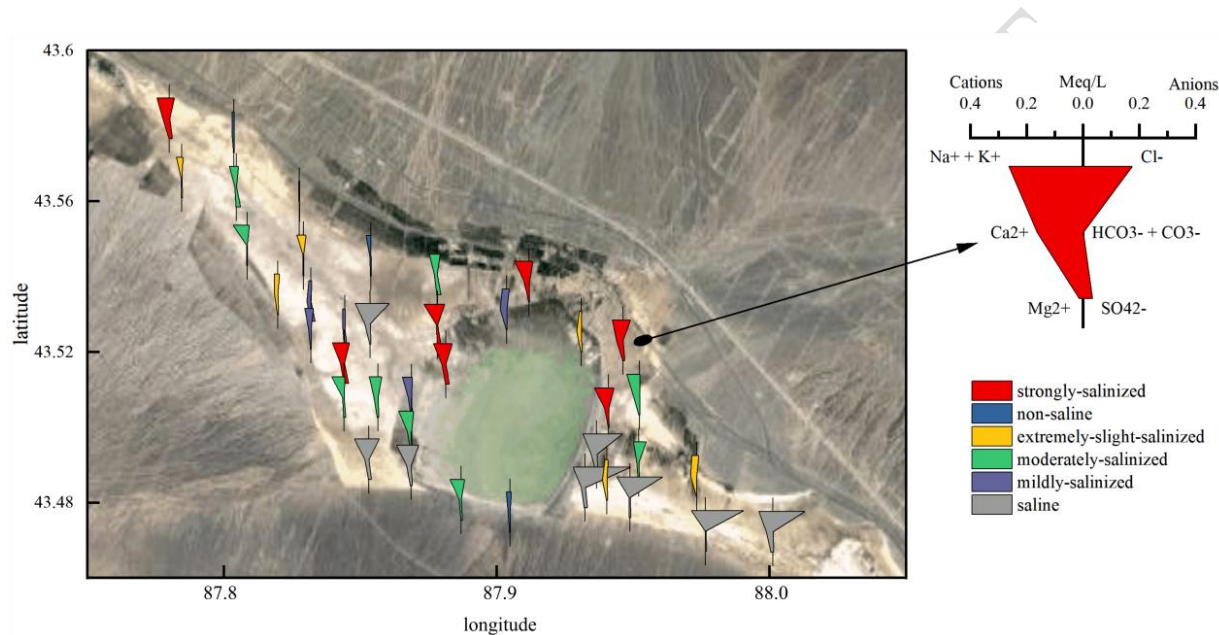


Fig. 4. Stiff diagram of Chaiwopu lake area

Comparison with Historical Context and Similar Arid-Lake Environments

The high proportion of moderately to severely salinized soils in the Chaiwopu lakeshore zone should be interpreted in the context of both typical arid-lake salinization processes and recent lakeshore degradation. On the one hand, strong evaporation, low precipitation, shallow or fluctuating groundwater, and closed-basin topography are common controls of salt accumulation in arid inland lake systems. A global synthesis of saline lakes showed that declining water levels and exposed lakebeds are widespread in many closed-basin lakes, often leading to salt-dust emission, habitat degradation, and land-surface deterioration around receding shorelines (Wurtsbaugh et al., 2017). Similar processes have been documented in Lake Urmia, where lake desiccation has been linked to combined climatic stress and human water-resource disturbance, and has been regarded as an “Aral Sea syndrome” requiring urgent management intervention (AghaKouchak et al., 2015). These studies indicate that salt accumulation around Chaiwopu Lake is consistent with a broader pattern typical of shrinking arid and semi-arid inland lakes.

On the other hand, the severity and spatial concentration of salinization observed in Chaiwopu Lake suggest more than a stable natural background condition. The Aral Sea case demonstrates that long-term lake shrinkage and water diversion can transform former lake margins into degraded saline surfaces, with serious environmental consequences for surrounding land systems (Micklin, 2007).

In Chaiwopu Lake, previous local studies have documented lake shrinkage, wind erosion around exposed lakeshore surfaces, and geochemical evidence of long-term climatic and anthropogenic disturbance (Ma et al., 2013; Liu et al., 2016; Lv et al., 2024). Therefore, the present distribution of saline and severely salinized soils should be interpreted as the combined result of typical arid inland-lake salt accumulation and progressive lakeshore degradation associated with lake shrinkage, groundwater alteration, and exposure of former lake-margin surfaces. Because this study is mainly based on 2023 surface-soil observations, it cannot directly quantify the acceleration rate of salinization; nevertheless, the high areal proportion and near-lake concentration of moderate to severe salinization are consistent with an intensifying land-degradation signal rather than a purely natural background pattern.

Factors Influencing Salinization

Natural Factors

Salinity patterns reflect the joint action of climate, topography, groundwater, and lake-margin exposure, producing clear spatial contrasts across the lakeshore zone. The Dabancheng meteorological records show that annual evaporation consistently exceeded annual precipitation during 1993 – 2022, resulting in a persistently high E/P ratio (Fig. 5). This long-term climatic water deficit restricts the downward leaching of soluble salts, while strong evaporative demand promotes capillary water movement and salt concentration in the near-surface soil. Therefore, the high-salinity zones mapped around the lake should not be interpreted only as local soil-chemical anomalies, but as the spatial expression of evaporation-dominated water–salt redistribution under arid climatic conditions. Similar evaporation-driven salinization processes have been reported in arid and semi-arid environments where evaporative concentration exceeds leaching capacity (Perri et al., 2022; Shokri et al., 2024). The unique topography of “three mountains flanking two basins” further causes surrounding soluble salts to flow into and deposit within the basins through irrigation water. The soil water-salt balance involves two main processes: groundwater rises to the surface through capillary action and evaporates, leaving its salts in the soil; meanwhile, precipitation dissolves the soil salts, which then percolate down to the groundwater under gravity.

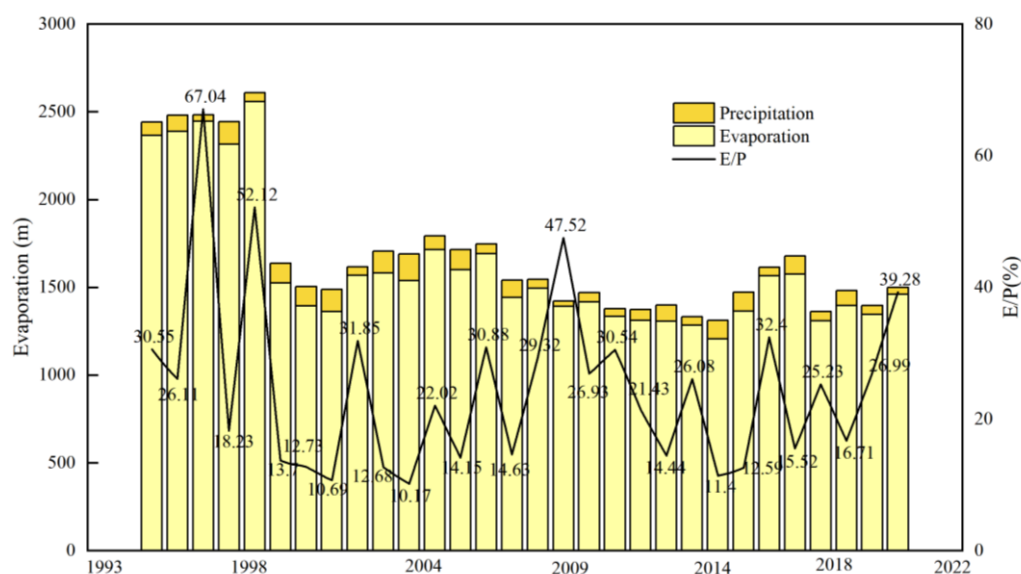


Fig. 5. Annual precipitation, station-observed evaporation, and evaporation-to-precipitation ratio (E/P) recorded at the Dabancheng meteorological station near Chaiwopu Lake during 1993 – 2022.

Topography anchors where salts accumulate (Fig. 6): flat micro-relief and slow drainage promote lateral convergence and depression-type salt accumulation, especially along low-lying belts.

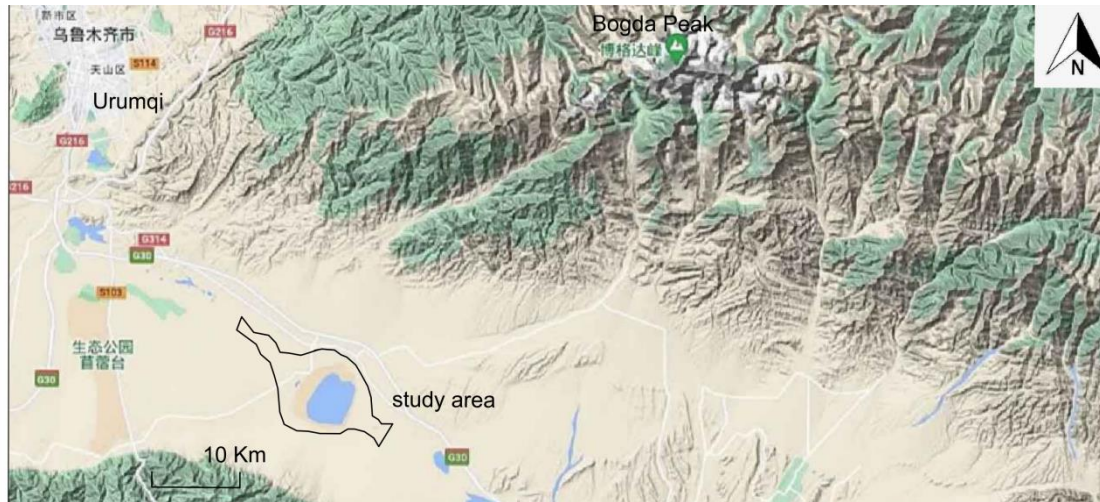


Fig. 6 Topographic Map of the Chaiwopu Lake lakeshore.

Figure 7 further links the evaporation-to-precipitation ratio (E/P) with the mapped TDS pattern. Areas with higher E/P generally correspond to stronger surface salinity, especially in near-shore and low-lying sectors where lake-level fluctuation, shallow groundwater, and weak drainage favor salt retention. In these areas, high evaporative demand enhances capillary rise and concentrates dissolved salts in the 0–20 cm soil layer, whereas limited precipitation is insufficient to leach salts downward. By contrast, the relatively weaker salinization toward the northwest is consistent with lower evaporative concentration, better drainage conditions, and reduced direct influence from lake-margin exposure. Thus, the spatial pattern of TDS is climatically constrained by the E/P gradient, but its local expression is further modified by topography and groundwater conditions.

From 1984 to 2023, long-term groundwater abstraction on the west and north flanks altered the regional groundwater field. The reconstructed groundwater-level contours for 1984 and 2023 show clear changes in the groundwater field around Chaiwopu Lake (Fig. 8). By differencing the two reconstructed groundwater surfaces, Gld values at the sampling locations were estimated to range from 5.1 to 19.5 m, indicating a pronounced regional hydrological disturbance gradient across the lakeshore zone. Areas with larger reconstructed groundwater decline generally correspond to sectors affected by water-source exploitation and lake-margin exposure, where changes in groundwater flow conditions can modify capillary rise, evaporation-driven salt accumulation, and lake–groundwater exchange. However, because the 1984 groundwater surface was reconstructed from historical groundwater-level contour information, Gld should be interpreted as a regional groundwater-decline gradient rather than an exact point-scale groundwater monitoring record. This uncertainty was considered when using Gld as an explanatory variable in the salinization risk model.

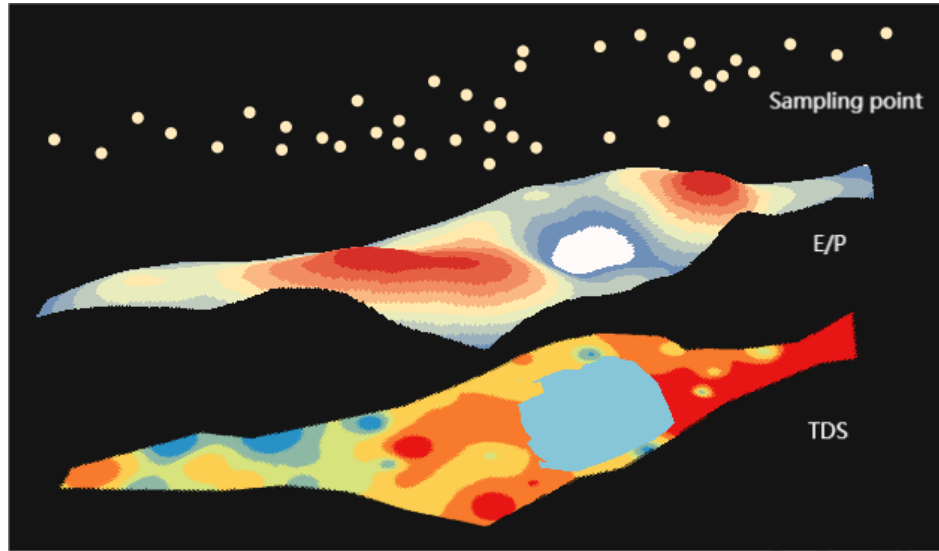


Fig. 7. Heat-map comparison of the evaporation-to-precipitation ratio (E/P) and soil salinity (TDS) across the Chaiwopu lakeshore

Previous studies have shown that soil salinization in arid and semi-arid regions is strongly controlled by vertical water–salt transport processes, in which evaporation, capillary rise, and groundwater dynamics jointly regulate the redistribution of salts within the soil profile (Perri et al., 2022; Ramos et al., 2023; Shokri et al., 2024). Because the present dataset was based on 0–20 cm soil samples, the mapped salinity and CR patterns mainly describe the surface expression of salinization. Deeper soil layers may further influence the observed surface pattern by regulating the upward salt supply under capillary rise, especially in low-lying lakeshore sectors affected by groundwater fluctuation. If salts are enriched in deeper layers, surface salinity may persist or reappear even after temporary leaching; conversely, if deeper layers contain lower salt contents, high surface salinity may mainly reflect recent evaporation-driven concentration or lake-level fluctuation/exposure processes. Therefore, the strong surface salinity observed around the lake should be understood as the near-surface manifestation of a broader water–salt redistribution process. Future work combining profile sampling with groundwater monitoring would help distinguish short-term surface salt accumulation from longer-term vertical salt migration.

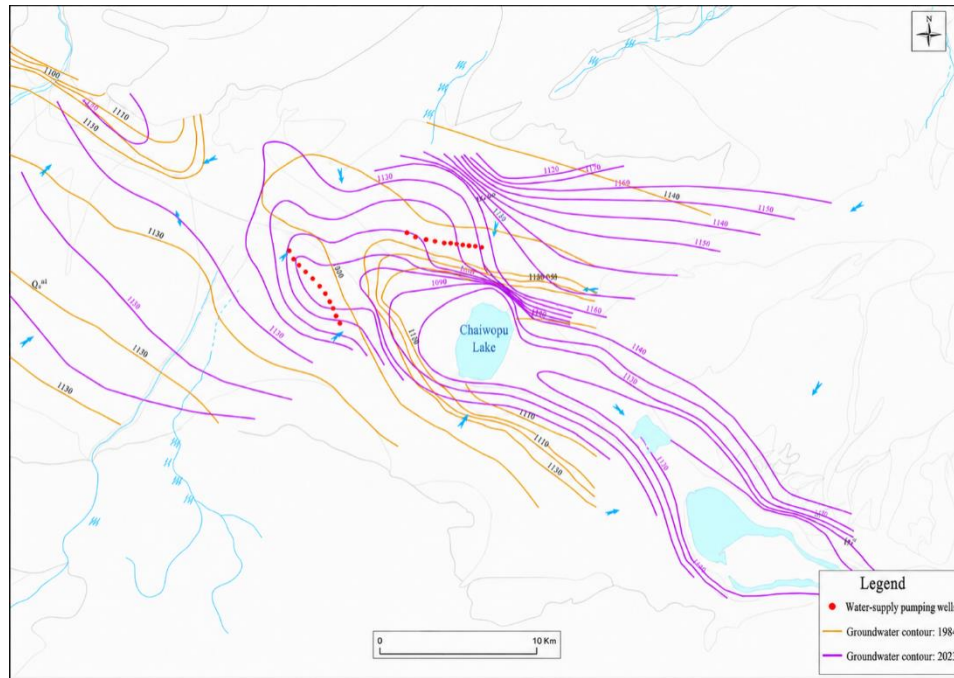


Fig. 8. Reconstructed groundwater-level contours for 1984 and 2023 in the Chaiwopu Lake area. Red dots denote water-supply pumping wells.

The strong contribution of Simpson's Diversity Index should be interpreted as both a potential ecological buffering effect and an indirect response to environmental gradients. Vegetation diversity and coverage can influence surface salinity by modifying near-surface microclimatic and soil conditions: more diverse and better-covered plant communities may reduce direct soil evaporation, improve soil structure, increase organic inputs, and stabilize the soil surface, thereby weakening evaporative salt accumulation. This interpretation is consistent with dryland studies showing that plant species richness is closely related to ecosystem multifunctionality and soil-function maintenance under water-limited conditions (Maestre et al., 2012), as well as with ecological theory suggesting that positive plant interactions and facilitative effects become more important under stressful environments (Bertness and Callaway, 1994; Bruno et al., 2003). However, the relationship between SDI and salinization should not be interpreted as a purely direct causal effect. In saline and arid lakeshore environments, plant communities are strongly filtered by salinity stress, water availability, elevation, and groundwater conditions; high salt concentrations restrict the establishment of less salt-tolerant species, whereas relatively favorable moisture and lower-salinity microsites support higher diversity and coverage (Flowers and Colmer, 2008). Therefore, in this study, the negative relationship between SDI and TDS likely reflects a combined mechanism: vegetation diversity may partly buffer salt accumulation, but it also serves as an integrated ecological indicator of underlying moisture, salinity, elevation, and groundwater gradients. This interpretation is consistent with the observed coupling between vegetation-related indicators and other environmental variables in the regression and collinearity diagnostics.

Anthropogenic Factors.

Anthropogenic actions amplify natural controls: groundwater abstraction, irrigation pressure, and water-quality deterioration can jointly intensify salinization risk in semi-arid basins (Bouchema et

al., 2024). Field investigations indicate that pumping from the sixth and seventh water plants (west and north of the lake) has intensified groundwater fluctuations, constituting a major driver of lakeshore salinization.

Comprehensive Evaluation of Salinization Risk

Factors Affecting Salinization Risk

Correlation between Surface Soil Salinity and Risk Factors. This study conducted a correlation analysis between ESP (Exchangeable Sodium Percentage), pH, Slope (Slo), Aspect (Asp), Distance to Chaiwopu Lake (DtC), Groundwater Level Decline (Gld), Simpson's Diversity Index (SDI), Vegetation Coverage (VC), Elevation (El), and Total Dissolved Solids (TDS) to elucidate the relationship between these risk assessment indicators and soil salinization. The exchangeable sodium percentage (ESP), pH, aspect (Asp), and groundwater level decline (Gld) are positively correlated with the degree of soil salinization, with correlation coefficients of 0.405, 0.653, 0.088, and 0.363, respectively. Simpson's Diversity Index (SDI) and Vegetation Coverage (VC) are negatively correlated with the state of soil salinization, with correlation coefficients of -0.753 and -0.751, respectively. Slope (Slo), Distance to Chaiwopu Lake (DtC), and Elevation (El) are negatively correlated with the state of soil salinization, with correlation coefficients of -0.184, -0.185, and -0.517, respectively. According to the absolute values of the correlations, the risk assessment indicators related to surface soil salinity from highest to lowest are SDI, VC, pH, El, ESP, Gld, DtC, Slo, and Asp.

Impact of Soil Salinization Risk Factors

Using TDS as the dependent variable and ESP, pH, Slo, Asp, DtC, Gld, SDI, VC, and El as independent variables, a standard multiple linear regression (ordinary least squares) model was fitted. Before interpreting the standardized regression coefficients, potential multicollinearity among the predictors was examined using VIFs, tolerance values, and pairwise correlation analysis. The VIF values ranged from 1.361 for aspect (Asp) to 5.316 for elevation (El), and all values were far below 10 (Table 8). Except for El, which slightly exceeded the conservative threshold of 5, all predictors had VIF values below 5, indicating that severe multicollinearity was not present in the regression model. The pairwise correlation matrix further showed that some landscape-gradient variables were correlated, particularly El with Gld ($r = -0.798$) and DtC ($r = 0.667$), SDI with VC ($r = 0.691$), pH with VC ($r = -0.606$), pH with SDI ($r = -0.547$), and DtC with Gld ($r = -0.505$). These correlations reflect the coupled terrain-groundwater-vegetation structure of the Chaiwopu lakeshore zone rather than simple redundancy among artificially duplicated predictors. Therefore, the regression coefficients were considered sufficiently stable for identifying relative explanatory contributions, but they should not be interpreted as fully independent causal effects of individual predictors. The results of the multivariate regression analysis (Table 7) yielded an R^2 value of 0.852, indicating that the selected nine indicators jointly explained 85.2% of the variance in TDS. Simpson's Diversity Index showed the largest relative contribution within the combined model, with a standardized coefficient of $\beta = 0.582$, followed by elevation ($\beta = 0.569$) and pH ($\beta = 0.411$). Slope showed the smallest relative contribution ($\beta = 0.088$). Ranked by the absolute value of β , the order was SDI, El, pH, VC, ESP, DtC, Gld, Asp, and Slo.

Table 7. Influence of Salinization Risk Factors

Risk factor	Influence value (Beta)	Rank	Risk factor	Influence value (Beta)	Rank
SDI	0.582	1	DtC	0.219	6
El	0.569	2	Gld	0.156	7
pH	0.411	3	Asp	0.133	8
VC	0.321	4	Slo	0.088	9
ESP	0.239	5			/

Table 8. Multicollinearity diagnostics for the predictors used in the multiple regression model

Predictor	VIF	Tolerance
ESP	1.777	0.563
pH	2.643	0.378
Slo	2.062	0.485
Asp	1.361	0.735
DtC	3.305	0.303
Gld	2.952	0.339
SDI	2.226	0.449
VC	2.686	0.372
El	5.316	0.188

Overall, the collinearity diagnostics indicate that the regression model was not affected by severe multicollinearity, although moderate coupling existed among several landscape-gradient variables. This pattern is consistent with the spatial organization of an arid lakeshore system: elevation generally changes from low-lying shoreline sectors toward peripheral zones, groundwater-level decline varies along the same terrain gradient, vegetation coverage and diversity respond to both salinity stress and hydrological conditions, and distance to the lake partly represents the transition from lake-dominated to background soil-controlled environments. Therefore, the relatively high explanatory power of the model ($R^2 = 0.852$) was not attributed to unstable coefficient inflation alone, but to the combined effect of soil chemical, topographic, hydrological, and vegetation indicators. Nevertheless, because some predictors are naturally coupled, the standardized coefficients and the derived CR weights were interpreted as relative contributions to the integrated salinization risk pattern rather than as isolated causal effects.

Comprehensive Assessment of Soil Salinization Risk

Risk factor weights were used to express the relative contribution of each indicator to the composite salinization risk index. To improve the transparency of the weighting procedure, the final weight of each indicator was derived by integrating two complementary sources of information: the correlation coefficient with TDS and the standardized regression coefficient from the multivariable model. Specifically, the correlation component describes the strength of the direct bivariate relationship between each indicator and surface soil salinity, whereas the regression component reflects the relative explanatory contribution of each indicator after the other predictors are considered. Both components were converted into normalized weights using their absolute values,

and the final composite weight was obtained by averaging the correlation-based and regression-based weights. Therefore, Table 9 presents the complete weighting chain from the original correlation coefficient and standardized regression coefficient to the final composite weight used in the CR calculation. Among all indicators, SDI had the highest final composite weight (0.210), followed by EI (0.130), VC (0.128), and pH (0.126), indicating that vegetation diversity, elevation, vegetation coverage, and alkalinity jointly made the largest relative contributions to the integrated salinization risk pattern. Because some landscape-gradient variables showed moderate collinearity, these weights should be interpreted as relative contributions within the integrated risk-assessment framework rather than as fully independent causal effects of individual indicators. In particular, the high weight of SDI indicates its strong explanatory value for the integrated salinization pattern, but does not imply that vegetation diversity alone independently controls soil salinity.

Table 9. Weighting procedure for indicators used in the composite salinization risk index

Risk factor	Correlation component		Regression component		Composite result	
	$ r_i $	$w_{r,i}$	$ \beta_i $	$w_{\beta,i}$	W_i	Rank
SDI	0.753	0.185	0.582	0.263	0.210	1
EI	0.517	0.117	0.569	0.122	0.130	2
VC	0.751	0.121	0.321	0.117	0.128	3
pH	0.653	0.118	0.411	0.119	0.126	4
ESP	0.405	0.114	0.239	0.116	0.074	5
Gld	0.363	0.114	0.156	0.075	0.053	6
DtC	0.185	0.114	0.219	0.110	0.045	7
Slo	0.184	0.096	0.088	0.017	0.019	8
Asp	0.088	0.021	0.133	0.061	0.010	9

Soil Salinization Risk

Using the standardized indicator values and the final composite weights listed in Table 9, the Comprehensive Risk Assessment Index (CR) for soil salinization was calculated and then normalized to obtain CR'. The CR' values at the sampling locations were interpolated using IDW to generate the spatial risk-zoning map, and the reliability of the zoning result was evaluated by comparing the mapped high-risk areas with observed TDS patterns and the CR'–TDS correlation. Considering the specific conditions of the Chaiwopu Lake area and related research findings, the study area was divided into four risk levels: low risk (0–0.1), medium risk (0.1–0.3), high risk (0.3–0.5), and extremely high risk (0.5–1). The spatial distribution of risk varies significantly across different regions: low-risk areas (0.73 km², accounting for 0.77%), primarily located in the northwest corner; medium-risk areas (18.64 km², accounting for 19.79%), distributed in the northwest; high-risk areas (31.52 km², accounting for 33.47%), located near the lake in the north and on the east and west sides; extremely high-risk areas (43.29 km², accounting for 45.97%), mainly on the eastern and western lakeside areas and the historical tidal zone on the east side.

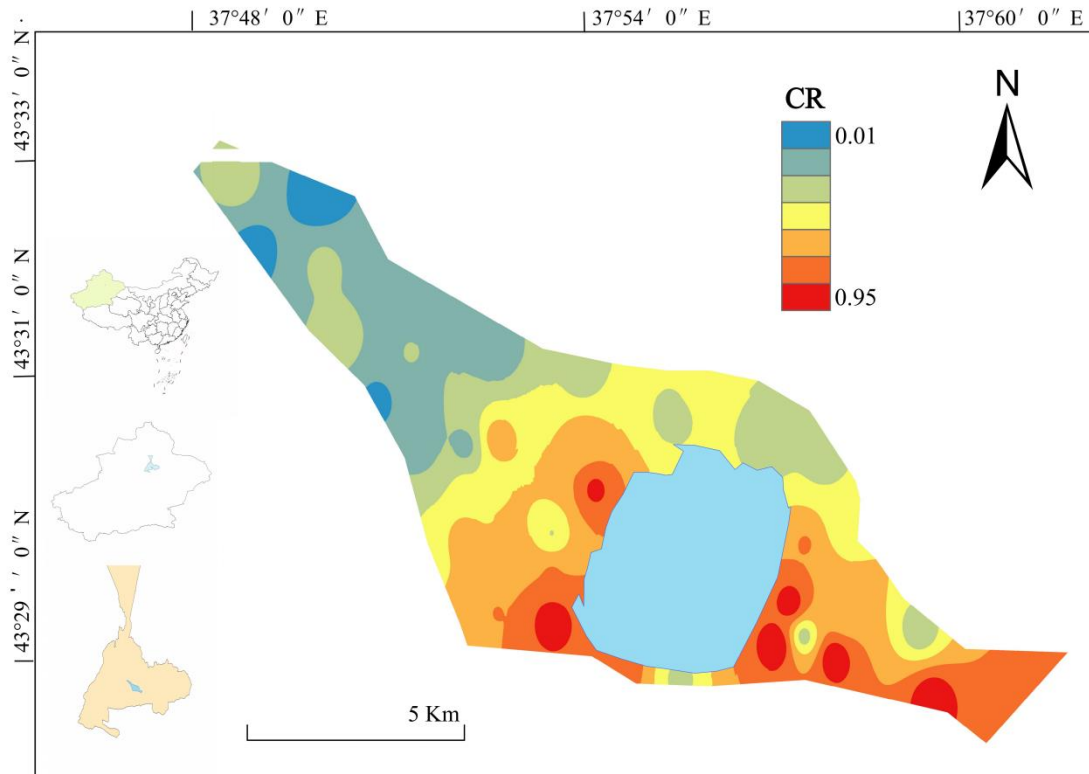


Fig. 9. Spatial distribution of soil salinization risk classes derived from the normalized composite risk index (CR) in the Chaiwopu lakeshore zone (0–20 cm) (IDW interpolation)

Accuracy and Uncertainty of the Salinization Risk Map

The reliability of the salinization risk assessment was evaluated from both index performance and spatial-interpolation uncertainty. The normalized CR index showed a strong positive correlation with measured TDS ($r = 0.801$), indicating that the integrated risk index was consistent with observed surface soil salinity and had diagnostic value for lakeshore salinization assessment. For the IDW-derived risk map, uncertainty mainly arises from the limited number of sampling points, the strong spatial heterogeneity of soil salinity, and possible edge effects in areas farther from sampling locations. Confidence in the mapped risk pattern is higher in the near-shore and key investigation areas where sampling density is greater and where high CR' values coincide with observed high TDS and severe salinization classes. In contrast, peripheral areas with fewer nearby sampling points should be interpreted more cautiously. Therefore, the generated risk map is most appropriate for identifying relative vulnerability zones and management priorities, rather than for exact cell-by-cell prediction of soil salinity.

Recommendations

Groundwater and lake-level management should be prioritized because the reconstructed groundwater-level decline, lake-margin exposure, and near-shore salinity patterns indicate that hydrological disturbance is closely associated with salt accumulation. Groundwater abstraction, groundwater levels, lake-surface changes, and soil salinity should therefore be jointly monitored, particularly around the eastern, western, and northern lakeshores. Further hydrological disturbance in these sensitive sectors should be minimized where practicable.

The CR-based risk map can be used to establish spatial management priorities. The eastern and western near-shore belts, where very high-risk areas are concentrated, should receive the highest priority for water–salt regulation and ecological rehabilitation, followed by the northern near-shore high-risk zone. In contrast, the northwestern low- and medium-risk areas should mainly be subject to preventive monitoring to avoid further salinization.

Vegetation management should focus on protecting existing plant communities and preventing further losses of vegetation coverage and diversity, because SDI and VC showed strong negative associations with surface-soil TDS. In severely salinized areas where natural recovery is limited, soil improvement and revegetation may be considered, but specific plant species, amendment materials, and application rates should be determined through site-

Conclusions

(1) Surface soils in the Chaiwopu lakeshore zone were extensively affected by salinization. Saline soils accounted for 20.95% of the study area and severely salinized soils for 24.61%, giving a combined proportion of 45.56%. Soil alkalization was generally less severe, with weakly alkaline soils occupying 74.25% of the area. The strongest salinization occurred mainly in near-shore and low-lying sectors, where chloride-related water–salt transport, strong evaporation, limited leaching, and lake-margin exposure promoted recurrent salt accumulation.

(2) The nine-indicator OLS model explained 85.2% of the variation in surface-soil TDS ($R^2 = 0.852$), and the collinearity diagnostics indicated no severe multicollinearity. SDI, elevation, pH, and vegetation coverage showed relatively high contributions within the integrated model. The negative associations of SDI and vegetation coverage with TDS suggest that vegetation condition is closely linked to surface salinity; however, SDI should be interpreted as an integrated indicator reflecting both potential ecological buffering and the influence of moisture, salinity, elevation, and groundwater gradients rather than as an independent causal driver.

(3) High- and very high-risk areas accounted for 33.47% and 45.97% of the study area, respectively, and together covered 79.44%. Very high-risk areas were concentrated mainly along the eastern and western lakeshores and the historical eastern lake-margin exposure zone, while high-risk areas also occurred along the northern near-shore belt. The strong correlation between CR' and measured TDS ($r = 0.801$) supports the use of the composite index for identifying relative risk zones and management priorities. The framework may provide a methodological reference for other arid lakeshore environments, but its indicators, weights, and risk thresholds should be recalibrated according to local hydrological conditions, salt composition, and vegetation characteristics before application elsewhere.

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