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Research Article

Effects of Groundwater Depth and Salt Content on Vegetation in Dry Lake Basins: A Case Study of Chahan Lake, Northern China

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Under the dual influences of global climate change and human activities, inland lakes in arid areas are shrinking and drying up, and a large area of bare lake bed has become the source of the release of chemical dust. The aim of this study is to study the control of groundwater on the distribution and development of natural vegetation and the effects of the groundwater conditions on soil salinization. In this study, a typical modern dry lake in northern China, Chahan Lake, was taken as the study area. Through field investigations, field sampling and analysis, and statistical analysis, the influence of groundwater on the ecosystem of this dry lake was studied. The results revealed that the vegetation communities in the lakeside zone were *Kalidium foliatum*, *Nitraria tangutorum*, *Suaeda glauca*, *Leymus chinensis*, *Chloris virgata*, and *Carex duriuscula* communities from the dry lake bed outwards. The groundwater table suitable for vegetation growth in Chahan Lake is 2.0–3.0 m deep. The groundwater table suitable for the growth of *Kalidium foliatum* vegetation is 1.5–2.5 m deep. The groundwater table suitable for the growth of *Leymus chinensis* vegetation is 3.0–4.0 m deep. In Chahan Lake, the critical groundwater depth and total dissolved solids (TDS) for moderate salinization, severe salinization, and saline soil occurrence are 4.0 m and 2.0 g/L, 3.0 m and 3.0 g/L, and 1.5 m and 4.0 g/L, respectively. Regarding the prevention and control of salt-dust storms, the ecological threshold of the groundwater, which can effectively increase the vegetation coverage and prevent soil salinization, is groundwater depths of 2.0–4.0 m and TDS values of <2 g/L.

1. Introduction

Inland lakes in arid regions are an important part of the water cycle in Central Asia [1]. In recent years, due to climate warming and unsustainable human development and utilization, several inland lakes have been on the verge of disappearing, including the Aral Sea [2], Caspian Sea [3], and Lake Balkhash [4] in Central Asia and Lop Nur [5], Lake Manas [6], and Lake Aibi [7] in northwestern China. As the lake water level decreases and the lake area shrinks, vegetation degradation, desert development, and salinization of the dry lake bottom occur in the lakeside area [8, 9]. Numerous studies have shown that dry salt lakes in arid areas have a huge potential to release fine particles (PM10 and PM2.5) that have a great impact on global climate and human health [10–12]. The amount of dust released from a dry lake bed is related to the vegetation coverage [13]. Some scholars have proposed increasing the vegetation coverage of the lake bed through the natural succession of vegetation to prevent the dry lake bed from becoming a source of atmospheric particulate matter [14]. However, natural succession is a long-term process, and it is difficult to achieve results in a short time. Therefore, the control of groundwater on the distribution and development of natural vegetation and the groundwater conditions under which soil salinization occurs have been studied to reduce the risk of salt dust storms and restore ecosystems by regulating the groundwater [15–17].

In arid and semiarid areas, the community composition and species distribution of the vegetation are significantly correlated with the groundwater. Because of the scarce precipitation, shallow groundwater is an important water

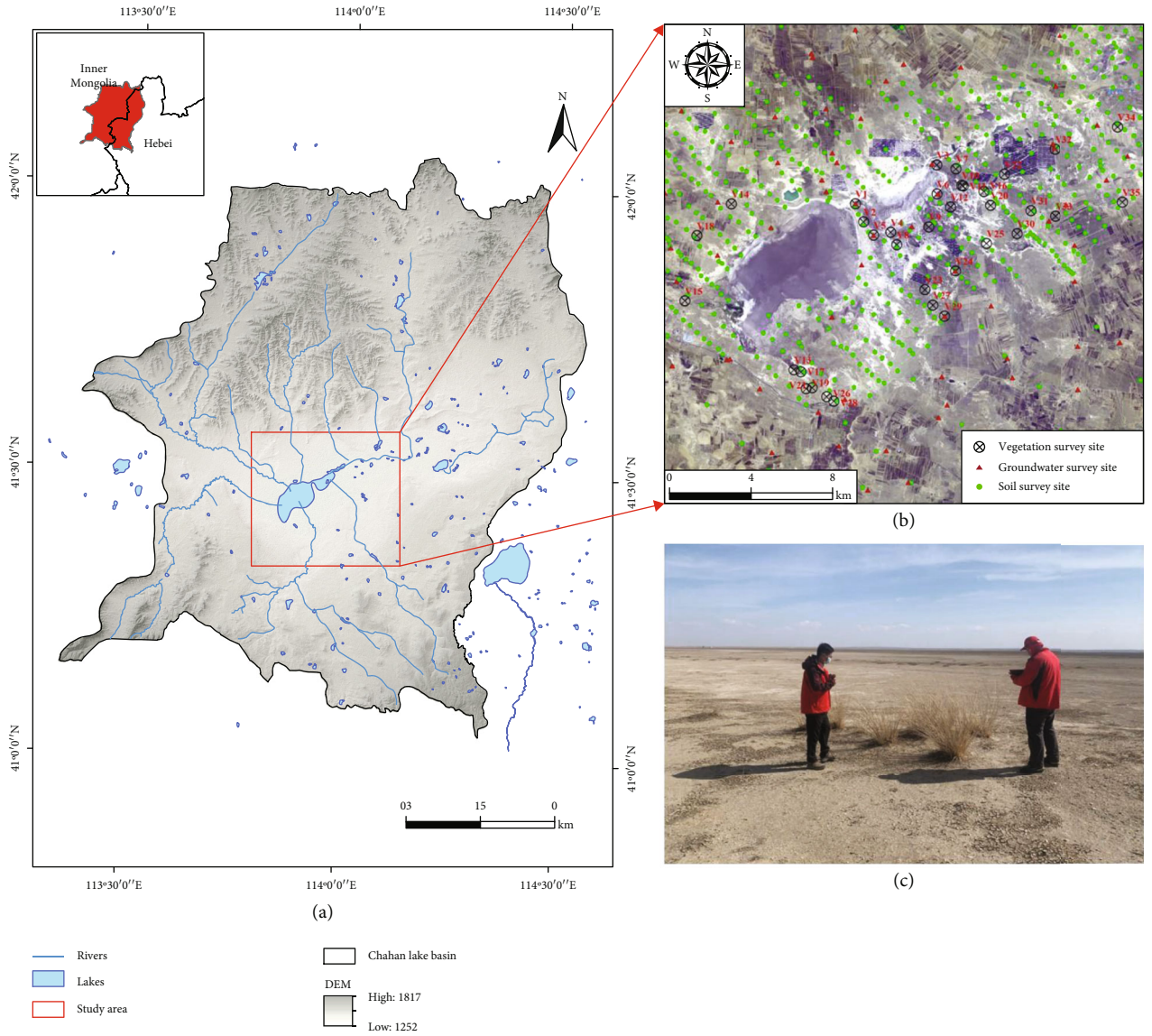


Figure 1: Geographic location and sampling point location map of the study area: (a) geographical location of the study area; (b) high-definition remote sensing images and sampling points in April 2021; (c) field survey in April 2021.

source for vegetation growth [18], and changes in the groundwater depth are the main factor controlling the species distribution in arid areas [19]. At present, the influence of the groundwater depth on the vegetation population distribution has mainly been studied using a combination of remote sensing and mathematical and statistical methods, such as the normalized difference vegetation index (NDVI) and the enhanced vegetation index (EVI) [20]. Soil salinization enhances droughts [21]. In arid and semiarid areas, soil salinity is negatively correlated with groundwater depth, and surface soil salinity accumulation is obvious. Under different groundwater depths, the salinity of the surface soil increases as the accumulated groundwater evaporation increases [22]. At present, the influence of groundwater on soil salinization has mainly been studied using a combination of field observations and indoor tests [23]. These studies investigated the relationships between groundwater and vegetation and between groundwater and soil salinization in-depth, but they only considered the groundwater depth and did not consider the total dissolved solids (TDS) in the groundwater.

Chahan Lake Basin is a typical inland lake basin in a semiarid region. The Bashang Plateau is a functional area for water conservation and an ecological barrier area in Beijing. High-intensity human activities have mainly been based on agricultural irrigation for a long time and have resulted in shrinkage and drying up of lakes and ecological-environmental problems. In this study, on the premise of the prevention and control of salt and dust storms, the groundwater ecological threshold for the study area was determined, which can not only effectively increase the vegetation coverage but can also help to prevent soil salinization.

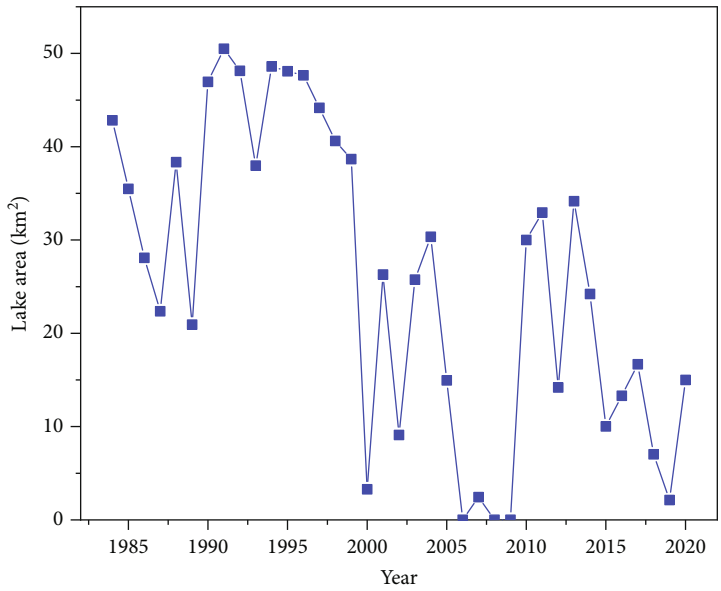


Figure 2: Evolution of Chahan Lake's area from 1984 to 2020.

2. Materials and Methods

2.1. Study Area. The Shangdu-Zhangjiakong Basin in the middle of the Chahan Lake Basin was taken as the study area, with a total area of 751.27 km^2. The Chahan Lake Basin is located on the west side of the Bashang Plateau in northern China, with a total area of about 6757.6 km^2. The terrain is low in the center and high in the surrounding areas, with strong cutting and well-developed valleys (Figure 1(a)). The study area has a continental monsoon climate and is located in the middle-temperature zone, with abundant sunlight, a large day-night temperature difference, a short period of drought, frequent winds, and water shortages. The annual average temperature is −0.3–3.7°C. The annual average precipitation is 361.61 mm, and it is mainly concentrated in June–September. The annual average evaporation is 1902.88 mm, which is 5.26 times the precipitation, and the frost-free period is about 100 days. The wind-driven soil erosion in this area is severe. The main soil zone is composed of chestnut calcareous soil. The main land-use type is cultivated land. The main crops planted in this area are potatoes, sugar beets, and naked oat.

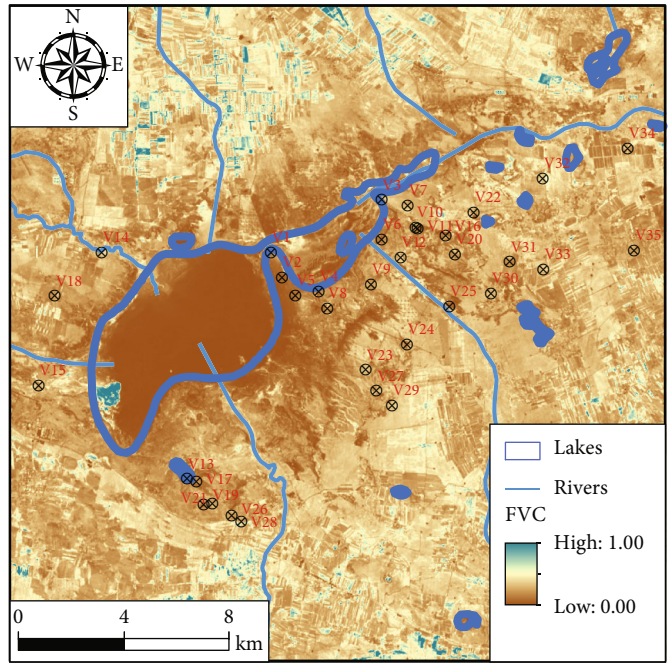
Overall, the water surface area of Chahan Lake has been shrinking over the past 40 years. Before 2000, there was water all year round. During 1994–1995, the water surface area reached a maximum of 50 km^2. After 1995, except in some individual years, that water surface area has continued to shrink overall. Since 2000, it has gradually become a seasonal lake, with water present only in July-August when the rainfall is concentrated (Figure 2).

2.2. Sample Collection and Analysis

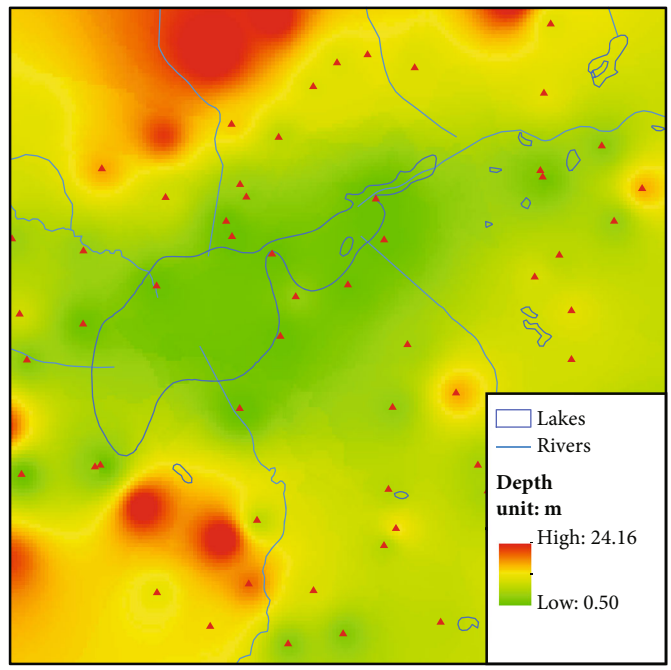
2.2.1. Vegetation Sampling. From the completely exposed dry lake bed to the lakeside grassland, the investigation points were selected based on the topographic relief (1270–1280 m) and the change in the vegetation community (Figure 1(b)). The field investigation was conducted in July 2021. The sizes of the vegetation quadrats were 5 m × 5 m for shrubs and 1 m × 1 m for herbs. The type and number of vegetation species, constructive species, vegetation coverage, crown width and plant height of the shrubs, and the plant height and plant number of the herbaceous vegetation were recorded [24–28]. A total of 35 vegetation quadrats were investigated during the vegetation survey. The fractional vegetation coverage (FVC) obtained using the field sampling method was calibrated and verified using the NDVI data extracted from remote sensing images (Landsat 8, 2021.4.3, Band 3), and an actual FVC map covering the entire basin was obtained (Figure 3(a)).

2.2.2. Groundwater Sampling. The water level distribution and depth of the groundwater were observed through well holes. Rural wells with depths of less than 30 m around the lake area were mainly selected for water level data using a water level gauge (Solinst Canada Ltd.), and a group of groundwater samples were collected from each observation well for water quality analysis. A total of 77 observation points were sampled in May 2021. Through Ordinary Kriging (OK) spatial interpolation in ArcGis10.2, the spatial distributions of the groundwater depth and TDS in the study area were obtained (Figures 3(b) and 3(c)).

2.2.3. Soil Sampling. Surface soil (0–30 cm) samples were collected around the lake area (two groups at each sampling point). After natural air drying, grinding, and sieving through a 2 mm sieve in the laboratory, the solution was extracted according to a soil : water mass ratio of 1 : 5 to determine the soil's salt content [23]. A total of 582 groups of soil samples were collected in June 2021.

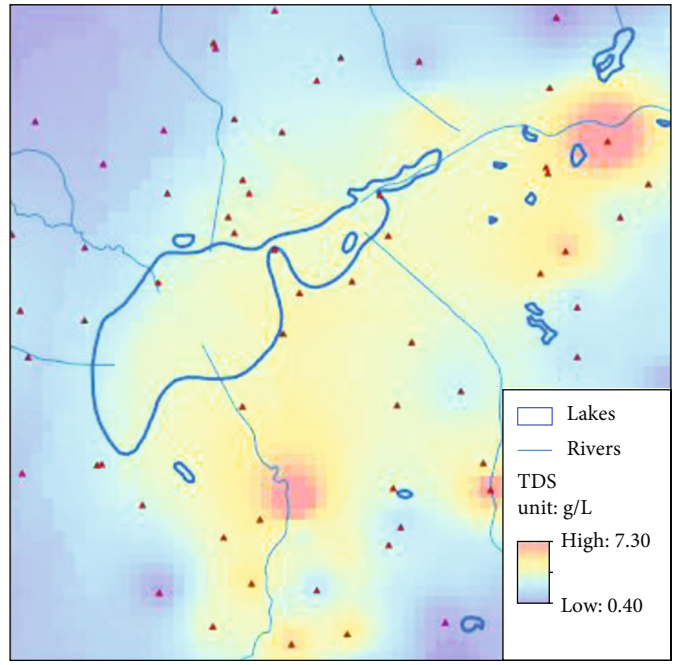


(a)



(b)

Figure 3: Continued.



(c)

Figure 3: Vegetation-groundwater characteristics in the study area: (a) fractional vegetation coverage; (b) groundwater depth; (c) groundwater TDS.

Several studies have shown that irrigated agricultural activities can result in soil salinization of farmland [29], and the risk of salinization is particularly high in the rainy season due to the change in the lake water volume [30]. However, in the study area, to restore the water volume of the lake, the local government prohibits irrigation activities around the lake area. In addition, the lake is dry for most of the year, and the water volume changes little. Therefore, the field investigation was conducted from May to July, and the timing of the field survey had little impact on the research results.

2.3. Research Method

2.3.1. Redundancy Analysis. Redundancy analysis (RDA) is an extension of the multiple regression model. The relationship between environmental variables and species is indirect gradient analysis by using the ranking method [31]. In this study, groundwater depth and TDS were used as explanatory variables, and vegetation quadrats' FVC and height were used as response variables. RDA was performed in Origin 2021 (https://www.originlab.com/).

2.3.2. Gamma Distribution. Although water conditions play an important role, the distribution of vegetation is still affected by many factors and exhibits some randomness [32]. The NDVI is an important indicator of the spatial distribution and coverage of surface vegetation, and it has been widely used in regional vegetation and ecological environmental monitoring [33]. Ma et al. [34] studied the mixed distribution characteristics of the NDVI using a normal

Table 1: Vegetation community characteristics.

Constructive species	Frequencies	Percentage (%)	Distance from dry lake bed (km)
Kalidium foliatum	9	25.71	0.01-2.33
Nitraria tangutorum	4	11.43	0.22-1.32
Suaeda glauca	3	8.57	0.29-9.56
Leymus chinensis	7	20.00	0.73-6.56
Chloris virgata	5	14.29	2.13-9.45
Carex duriuscula	3	8.57	2.35-3.56
Achnatherum splendens	1	2.86	3.06
Heteropappus hispidus	2	5.71	3.34-5.23
Stipa capillata	1	2.86	4.58

Table 2: Statistical characteristic values of soil salt content, groundwater, and TDS.

Indicators	Min	Max	Mean	Std	Cv
Soil salt content (%)	0	45.62	1.92	3.03	157.81
Groundwater depth (m)	0.5	24.16	9.06	4.05	44.70
TDS (g/L)	0.4	7.3	2.51	1.08	43.03

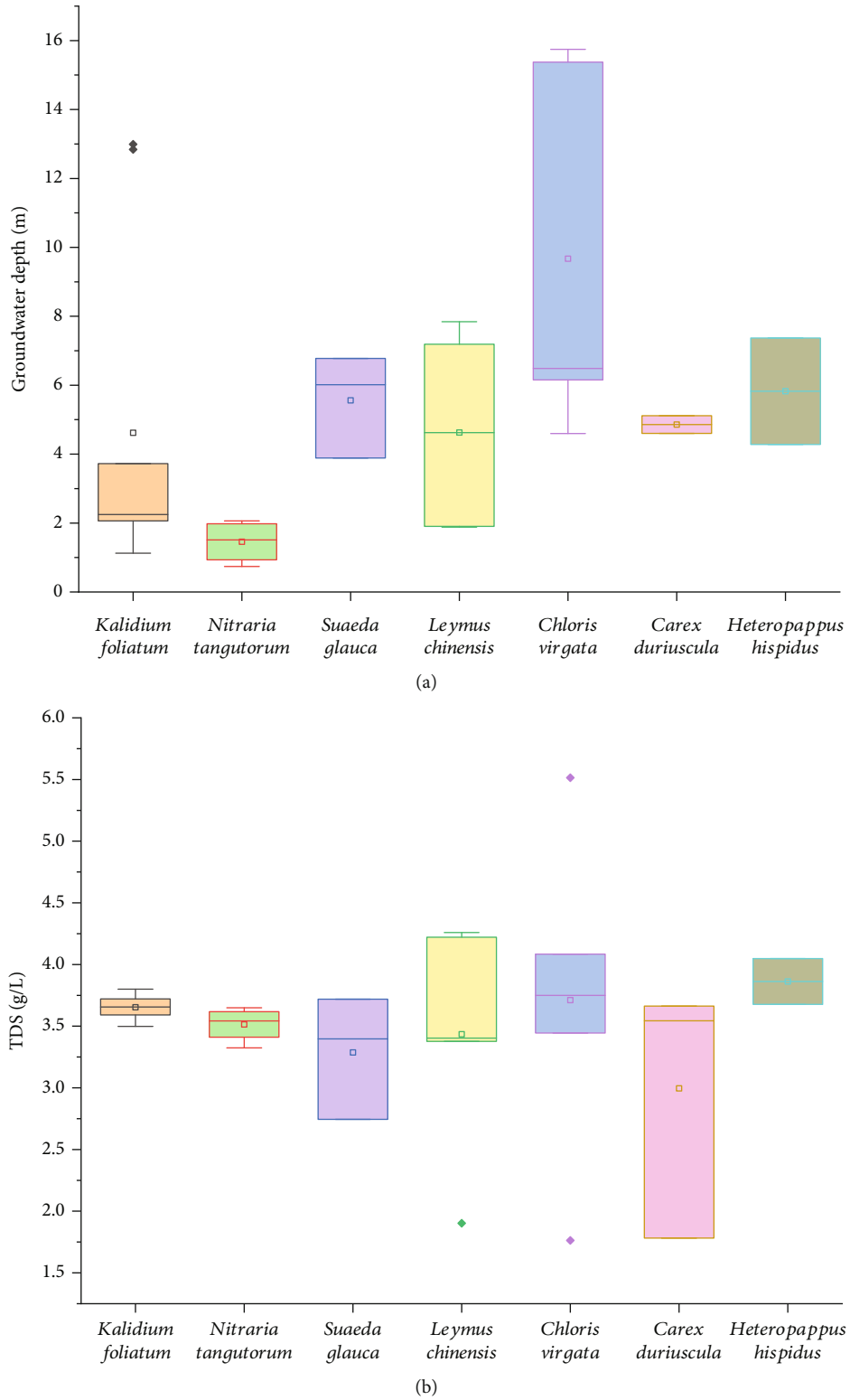


Figure 4: Relationship between groundwater characteristics and natural vegetation: (a) groundwater depth; (b) TDS.

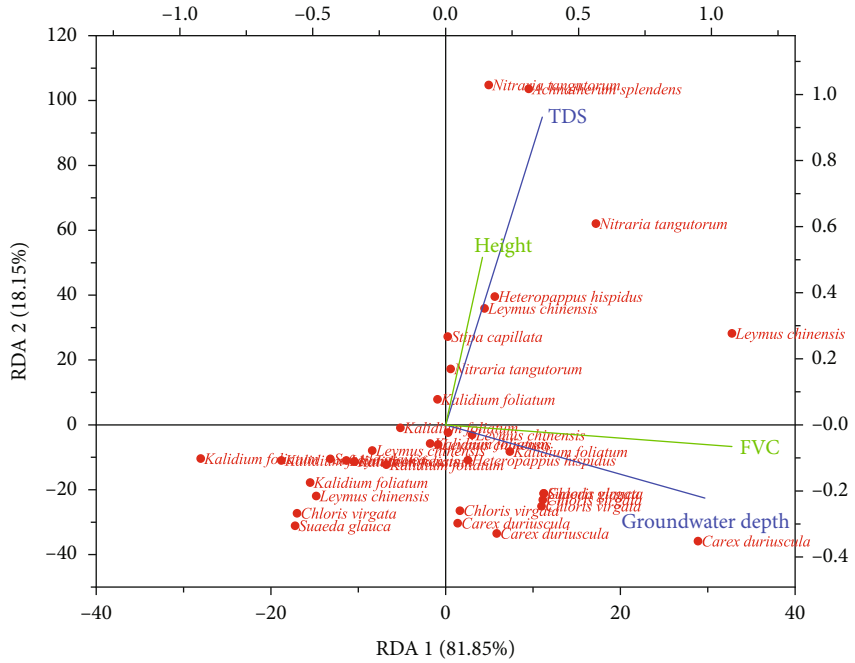


Figure 5: RDA of groundwater characteristics and natural vegetation.

distribution. Vova et al. [35] found that the NDVI approximately conforms to a gamma distribution. In this study, the gamma distribution is used to describe the distribution characteristics of the vegetation communities, and its probability density function was as follows:

$$f(x, \alpha, \beta) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} \exp(-x/\beta), \quad (1)$$

where x is the depth of the groundwater; α is the shape parameter; and β is a scale parameter. This formula represents the frequency of the vegetation communities at different groundwater depths.

2.3.3. Indicator Kriging. To predict the salinization risk or conditional probability for the entire study area, indicator kriging (IK) was used. Indicator kriging is a nonparametric estimation method [36], which can be used to estimate the conditional probability of indicator variables with a given threshold and to draw a corresponding spatial distribution map or risk distribution map [37, 38]. Wang et al. [30] used a geographic information system (GIS) and geostatistics to quantitatively evaluate the temporal and spatial changes in the soil salinization risk.

The indicator function is a two-dimensional random function, which is defined as follows:

$$I(x_i; z_c) = \begin{cases} 1 & \text{if } z(x_i) > z_c, \quad i = 1, \cdots, n, \\ 0 & \text{if otherwise,} \end{cases} \quad (2)$$

where z_c is the boundary value and $I(x_i; z_c)$ is the indicator function.

A variogram can not only describe the spatial structure of regional variables, but it can also describe their randomness. It is a good tool for describing geological parameters. If the position of a point in space is $X(x, y, z)$, then half of the variance of the difference between the values of $Z(x)$ at X, i.e., $X + h$, is defined as the spatial variogram of $Z(x)$, which is recorded as $\gamma(X, h)$. In geostatistical research, the intrinsic assumption is often made. In this case, the variogram has nothing to do with the spatial position X, but only with h, so the experiment indicates that the semivariogram is as follows:

$$\gamma_i^*(h, z_c) = \frac{1}{N(h)} \left(\sum_{i=1}^{N(h)} (I(X_i + h, z_c) - I(X_i, z_c))^2, \quad (3) \right.$$

where $N(h)$ is the number of data points separated by $|h|$.

The indicated semivariance can be fitted using the following spherical model:

$$\gamma(h) = \begin{cases} 0 & h = 0, \\ C_0 + C\left(\frac{3}{2} \cdot \frac{h}{\alpha} - \frac{1}{2} \cdot \frac{h^3}{\alpha^3}\right) & 0 < h \le \alpha, \\ C_0 + C & h > \alpha, \end{cases} \quad (4)$$

where C_0 is the nugget.

3. Results

3.1. Statistics and Analysis. It can be seen from Table 1 that from the completely exposed dry lake bed to the lakeside grassland, the heterogeneity of the vegetation community distribution was obvious. From the dry lake bed to the surrounding grassland, the lakeside vegetation communities

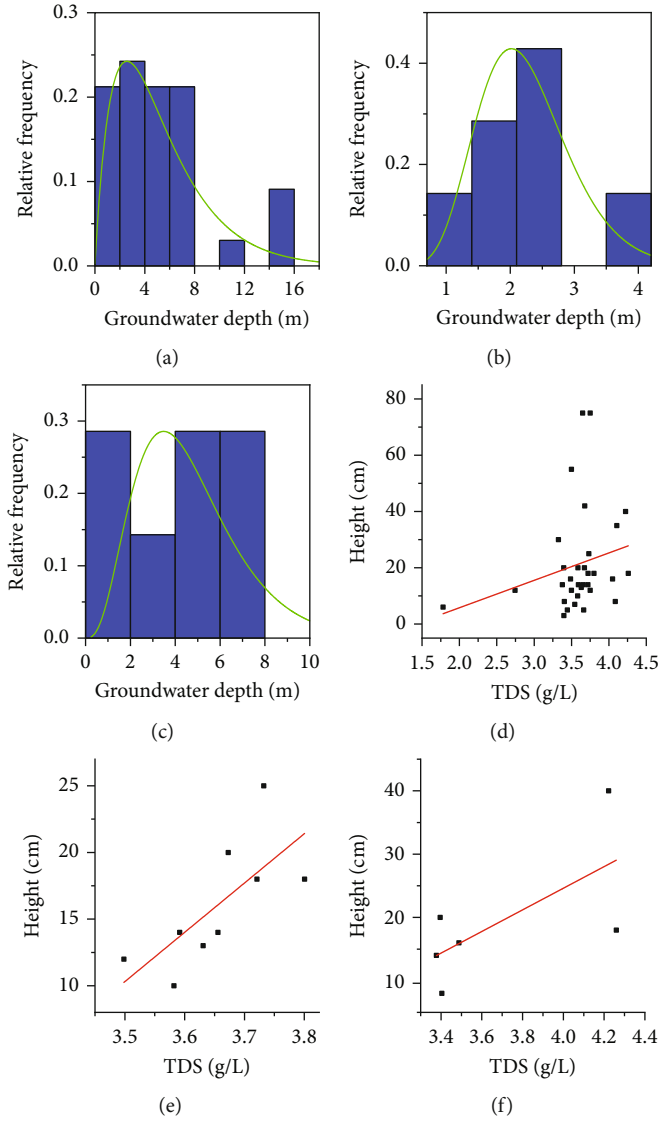


Figure 6: The effect of groundwater characteristics on natural vegetation. Depth: (a) all; (b) *Kalidium foliatum*; (c) *Leymus chinensis*; TDS: (d) all; (e) *Kalidium foliatum*; (f) *Leymus chinensis*.

were *Kalidium foliatum*, *Nitraria tangutorum*, *Suaeda glauca*, *Leymus chinensis*, *Chloris virgata*, *Carex duriuscula*, *Achnatherum splendens*, *Heteropappus hispidus*, and *Stipa capillata* communities, with a total of nine constructive species and dozens of plant species. Among them, the occurrence frequencies of the *Kalidium foliatum* community and *Leymus chinensis* community were the highest (>20%), and the distribution range of *Suaeda glauca* was the widest (0.29–9.56 km from the lake bed).

It can be seen from Table 2 that the mean salt content of the surface soil in the study area was 1.92%, and the coefficient of variation was 157.81%, indicating severe saline soil. The average depth of the groundwater was 9.06 m, and the coefficient of variation was 44.70%. The average TDS of the groundwater was 2.51 g/L, and the coefficient of variation was 43.03%, indicating brackish groundwater. Regarding the variability of the different indicators, the groundwater depth and TDS exhibited medium variability, and the salt content of the surface soil exhibited strong variability. This may be due to the combined action of the natural drainage of groundwater, land use mode, crop type, irrigation mode, and other factors in the study area, which resulted in the large variability of the salt content of the surface soil.

Table 3: Relationship between groundwater TDS and vegetation height.

Community	Regression model	R^2
All	Height = 9.74 × TDS − 13.7	0.055
Kalidium foliatum	Height = 36.99 × TDS − 119.2	0.521
Leymus chinensis	Height = 17.08 × TDS − 43.7	0.447

The relationship between the groundwater attributes and the natural vegetation in the Chahan Lake area is shown in Figure 4. From the bare land of the lake bed, the depth of

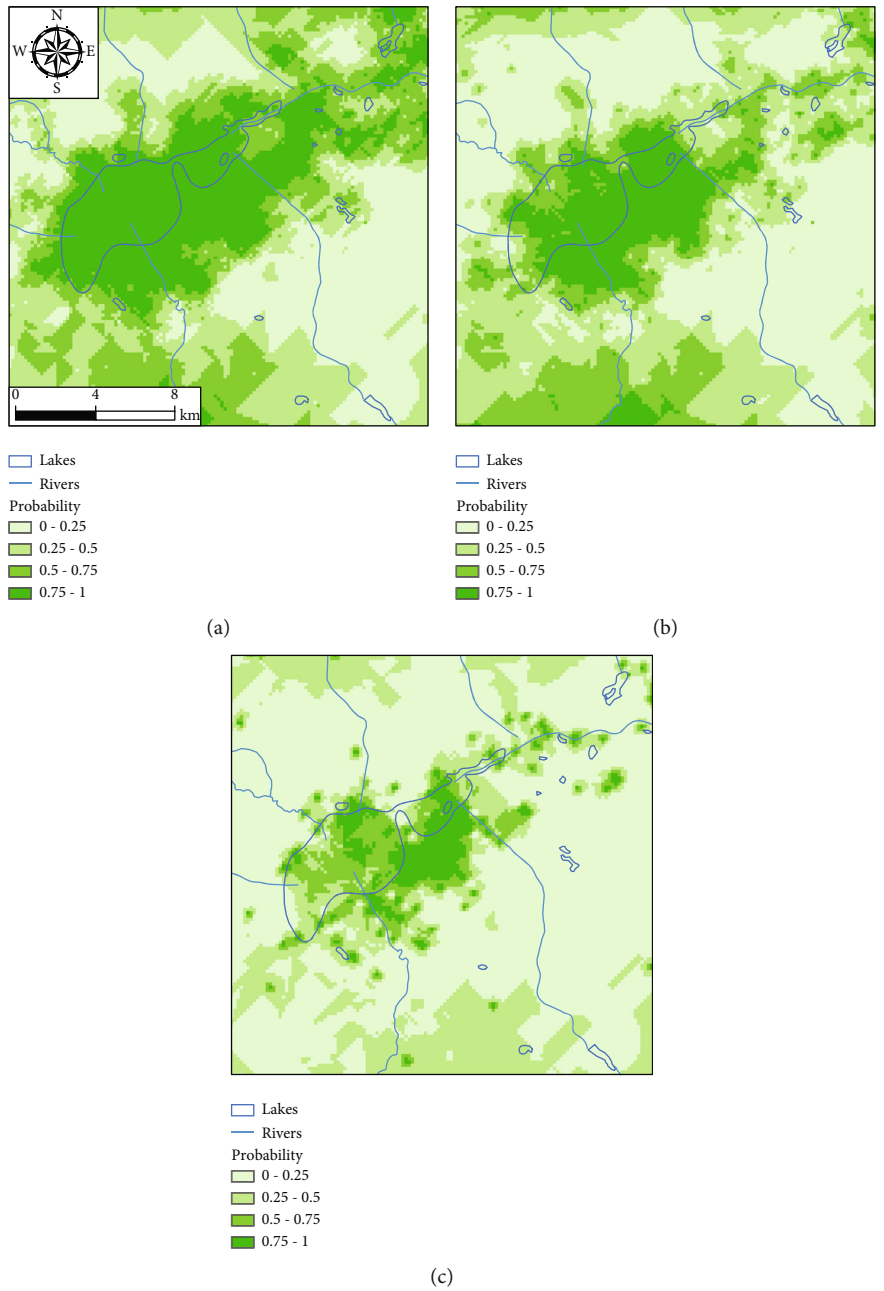


Figure 7: Probability spatial distribution of soil surface salt content under different thresholds: (a) 0.5%; (b) 1.0%; (c) 2.0%.

the groundwater gradually increased outward from the lake bed, and the TDS of the groundwater roughly decreased. As can be seen from Figure 4, the *Kalidium foliatum* and *Nitraria tangutorum* communities prefer the water, and all of the vegetation communities are relatively alkali-salt resistant. Among them, the groundwater depth and TDS fluctuation ranges of the *Suaeda glauca*, *Leymus chinensis*, and *Chloris virgata* communities are large.

3.2. Influence of Groundwater on Vegetation Distribution. RDA is conducted to investigate the relationship between each vegetation quadrat (FVC and height) and the groundwater to determine which groundwater variables affected the natural vegetation. Based on the results of the RDA (Figure 5), there were correlations between the vegetation coverage and groundwater depth and between the vegetation height and the TDS of the groundwater.

After removing the outliers (Figure 4), according to the characteristics of the gamma distribution, the relative frequencies of the vegetation communities in the areas with different groundwater depths were determined, and the groundwater depth interval with the highest relative frequency was regarded as the groundwater depth suitable for vegetation growth (Figure 6(a)). The vegetation communities with occurrence frequencies of greater than 20% were analyzed separately (*Kalidium foliatum* and *Leymus chinensis* communities) (Figures 6(b) and 6(c)). It can be seen that the groundwater level suitable for vegetation growth in the

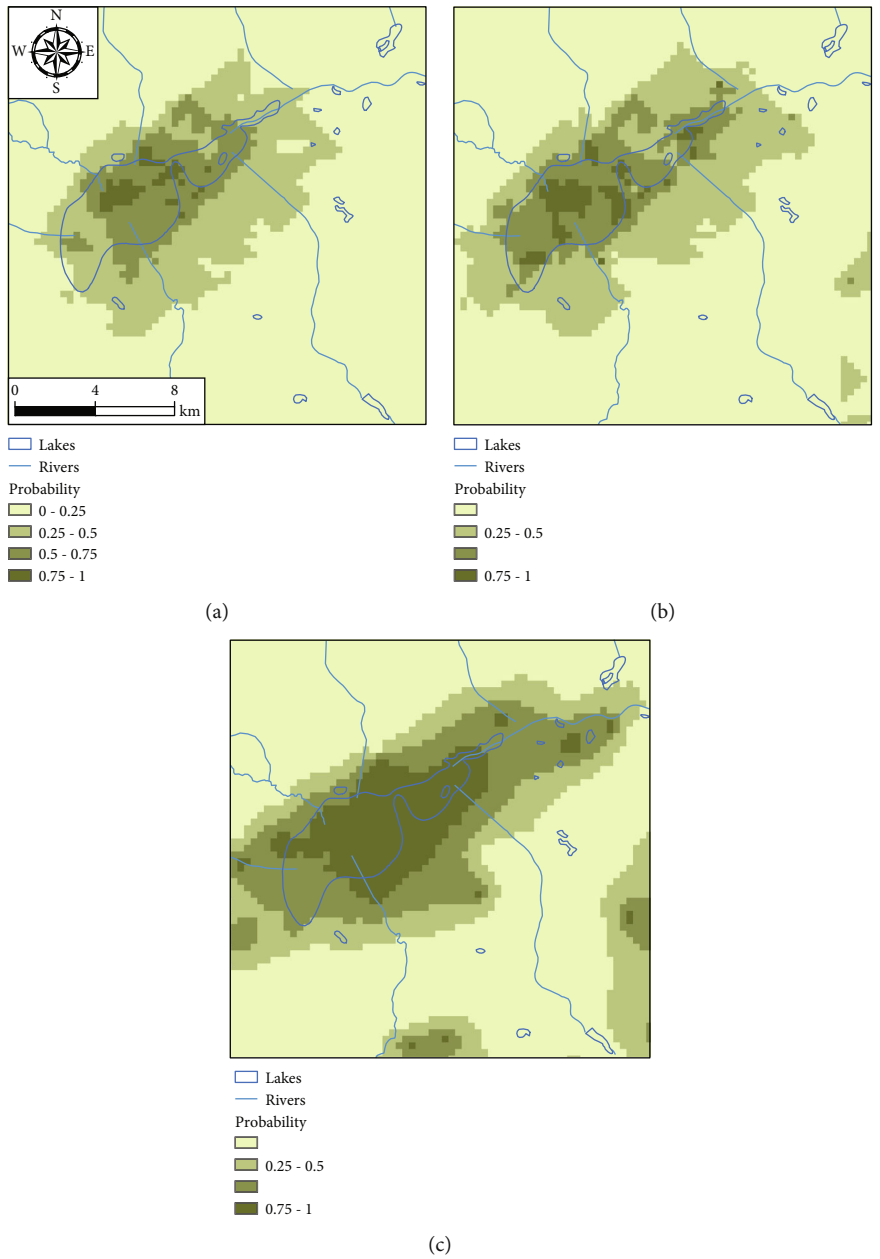


Figure 8: Probability spatial distribution of groundwater depth under different thresholds: (a) 1.5 m; (b) 3.0 m; (c) 4.0 m.

Chahan Lake area is 2.0–3.0 m. The groundwater level suitable for the growth of *Kalidium foliatum* vegetation is 1.5–2.5 m. The groundwater level suitable for the growth of *Leymus chinensis* vegetation is 3.0–4.0 m. In addition, the TDS of the groundwater had a significant impact on the vegetation height (Figures 6(d)–6(f); Table 3).

3.3. Effect of Groundwater on Soil Salinization. The key to the indicator kriging method is the reasonable determination of the threshold value [39]. By considering many factors, such as the topography, hydrological conditions, and soil salinization in the Chahan Lake Basin, and referring to the research results for similar areas [40–42], based on the salt content data, 0.5–1% of the surface soil was moderately salinized, 1.0–2.0% was heavily salinized, and >2.0% was saline soil. The groundwater depth threshold values were determined to be 1.5 m, 3.0 m, and 4.0 m. The TDS threshold values of the groundwater were determined to be 2.0 g/L, 3.0 g/L, and 4.0 g/L. In this study, when the salt content of the surface soil was greater than or equal to the threshold value (0.5%, 1.0%, and 2.0%) and the TDS threshold of the groundwater was greater than or equal to the threshold value (2.0 g/L, 3.0 g/L, and 4.0 g/L), the indicator transformation value was 1; otherwise, it was 0. When the groundwater depth was less than or equal to the threshold value (1.5 m, 3.0 m, and 4.0 m), the indication transformation value was 1; otherwise, it was 0.

Indicator kriging interpolation was conducted in ArcGIS10.2 to obtain the spatial distribution of the probability of the groundwater depth, surface soil salinity, and the

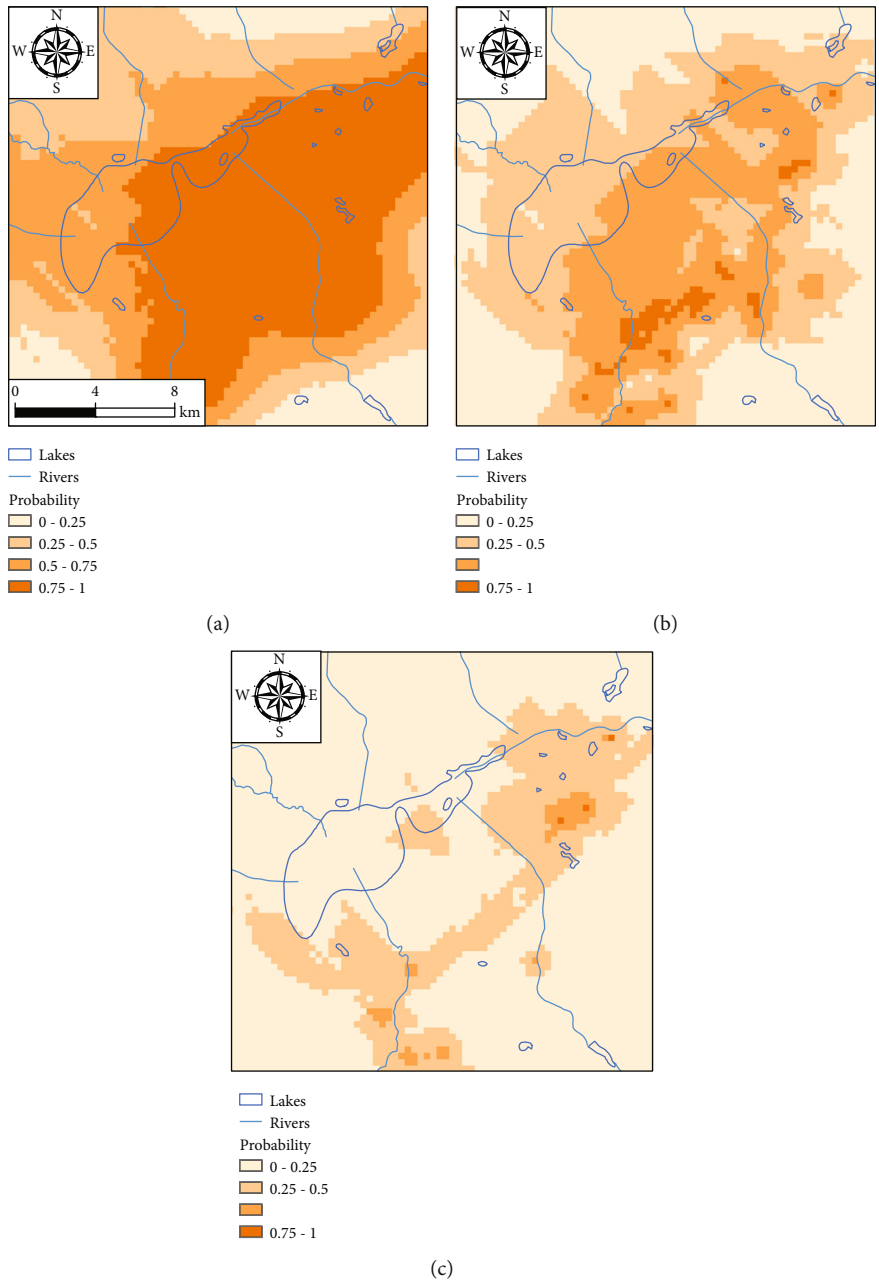


Figure 9: Probability spatial distribution of groundwater TDS under different thresholds: (a) 2.0 g/L; (b) 3.0 g/L; (c) 4.0 g/L.

TDS of the groundwater meeting the corresponding threshold values (Figures 7–9). The dividing line was the 50% probability. Values of greater than 50% were defined as the high probability area, and values of less than 50% were defined as the low probability area.

In general, the probability of salinization in the study area was high, and it was mainly concentrated near the lake (Figure 7). Statistical analysis of the high-risk area (probability more than 50%) revealed that ~40% of the study area was at high risk of moderate salinization; ~30% was at high risk of severe salinization; and ~10% was at high risk of the occurrence of saline soil. Based on Figures 8 and 9, the overlap between the high-risk area with groundwater depths of less than 4.0 m and the high-risk area with TDS values of greater than 2.0 g/L was quite similar to the spatial distribution of the area at high risk of moderate salinization. The overlap between the high-risk areas with groundwater depths of less than 3.0 m and high-risk areas with TDS values of greater than 3.0 g/L was similar to the spatial distribution of the area in high-risk areas of severe salinization. The overlap between the high-risk areas with groundwater depths of less than 1.5 m and the high-risk areas with TDS values of greater than 4.0 g/L was quite similar to the spatial distribution of the area at high risk of the occurrence of saline soil.

It is preliminarily concluded that the critical groundwater depth for moderately saline surface soil is 4.0 m, and the critical TDS value is 2.0 g/L. The critical groundwater

depth for severe salinization is 3.0 m, and the critical TDS value is 3.0 g/L. The critical groundwater depth for the occurrence of saline soil is 1.5 m, and the critical TDS value is 4.0 g/L.

4. Discussion

4.1. Relationships among Groundwater, Species, and Soil Properties. Many environmental factors affect the distribution of vegetation [32], and the changes in groundwater conditions and soil properties are the most important factors [19, 43]. Groundwater degradation and soil salinization threaten ecosystems in arid and semiarid regions where rainfall is scarce and evaporation is intense [17]. Ecosystems are partially or totally dependent on groundwater [44]. The groundwater depth is one of the most important ecological-environmental indicators. Other factors, such as the salt content and water content of the soil and the TDS of the groundwater, can be controlled by adjusting the groundwater depth [45]. As Chahan Lake is a natural drainage zone for regional groundwater, the groundwater depth gradually increases with distance from the lake, and the TDS gradually decreases with distance from the lake. In addition, a large amount of groundwater is exploited for agricultural irrigation, which has a direct impact on the TDS of the groundwater and the salt content of the surface soil [46]. The salt content of shallow soil and the water content of deep soil are important factors affecting the risk of salinization [30]; therefore, soil salinization can very easily occur in the lake area. With the occurrence of soil salinization, only salt and alkali-resistant plant species survive, resulting in a reduction of the surface vegetation coverage. Several studies have shown that water consumption through vegetation canopy interception and vegetation transpiration decrease as the vegetation coverage decreases, and the soil water mainly moves downward, which increases the groundwater recharge [47].

4.2. Groundwater Ecological Threshold. In arid and semiarid areas, a suitable groundwater level is an important condition for maintaining the health of the ecological environment. Groundwater degradation and soil salinization affect vegetation growth, cause land degradation, and increase ecological risks [17]. Wang et al. [48] suggested that the groundwater level should be controlled at more than 1.29 m in the Luocheng Irrigation Area of the Heihe River to prevent soil salinization, and a groundwater level of 6.0–13.0 m is suitable for vegetation growth. Qi et al. [49] identified the ecological thresholds of the groundwater depth and TDS content (groundwater depth: 4.8–6.1 m, TDS: 0.37–1.25 g/L) in Qian'an County by combining indoor tests with remote sensing technology. Cao et al. [50] suggested that the groundwater depth should be maintained at 4–10 m and the TDS at <3 g/L to alleviate salinization and desertification in the Shiyang River Basin. These studies suggest that studying the ecological thresholds of the groundwater depth and TDS can provide scientific support for groundwater management in oasis areas to prevent salinization and desertification. Therefore, the results of this study provide suggestions for ecological environment protection and promote regional ecosystem restoration in the Chahan Lake Basin.

4.3. Influence of Lake Water Restoration on Soil Salinization. Previous studies have revealed that the changes in the volume of water in the lake have caused increased soil salinization and dramatic ecological changes [30]. To restore the lake's water level, the local government has raised the water table near the lake by prohibiting irrigation activities. The risk of soil salinization changes when the lake's water volume is restored. The range of soil salinization is larger, the risk level is lower, and seasonal changes occur.

5. Conclusions

In this study, Chahan Lake was taken as an example, through field investigation of the vegetation, soil, and groundwater. The influences of the groundwater in the area around the dry salt lake on the ecosystem were explored. Statistical analysis of the samples revealed that the vegetation communities in the lakeside zone are *Kalidium foliatum*, *Nitraria tangutorum*, *Suaeda glauca*, *Leymus chinensis*, *Chloris virgate*, and *Carex duriuscula* communities from the dry lake bed outwards. The gamma distribution revealed that the groundwater depths suitable for vegetation growth around Chahan Lake are 2.0–3.0 m. The groundwater depths suitable for the growth of *Kalidium foliatum* vegetation are 1.5–2.5 m. The groundwater depths suitable for the growth of *Leymus chinensis* vegetation are 3.0–4.0 m. Through indicator kriging, it was determined that the critical groundwater depth for moderate salinization in the Chahan Lake Basin is 4.0 m, and the critical TDS value is 2.0 g/L. The critical groundwater depth for severe salinization is 3.0 m, and the critical TDS value is 3.0 g/L. The critical groundwater depth for the occurrence of saline soil is 1.5 m, and the critical TDS value is 4.0 g/L. Based on the above results and the premise of the prevention and control of salt and dust storms, the following groundwater ecological threshold applicable to the study area is proposed: groundwater depths of 2.0–4.0 m and TDS values of <2 g/L. Maintaining these thresholds can effectively increase vegetation coverage and prevent soil salinization.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no competing interests.

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