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Abstract

To explore the interactive driving mechanisms of natural and anthropogenic factors on surface water quality, this study focused on Bosten Lake and its inflowing and outflowing rivers. The Nemerow index method was used to evaluate water quality, and grey relational analysis, spatial autocorrelation, and the optimal parameters-based geographical detector model were combined to identify the correlation characteristics, spatial clustering, and factor interactions of water quality indicators. The results showed that: (1) the source of the Kongque River had Class II water quality, while all other rivers were Class I; lake water was dominated by Class II water quality (59.3%), and overall river water quality was better than that within the lake. (2) The mean TDS concentration in lake water (819.49 mg·L-1) was significantly higher than that in rivers and showed a weak association with riverine transport. (3) CODMn, F-, pH, and TDS exhibited significant spatial clustering characteristics. (4) Annual precipitation (a natural factor) was the primary driving factor, followed by distance to main roads (an anthropogenic factor), with natural factors exerting a stronger overall influence; interactions between any two factors showed a bivariate enhancement effect, with explanatory power higher than that of individual factors. This study reveals the complex mechanisms underlying the synergistic effects of natural and anthropogenic factors on lake water quality in arid regions, highlights the nonlinear responses of river-lake systems under the intertwined influences of climate and human activities, and provides a scientific basis for the sustainable management of lake-watershed systems in the arid regions of Northwest China.

Full Text

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Natural-Anthropogenic Driving Mechanisms of Spatial Differentiation in Water Quality of Bosten Lake

Huang Zehong[1,2,3], Zeng Yanyan[1,2,3], Zhou Jinlong[1,2,3], Duan Xiurong[4], Tan Lan[4]

(1. College of Water Conservancy and Civil Engineering, Xinjiang Agricultural University, Urumqi, Xinjiang 830052; 2. Xinjiang Hydrology and Water Resources Engineering Technology Research Center, Urumqi, Xinjiang 830052; 3. Xinjiang Key Laboratory of Hydraulic Engineering Safety and Water Disaster Prevention and Control, Urumqi, Xinjiang 830052; 4. Bosten Lake Scientific Research Institute of Bayingolin Mongol Autonomous Prefecture, Korla, Xinjiang 841000)

Abstract: To explore the interactive driving mechanisms of natural and anthropogenic factors on surface-water quality, this study took Bosten Lake and its inflowing and outflowing rivers as the research objects. Water quality was evaluated using the Nemerow index method, and gray relational analysis, spatial autocorrelation, and the optimal-parameter geodetector model were combined to identify the association characteristics, spatial clustering, and factor interactions of water-quality indicators. The results show that: (1) the source of the Kongque River had Class II water quality, while all other rivers were Class I; lake water was dominated by Class II water quality (59.3%), and river water quality was generally better than that within the lake. (2) The mean TDS of lake water ($819.49\ mg \cdot L^{-1}$) was significantly higher than that of the rivers, and its association with river transport was relatively weak. (3) COD_{Mn}, F^-, pH, and TDS exhibited significant spatial clustering characteristics. (4) Annual precipitation (a natural factor) was the principal driving factor, followed by distance to major roads (an anthropogenic factor); natural factors exerted a stronger overall influence. Interactions between any two factors all showed a two-factor enhancement effect, with explanatory power greater than that of single factors. This study reveals the complex mechanisms by which natural and anthropogenic factors jointly affect lake water quality in arid regions, highlights the nonlinear response of river–lake systems under the intertwined influence of climate and human activities, and provides a scientific basis for the sustainable management of lake–watershed systems in the arid regions of Northwest China.

Keywords: gray relational analysis; spatial autocorrelation; optimal-parameter geodetector (OPGD); driving mechanism; Bosten Lake

Surface water bodies (SWBs) include widely distributed natural lakes, artificial reservoirs, and rivers. They carry important freshwater resources and constitute an important foundation for China's geographical environment, ecosystems, and socioeconomic development. As important carriers of surface-water resources, lakes possess unique resource, ecological, and cultural values. From a global perspective, lake ecological and environmental problems caused by industrialization, urbanization, and modern agriculture have become a shared challenge for all countries[1]. Water-resource scarcity can be divided into "water-quantity scarcity" and "water-quality scarcity" [2]. Water-quality degradation is one of the most serious threats facing lake ecosystems, and human activities and climate change are both major driving factors leading to such degradation[3]. Therefore, an in-depth understanding of the driving factors affecting lake water quality, together with reasonable measures to improve the quality of the aquatic environment, is of great significance for alleviating increasingly severe water-resource scarcity.

Surface-water quality is usually jointly determined by natural and anthropogenic factors[4]. At present, numerous studies have examined the factors influencing surface-water quality, but most are limited to single factors and tend to focus on the influence of either natural or anthropogenic factors. Research on natural factors has focused on topography, air temperature, precipitation, and related variables; for example, the influence of topography on surface-water quality shows seasonal differences[5], and fluctuations in air temperature and precipitation likewise affect surface-water quality[6]. In addition, the water quality of inflowing rivers connected to a lake system also has a direct influence on lake water quality[7]. The influence of anthropogenic factors is even more rapid and intense. For example, in 2020, owing to a reduction in regional human activities, water quality improved rapidly across large areas of Vembanad Lake in India[8]. Meanwhile, the rapid socioeconomic development around Dongting Lake has caused the lake to face the challenge of deteriorating water quality[9]. Among 73 lakes of different types located in Mediterranean and cold-temperate climatic zones, changes in land use also had significant effects on water quality[10]. Common methods for assessing factors influencing water quality include correlation tests and multiple linear regression. These approaches are widely applied, but they still have certain limitations: the spatial dimensionality of the models is limited, the study objects are relatively singular, and it is difficult to accurately determine the strength of the synergistic effects of multiple factors on water quality and their linear relationships[11]. These issues restrict research on the driving mechanisms of water quality and make it difficult to fully meet the needs of aquatic-environment management and protection.

As an effective tool for detecting spatial heterogeneity, the geodetector

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Author biography: Huang Zehong (1999-), male, master' s student, mainly engaged in research on lake water environments. E-mail: h2300344458@163.com
Corresponding author: Zeng Yanyan. E-mail: zengyanyan@xjau.edu.cn

and the spatial statistical means for the underlying driving factors; it has clear physical meaning and the advantage of not necessarily having to strictly satisfy the assumptions of traditional statistical methods, and, compared with general statistics, it can better reveal the characteristics of causal relationships[^12]. For example, Yang Huangqun et al.[^13] quantitatively detected the influencing factors of water pollution in the Chengyang River basin based on the geographical detector model; Cheng Peng et al.[^14] used a geographical detector to quantitatively reveal the factors influencing river water quality upstream of Guanting Reservoir in different seasons. In addition, the optimal-parameters geographical detector (OPGD) can intelligently optimize the discretization strategy for spatial data, automatically select the optimal segmentation method and spatial-scale parameters, and achieve optimal parameter configuration[^15]. Therefore, combining data on natural and anthropogenic factors with the optimal-parameters geographical detector can more accurately reveal the spatial association rules and dominant controlling factors of surface-water quality.

Bosten Lake is located in the arid region of northwestern China and is the largest inland freshwater lake in China. Scholars have studied changes in mineralization and their driving factors, spatial variation and assessment of water quality, and the effects of land use on water quality in Bosten Lake. However, relatively few studies have comprehensively explored the driving effects of natural and anthropogenic factors on the water quality of Bosten Lake and its inflowing and outflowing rivers. Based on data on natural and anthropogenic factors of lake-river water quality, this paper comprehensively applies descriptive statistics, spatial autocorrelation, and grey relational analysis to analyze water-quality characteristics and associations, evaluates pollution status using the Nemerow index, and identifies the main driving factors of water quality in Bosten Lake using the optimal-parameters geographical detector, with the aim of providing scientific reference for the governance of the lake aquatic ecological environment.

1 Overview of the Study Area and Methods

1.1 Overview of the Study Area

Bosten Lake (41.74°-42.36°N, 85.87°-87.44°E) belongs to the Mongolian-Xinjiang Plateau lake region (Figure 1). It is a typical representative lake in the arid region of western China and is also China’ s largest inland freshwater lake. It receives inflow from the Kaidu River, Huangshuigou, and Qingshui River, and is the source of the Kongque River, playing an important role in runoff regulation in the Kaidu-Kongque River basin. The planform outline of Bosten Lake is roughly triangular. The total catchment area of the lake is about 4.4×10^4 km^2, the surface-water resources of the basin are 40×10^8 m^3, and the average water-surface area is 972 km^2. The lake basin is deep-dish shaped, with a relatively flat central bottom. The average water depth is about 7.38 m, the maximum depth is 16 m, and the shoreline length is 220 km; water depth becomes sharply shallower near the lakeshore. Over the past 30 years, affected by agricultural development and industrial wastewater discharge in the basin, inflow to the lake has decreased and pollution loads have increased, leading to problems such as water-resource shortage, salinization and alkalization, wetland degradation, and obstructed ecological connectivity. The pressure on the lake ecological environment has intensified markedly, bringing substantial pressure to the ecological security of Bosten Lake and its basin.

1.2 Water-Sample Collection and Testing

Water-quality data were derived from 34 river-lake water-quality sampling sites set up in Bosten Lake and its inflowing and outflowing rivers in August 2024 (27 lake-water sites and 7 water-quality sampling sites in inflowing and outflowing rivers) (Figure 1). The water-sample collection process followed the relevant provisions of the *Technical Specifications Requirements for Monitoring of Surface Water and Waste Water* (HJ/T 91-2002) and the *Technical Specifications for Environmental Monitoring of Groundwater* (HJ 164-2020). Surface water samples were collected at 0.5 m below the water surface. Before sampling, the sampling bottles were rinsed three times with sample water, and the samples were then filtered using 0.22 μm polyethersulfone (PES) syringe filters, sealed, and stored. Samples to be measured for total nitrogen (TN), total phosphorus (TP), and BOD_5 were placed in 1 L brown glass bottles, with no air bubbles left in the bottle and without filtration; samples for the determination of cations and oxygen demand (COD_{Mn}, COD_{Cr}) were acidified with 1:1 HNO_3 to pH < 2 and sealed in high-density polyethylene bottles; samples for anion analysis were placed in 1.5 L plastic bottles, without preservative and without filtration. A multiparameter analyzer (HANNA, HI9828) was used for on-site determination of indicators such as water temperature and pH. Samples were stored protected from light and refrigerated at 4 °C, and were transported to the laboratory for indoor testing. The cations, anions (Table 1), and oxygen demand of the water samples were tested by the Hydrogeological and Environmental Geological Survey Center of the Xinjiang Geological Bureau; TN, TP, and BOD_5 were tested by the Ku-Wei-Lun Joint Monitoring Station of the Ecology and Environment Bureau of Bayingolin Mongol Autonomous Prefecture. The cation-anion balance errors (CBE) of all tested water samples were $< \pm 5\%$.

1.3 Data Sources

The data sources for water-quality driving factors are shown in Table 2. Among them, human activity footprint data are annual dynamic data for the global terrestrial human footprint developed by combining multiple variables that reflect different aspects of human pressure, such as the built environment, population density, nighttime lights, cropland, and pasture; they can systematically reflect the overall intensity of human activities. Land-use data are used to describe and understand information such as the utilization types, spatial locations, and area sizes of various land categories on the Earth’ s surface, and are the most direct observable result formed on the land surface through the joint action of nature and human activities.

1.4 Research Methods

1.4.1 Nemerow Index Method The Nemerow index method is based on the arithmetic mean and maximum value of the single-factor pollution index, and comprehensively reflects the water-quality status of Bosten Lake and its inflowing and outflowing rivers. The calculation formulas are as follows:

$$P_{ij} = \frac{C_i}{S_{ij}} \tag{1}$$

$$P_j = \sqrt{\frac{P_{j,\max}^2 + P_{j,\text{ave}}^2}{2}} \tag{2}$$

where P_{ij} is the single-factor pollution index; C_i and S_{ij} are the measured value and standard value of the monitoring factor, respectively, and the standard value is the Class III water-quality standard limit in the *Environmental Quality Standards for Surface Water* (GB 3838—2002); $P_{j,\max}$ and $P_{j,\text{ave}}$ are the maximum value and mean value of P_{ij}, respectively; P_j is the Nemerow comprehensive

Fig. 1 Geographical location of Bosten Lake and distribution of water-quality sampling points

Legend in Fig. 1: lake water-quality sampling points; river water-quality sampling points; county-level administrative centers; contour lines; rivers; study area; Bosten Lake; elevation/m; scale 0–20 km.

Tab. 1 Detection method and detection limit of anions and cations in water samples

Chemical indicator	Detection method	Experimental equipment	Detection limit / $(\text{mg} \cdot \text{L}^{-1})$
K^+, Na^+	Flame atomic absorption spectrophotometry	Atomic absorption spectrophotometer / WFX-110B	0.05, 0.1
Ca^{2+}, Mg^{2+}	Disodium ethylenediaminetetraacetate titration	Burette / 25 mL	1
Cl^-	Argentometric titration	Burette / 25 mL	1
SO_4^{2-}	Disodium ethylenediaminetetraacetate–barium titration	Burette / 25 mL	5
HCO_3^-	Acid titration	Burette / 25 mL	0.05

Tab. 2 Data source of water quality driving factors

Influencing factor	Data name	Year	Resolution	Source
Natural factor	Annual precipitation	2023	1 km	National Tibetan Plateau Data Center (https://data.tpdc.ac.cn/home)

Influencing factor	Data name	Year	Resolution	Source
Natural factor	Annual mean air temperature	2023	1 km	National Tibetan Plateau Data Center (https://data.tpdc.ac.cn/home)
Natural factor	Elevation	–	30 m	Geospatial Data Cloud (https://www.gscloud.cn/)
Human factor	Human activity footprint	2020	1 km	[16]
Human factor	Land-use type	2023	30 m	[17]
Human factor	Distance from major roads	2024	–	Open Street Map (https://osgeo.cn/)

composite index [18]. According to different scores, when $P_j < 0.59$, the water-quality grade is Grade I; when $0.59 \le P_j < 0.74$, the water-quality grade is Grade II; when $0.74 \le P_j < 1$, the water-quality grade is Grade III; when $1 \le P_j < 2.5$, the water-quality grade is Grade IV; and when $P_j \ge 2.5$, the water-quality grade is Grade V.

1.4.2 Grey relational analysis

Grey relational analysis is used to analyze the degree of association between the water quality of inflowing and outflowing rivers of Bosten Lake and that of the lake. Taking the lake water-quality indicators as the reference series and the corresponding river indicators as the comparison series, the relational coefficient ξ_i can be calculated by the following formula:

$$\xi_i(k) = \frac{\min_i \min_k \Delta i(k) + \zeta \max_i \max_k \Delta i(k)}{\Delta i(k) + \zeta \max_i \max_k \Delta i(k)} \tag{3}$$

where ζ is the distinguishing coefficient; in this paper the distinguishing coefficient is set to 0.5. $\min_i \min_k \Delta i(k)$ is the two-level minimum difference, and $\max_i \max_k \Delta i(k)$ is the two-level maximum difference; $\Delta i(k)$ is the absolute difference between each comparison series X_i and the measured series X_0. The average value of the relational coefficient ξ_i is the relationship between the comparison series and the measured···

the grey relational degree of the data series.

1.4.3 Spatial autocorrelation analysis To reveal the spatial associations of water-quality indicators in Bosten Lake and its inflow/outflow rivers, the Global Moran' s I index was first used to evaluate overall spatial autocorrelation. The value range of this index is $[-1, 1]$: values greater than 0 indicate positive correlation and spatial clustering; values less than 0 indicate negative correlation and significant differences among adjacent areas; values equal to 0 indicate a random distribution and no spatial correlation. On the basis of the global analysis, the Local Moran' s I index was further tested to identify local clustering patterns of water-quality indicators[19]. The correlation-test results were verified using P values and Z values.

1.4.4 Optimal parameters-based geographical detector (OPGD) The geographical detector is a statistical method used for attribution of spatial differentiation. Traditional methods rely on artificial classification of variables and have problems such as strong subjectivity and insufficient discretization. The optimal parameters-based geographical detector (OPGD) automatically optimizes variable discretization through multiple classification methods, such as natural breaks and geometric intervals, to obtain the maximum q value[20]. In this study, the optimal parameters-based geographical detector was applied to explore the driving factors of river and lake water quality.

Factor detection is mainly used to detect the extent to which a factor X explains the spatial differentiation of an attribute Y. The q value is used for measurement; the larger the q value, the stronger the explanatory power of X for the target attribute Y. The calculation formula is:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2} = 1 - \frac{SSW}{SST} \tag{4}$$

$$SSW = \sum_{h=1}^{L} N_h \sigma_h^2 \tag{5}$$

$$SST = N\sigma^2 \tag{6}$$

where h is the stratification of variable Y or factor X; N_h and N are the numbers of units in stratum h and in the entire region, respectively; σ_h^2 and σ^2 are the variances of the Y values in stratum h and in the entire region, respectively. SSW and SST are the sum of within-stratum variances and the total variance of the entire region, respectively. The value range of q is $[0, 1]$. A larger value indicates more obvious spatial differentiation of Y; if the stratification is generated by X, then a larger q value indicates stronger explanatory power of X for Y, and vice versa.

Interaction detection is used to identify interactions among different risk factors X_s, that is, to assess whether the joint action of factors X_1 and X_2 increases or weakens the explanatory power for the dependent variable Y, or whether the effects of these factors on Y are mutually independent. The interaction relationships between two factors can be divided into five categories, as shown in Table 3.

Table 3 Judgment basis for interactions
Tab. 3 Judgment basis of interaction

Judgment basis	Interaction
$q(X_1 \cap X_2) < \min[q(X_1), q(X_2)]$	Nonlinear weakening
$\min[q(X_1), q(X_2)] < q(X_1 \cap X_2) < \max[q(X_1), q(X_2)]$	Single-factor nonlinear weakening
$q(X_1 \cap X_2) > \max[q(X_1), q(X_2)]$	Two-factor enhancement
$q(X_1 \cap X_2) = q(X_1) + q(X_2)$	Independent
$q(X_1 \cap X_2) > q(X_1) + q(X_2)$	Nonlinear enhancement

2 Results and Analysis

2.1 Characteristics of water-quality indicators and water-quality assessment in the Bosten Lake Basin

2.1.1 Descriptive statistics of water-quality indicators Statistics of the characteristic values of water-quality indicators for river water and lake water show that the average pH of Bosten Lake water is 8.44, while the average pH of the inflow/outflow rivers—the Kaidu River, Qingshui River, Huangshuigou, Wulasitai River, and Kongque River—is 7.92; both are weakly alkaline. The remaining indicators are detailed in Table 4. It can be seen that the mean values of the water-quality indicators within the lake are generally higher than those of the inflow/outflow rivers.

The coefficient of variation (C_v) reflects the degree of dispersion of an indicator; the larger the value, the stronger the spatial fluctuation of water quality. The coefficient of variation (C_v) is divided into three categories: $C_v \leq 20\%$ indicates low variability, $20\% < C_v \leq 50\%$ indicates moderate variability, and $C_v > 50\%$ indicates high variability[21]. For lake water, the concentration of $NH_4^+ - N$ exhibits high variability; TP, TN, BOD_5, and COD_{Cr} exhibit moderate variability; and the remaining indicators exhibit low variability. For river water, pH, Ca^{2+} concentration, and HCO_3^- concentration exhibit low variability; COD_{Mn} concentration, BOD_5 concentration, and F^- concentration exhibit moderate variability; and the remaining indicators exhibit high variability. This indicates that these water-quality indicators fluctuate strongly in spatial distribution, and that the water bodies are complex and unstable.

2.1.2 Water-quality assessment Based on the Nemerow index method, the water quality of 34 river and lake sampling sites was evaluated (Fig. 2). For lake-water quality, there were 2, 16, 6, and 3 samples in Classes I, II, III, and IV, respectively, accounting for 7.4%, 59.3%, 22.2%, and 11.1%, respectively. For river-water quality, there were 6 and 1 samples in Classes I and II, respectively, accounting for 85.7% and 14.3%. Overall, the water quality in the study area was dominated by Class II and was relatively good. Except for the sampling point at the source of the Kongque River, the water quality of the other inflow/outflow rivers was Class I, obviously better than that within the lake.

2.2 Correlation analysis between inflow/outflow rivers and lake water quality

The grey relational analysis method was adopted, with the mean values of lake water-quality indicators used as the reference sequence and the water-quality indicators of sampling sites in the inflow/outflow rivers—including the Wulasitai River, Kaidu River, Huangshuigou, Qingshui River, and Kongque River—used as comparison sequences. The grey relational degree between each river and lake water quality was calculated (Fig. 3). The results show that, except for TDS, all other water-quality indicators exhibit high relational degrees.

The river and lake water-sample data from the study area were plotted on a Gibbs diagram (Fig. 4a). The samples all fall within the rock-weathering control zone and are slightly close to the evaporation–crystallization zone, indicating that the hydrochemical components are mainly affected by rock weathering, with evaporation–crystallization playing a secondary role. The ion-ratio end-member diagram (Fig. 4b) shows that the lake-water samples are concentrated near the silicate-rock dissolution end-member, reflecting that their hydrochemical composition is mainly controlled by silicate-rock weathering, while the influences of carbonate rocks and evaporites are relatively weak. The river-water samples are also concentrated near the silicate-rock end-member,

Tab. 4 Statistical characteristics of water quality indicators in lake and river water

Water-quality indicator	Lake/river concentration / $(mg \cdot L^{-1})$: maximum	Lake/river concentration / $(mg \cdot L^{-1})$: minimum	Lake/river concentration / $(mg \cdot L^{-1})$: mean	Lake/river concentration / $(mg \cdot L^{-1})$: standard deviation	Lake/river coefficient of variation / %
pH	8.53/8.36	8.3/8.16	8.44/7.92	0.06/0.19	0.71/2.27
NH_4^+-N	0.22/0.14	0.02/0.04	0.11/0.02	0.06/0.05	51.48/107.48
TDS	904.77/631.66	645.93/377.36	819.49/175.4	61.77/207.29	7.54/54.93
COD_{Mn}	4.37/3.07	2.52/1.7	3.69/0.67	0.44/0.79	12.05/46.52
TP	0.04/0.12	0.02/0.06	0.03/0.01	0.01/0.04	26.78/67.04
TN	1.44/2.35	0.49/0.93	0.71/0.27	0.17/0.7	24.23/74.6
BOD_5	1/1	0.5/0.59	0.57/0.5	0.13/0.19	23.47/31.83
F^-	0.35/0.29	0.27/0.19	0.33/0.13	0.02/0.08	6.59/39.71

Water-quality indicator	Lake/river concentration / (mg · L^{-1}): maximum	Lake/river concentration / (mg · L^{-1}): minimum	Lake/river concentration / (mg · L^{-1}): mean	Lake/river concentration / (mg · L^{-1}): standard deviation	Lake/river coefficient of variation / %
COD_{Cr}	28/18	10/6.71	17.07/2	4.47/6.55	26.19/97.56
K^+	8.34/1.56	11.96/8.34	10.76/4.48	0.91/2.90	8.42/64.60
Na^+	103.76/5.15	154.1/99.01	134.32/43.47	12.77/44.33	9.51/101.98
Ca^{2+}	48.14/44.53	58.98/68.20	53.02/53.76	2.67/8.36	5.03/15.56
Mg^{2+}	44.29/9.25	65.7/46.24	60.20/23.57	4.55/16.59	7.56/70.38
Cl^-	120.75/9.94	220.19/129.27	168.41/58.24	19.47/53.75	11.56/92.28
SO_4^{2-}	212.85/27.58	308.62/196.51	277.93/99.05	23.55/80.70	8.47/81.47
HCO_3^-	193.13/150.35	227.36/202.91	214.64/185.10	7.87/18.18	3.67/9.82
CO_3^{2-}	4.81/0	9.62/6.01	7.53/2.23	1.44/2.81	19.11/126.01

Note: pH is dimensionless; n is the number of samples.

Visible labels in the figure include: Ulastai River, Huangshuigou, Kaidu River, Kongque River, Qingshui River, Hejing County, Heshuo County, Yanqi Hui Autonomous County, and Bohu County. The legend indicates county-level administrative centers, rivers, the study area, Bosten Lake, lake-water quality categories Class I–IV, and river-water quality categories Class I–II. The map also shows north orientation and a 0–25 km scale.

Fig. 2 Distribution of water quality categories of lake water and inflow and outflow rivers

Some samples shift toward the carbonate-rock end member, indicating that their hydrochemical composition is mainly controlled by silicate-rock weathering and is also influenced to a certain extent by carbonate-rock weathering. This is consistent with the basin background, which is dominated by silicate rocks such as granite and diorite [22].

2.3 Spatial variation characteristics of water quality indicators

2.3.1 Global spatial autocorrelation analysis

The global Moran’ s index (Global Moran’ s I) was used to analyze the spatial autocorrelation of water quality indicators in Bosten Lake and its inflow and outflow rivers. The global Moran’ s index analysis showed that,

Fig. 3 Correlation degree between inflow and outflow rivers and lake water quality

In the circular chart, the center is labeled "grey relational degree." The visible indicators and values are: COD_{Mn} 0.99, TDS 0.49, NH_4^+-N 0.99, pH 0.99, Pb 0.99, Hg 0.99, As 0.99, COD_{Cr} 0.96, F^- 0.99, BOD_5 0.99, TN 0.99, and TP 0.99.

Fig. 4 Gibbs distribution and ion-ratio endmember diagram of river and lake water chemistry in Bosten Lake

In-figure labels include: (a) $TDS/(mg \cdot L^{-1})$, $Cl^-/(Cl^- + HCO_3^-)$, "rock weathering," "evaporative concentration," and "atmospheric precipitation" ; (b) HCO_3^-/Na^+, Ca^{2+}/Na^+, "carbonate rocks," "silicate rocks," "evaporites," with the legend "river water" and "lake water."

The concentrations of COD_{Mn}, F^-, pH, TDS, and the Nemerow index P_j were significant ($P < 0.05$) and corresponded to the Z values, indicating significant positive spatial autocorrelation and an aggregated distribution; by contrast, the TN concentration showed significant negative spatial autocorrelation, appearing as a dispersed distribution (Table 5).

2.3.2 Moran' s index analysis of water quality indicators

By analyzing the LISA (local indicators of spatial association) maps for the four water quality indicators with significant positive spatial autocorrelation—COD_{Mn} concentration, F^- concentration, pH, and TDS (Fig. 5)—the clustering-zone characteristics of the four types of water quality indicators were obtained. The results show that pH exhibits "high-high" clustering, mainly concentrated in the eastern half of the lake, indicating that the water body is significantly alkaline. TDS and F^- both show "high-high" clustering and are concentrated at the lake inlets of the Qingshui River and Huangshuigou, as well as in the eastern half of the lake, reflecting enrichment of salts and fluorides in these areas. COD_{Mn} exhibits both "high-high" and "high-low" clustering patterns. The former is distributed in both the eastern and western halves of the lake, indicating contiguous distribution of organic pollution; the latter occurs in the lake center and the southwestern waters of the lake area, indicating that COD_{Mn} concentrations there are significantly higher than in surrounding areas and that organic pollution is most prominent.

2.4 Analysis of factors influencing water quality

2.4.1 Influencing factors and optimal parameter selection

This study selected six categories of factors influencing water quality. Anthropogenic factors include land-use type (X_1), human activity footprint (X_2), and distance to major roads (X_3); natural factors include annual precipitation (X_4), mean annual temperature (X_5), and elevation (X_6). Their spatial distributions are shown in Fig. 6. Four classification methods—equal interval, natural breaks, geometric interval, and quantile—were adopted. Except for the categorical variable X_1, the number of classes for continuous variables was set to 3-10, and the classification combination with the largest q value was selected as the optimal parameter. The results show that different classification methods and levels have significant effects on the q value (Fig. 7). The optimal parameter selection for the factors presents two patterns: X_3 and X_4 are more suitable for quantile classification, whereas the remaining factors perform best with natural breaks classification. Except for X_6, whose optimal number of classes is 6, all other factors achieve the best effect when the number of classes is 10.

Tab. 5 Calculation results of global Moran' s index for water quality indicators of Bosten Lake and its inflow and outflow rivers

Water quality indicator	Global Moran' s index	P value	Z value
NH_4^+-N	0.11	0.41	0.83
TP	0.06	0.04	0.03
BOD_5	-0.01	0.67	0.43
COD_{Cr}	0.06	0.06	1.91
P_j	0.12	0.001	3.39
TDS	0.13	0.001	3.36
COD_{Mn}	0.15	0.000	3.67
F^-	0.14	0.001	3.47
pH	0.11	0.002	3.14
TN	-0.19	0.000	-4.22

(a) pH value **(b) TDS**
(c) COD_{Mn} **(d)** F^-

Legend: county-level administrative center; river; study area; Bosten Lake; no significant clustering feature; high-high cluster; low-high cluster.

Map labels shown include: Ulastai River, Huangshui Gully, Qingshui River, Kaidu River, Kongque River, Hejing County, Heshuo County, Yanqi Hui Autonomous County, and Bohu County.

Fig. 5 Spatial LISA agglomeration map of lake water and river water quality indicators

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(a) X_1

Legend: river-water quality sampling sites; lake-water quality sampling sites.
Land-use type: cropland; forest; grassland; water body; bare land; impervious surface; wetland.

(b) X_2

Legend: river-water quality sampling sites; lake-water quality sampling sites.
Human activity footprint: 0.25–5.30; 5.31–10.92; 10.93–16.72; 16.73–22.89;

22.90–30.94; 30.95–47.97.

(c) X_3

Legend: river-water quality sampling sites; lake-water quality sampling sites; major roads.
Distance to major roads / m: 0–69645.1.

(d) X_4

Legend: river-water quality sampling sites; lake-water quality sampling sites.
Annual precipitation / mm: 56.60–67.60; 67.61–77.13; 77.14–87.76; 87.77–99.13; 99.14–116.36; 116.37–150.09.

(e) X_5

Legend: river-water quality sampling sites; lake-water quality sampling sites.
Mean annual temperature / °C: 8.44–9.94; 9.95–10.45; 10.46–10.86; 10.87–11.28; 11.29–11.74; 11.75–12.50.

(f) X_6

Legend: river-water quality sampling sites; lake-water quality sampling sites.
Elevation / m: 967–1074; 1075–1126; 1127–1190; 1191–1263; 1264–1412; 1413–1983.

Fig. 6 Spatial distribution of water quality impact factors

Fig. 7 Statistics of the q values for different classification methods and levels of the geographic detector

Legend: equal-interval classification; natural-break classification; geometric-interval classification; quantile classification.

2.4.2 Analysis of water-quality driving factors

(1) **Single-factor detection** Single-factor detection was used to quantify the explanatory power of each water-quality influencing factor for the spatial distribution of the Nemerow water-quality index (Y is the Nemerow index, X is an influencing factor, and a larger q value indicates stronger explanatory power). Six types of factors were detected, and all P values were less than 0.01, indicating that all factors had significant effects on the spatial distribution of water quality (Fig. 8). In descending order, the q values of the factors were annual precipitation (X_4, 0.59), distance to major roads (X_3, 0.49), annual mean temperature (X_5, 0.48), human activity footprint (X_2, 0.42), land-use type (X_1, 0.42), and elevation (X_6, 0.38). Among the natural factors, X_4 ranked first, X_5 ranked third, and X_6 ranked last; among the anthropogenic factors, X_3 ranked second, X_2 ranked fourth, and X_1 ranked fifth.

Fig. 8 Single-factor detection results

(2) **Interaction-factor detection** On the basis of single-factor detection, interaction detection was carried out (Table 6). The results show that all factors exhibited a two-factor enhancement effect; that is, the driving effect of the interaction between any two factors on water quality was stronger than that of a single factor. Among them, the q value of distance to major roads (X_3) ∩ annual precipitation (X_4) was the largest, followed by distance to major roads (X_3) ∩ annual mean temperature (X_5), while human activity footprint (X_2) ∩ annual precipitation (X_4) ranked third. The top three interaction combinations in terms of q value all included climate factors (X_4 or X_5), and the enhancement effect was significant. In addition, $X_4 \cap X_5$, $X_2 \cap X_5$, and $X_2 \cap X_3$ also showed relatively strong interactions. Overall, the explanatory power of the interaction between any two factors for the spatial differentiation of water quality was higher than that of single factors, and the explanatory power was stronger after the interaction between natural and anthropogenic factors. This indicates that the spatial differentiation of water quality in Bosten Lake and its inflow and outflow rivers is not dominated by a single factor, but rather by

Table 6 Interaction detection of influencing factors

Influencing factor	X_1	X_2	X_3	X_4	X_5
X_2	0.49				
X_3	0.52	0.71			
X_4	0.65	0.86	0.98		
X_5	0.54	0.79	0.94	0.85	
X_6	0.48	0.45	0.59	0.64	0.50

···is the result of the combined action of natural and anthropogenic factors, reflecting the complexity of the mechanisms driving water quality.

3 Discussion

This study comprehensively evaluated the water-quality characteristics of Bosten Lake and its inflow and outflow rivers, and revealed the coupled mechanisms by which natural and anthropogenic factors affect the aquatic environment. The water-quality indicators varied markedly among sampling sites. On the one hand, this is attributable to differences in hydrological conditions: discharge and flow velocity differ among rivers, and flow velocities within the lake also vary. Under low-flow conditions, the dilution capacity for pollutants decreases; under high-flow conditions, although some pollutants may be diluted, inputs of suspended matter and nutrients may increase [23]. Significant differences in runoff recorded at the four hydrological stations in the Bosten Lake Basin—Dashankou, Yanqi, Huangshuigou, and Kuergeti [24]—confirm the important influence of hydrological conditions on water-quality fluctuations. In addition, rivers traverse extensive areas; most flow from the western mountains into the plain before entering the lake. Water quality is better in high-altitude areas, whereas the human-activity footprint distribution map shows (Figure 6) that human activities intensify near the river system. Along their courses, rivers are clearly affected by domestic point-source pollution and agricultural non-point-source pollution, resulting in spatial differentiation of water quality. Overall, river water quality, dominated by Class I water, is better than lake water quality, dominated by Class II water. The main reasons include the fact that the lake serves as the terminal collection area of the basin, where pollutants accumulate over the long term [25]. Meanwhile, the main inflow to Bosten Lake, the Kaidu River, and the outflow, the Kongque River, are both located in the southwest corner, leading to differences in hydrodynamic conditions between the eastern and western lake areas. The eastern lake area has a long water residence time, making pollutants more likely to accumulate.

In the southwest corner of Bosten Lake, the inflow and outflow rivers have relatively high flow velocities and frequent water exchange, whereas the lake as a whole has low flow velocity and insufficient hydrodynamic conditions [26]. On the one hand, this leads to significant differences in water-quality indicators among sampling sites within the lake; on the other hand, frequent water exchange allows low-TDS water to enter continuously, reducing TDS values around the inflow and outflow mouths. Within the lake, however, weak hydrodynamics and long water residence times cause dissolved substances to accumulate gradually under evaporative concentration, increasing TDS. In addition, residential activities, such as domestic sewage discharge, together with natural factors such as precipitation and evaporation, introduce suspended particles and sediments into the lake, causing TDS to show a distribution pattern of low values around the periphery and high values in the center. Notably, lake TDS is significantly higher than river TDS, and the correlation between the two is weak; in addition to the effects of water exchange and human activities, this may also be due to dissolution from sediments at the bottom of the lake basin [27]. The spatial clustering characteristics of COD_{Mn}, F^-, pH, and TDS revealed by spatial autocorrelation analysis further demonstrate the spatial heterogeneity of hydrochemical processes in the lake. The four water-quality indicators are dominated by high-value clusters. Only in the southwest corner, where the Kaidu River and Kongque River flow into and out of the lake and where water circulation is strong and water exchange frequent, high-value clusters did not form; low TDS values also occur in this area. Although the northwest corner receives inflow from the Huangshuigou and Qingshui rivers, the discharge of the two rivers is small, flow velocities are slow, hydrodynamic conditions are insufficient, and the water-exchange cycle is relatively long, creating conditions for high-value clustering. The eastern half of the lake has no river inflow or outflow and weak water exchange, so high-value clusters are likewise easy to form.

The results of the improved geographic detector analysis show that climatic factors, representing natural factors, and distance to major roads, representing anthropogenic factors, are the dominant factors influencing the spatial differentiation of water quality, with annual precipitation having the highest explanatory power. From 1980 to 2018, the mean annual air temperature in the Bosten Lake Basin fluctuated upward, and climate change directly or indirectly affects water quality by influencing processes such as evaporative concentration and weathering rates [28]. Distance to major roads ranked second in explanatory power. Road runoff [29] is an important pollution source, reflecting the potential impact of transportation infrastructure on the surrounding environment. In addition, the human-activity footprint [16] and land-use type also have relatively high explanatory power. Considering the actual conditions of the study area, agricultural and sideline-product processing plants, aquaculture farms, and tourist attractions are distributed along the southern shore of the lake, while paper mills, coal mines, sugar refineries, and domestic sewage outlets are located on the western shore; industrial and domestic wastewater discharges are substantial. All natural–anthropogenic factor interactions exhibit nonlinear enhancement effects, indicating that when climatic warming, reduced precipitation, and intensified human activities coexist, they synergistically amplify negative impacts on water quality [30]. These findings have important guiding value for basin management. Particular attention should be paid to the alkaline environmental risks in the high-pH clustering area of the eastern half of the lake. In view of the spatial clustering characteristics of TDS and F^-, salt-transport interception should be strengthened in the southwestern lake area. The layout of transportation infrastructure should fully consider the distance over which it may potentially affect the water environment. At the same time, the influence of distance to major roads may act on the water environment indirectly by promoting development along transport corridors, altering land-use patterns, and increasing vehicle emissions [31].

The present study still has certain limitations, mainly in three aspects: data precision, mechanistic understanding, and management practice. Owing to limitations in data resolution, the spatial pathways by which human activities affect the water environment have not yet been characterized in sufficient detail. The nonlinear response processes and key thresholds in the interactions between natural and anthropogenic factors remain unclear, and the buffering range of lake water-environment carrying capacity under climatic warming, as well as the critical conditions for abrupt changes in water quality, still require clarification [32]. In addition, quantitative research on ecological-flow assurance and water-cycle regulation at the basin scale remains relatively weak. To address these limitations, future studies should introduce higher-resolution spatial data, such as high-precision land-use data and real-time traffic-flow data, to characterize influence pathways more finely. Long-term fixed-site observations and dynamic model simulations should be combined to reveal nonlinear response mechanisms and their critical conditions. At the same time, studies on basin water-allocation regulation should be strengthened. By rationally regulating the inflow and outflow volumes of Bosten Lake and enhancing circulation in the eastern lake area, pollutant accumulation and salt concentration can be alleviated [33], thereby providing a scientific basis for adaptive management of lakes in arid regions.

4 Conclusions

(1) The waters of Bosten Lake are weakly alkaline, and the mean values of water-quality indicators within the lake are generally higher than those in the inflow and outflow rivers. The Nemerow index evaluation results

show that lake water quality is mainly Class II (59.3%), while Classes III and IV together account for 33.3%, and Class I accounts for only 7.4%; river water quality is mainly Class I (85.7%). Overall, river water quality is better than lake water quality, and lake water shows an obvious pollution-gradient pattern, with the proportion worse than Class III exceeding 30%.

(2) The hydrochemical composition of the rivers and lakes in the study area is mainly controlled by rock weathering. Specifically, both lake and river components are dominated by silicate-rock weathering, while river components are also influenced to some extent by carbonate-rock weathering.

(3) COD_{Mn} concentration, F^- concentration, pH, and TDS show spatial clustering, whereas TN shows a discrete distribution. TDS and F^- concentrations exhibit "high-high" clustering at the lake inlets and in the eastern half of the lake, indicating enrichment of salts and fluorides; pH shows "high-high" clustering in the eastern half of the lake, indicating alkaline water. COD_{Mn} has both "high-high" clustering—distributed continuously in the eastern and western half-lake areas—and "high-low" clustering—located in the lake center and near the southwestern lake area—forming local pollution hotspots. The spatial differentiation of lake water quality is significant, characterized mainly by stronger alkalinity in the eastern half of the lake, enrichment of salts and fluorides, and spatial heterogeneity of organic pollution.

(4) The optimal-parameter geographical detector results show that the water quality of Bosten Lake and its inflowing and outflowing rivers is jointly affected by multiple factors. Among them, annual precipitation, distance to major roads, mean annual temperature, and human-activity footprint are the main driving factors. Interactions between any two factors all show two-factor enhancement, indicating that both natural and anthropogenic factors have important impacts on water quality.

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Interactive effects of natural and human factors on the water quality of Bosten Lake

HUANG Zehong1,2,3, ZENG Yanyan1,2,3, ZHOU Jinlong1,2,3, DUAN Xiurong4, TAN Lan4

(1. College of Hydraulic and Civil Engineering, Xinjiang Agricultural University, Urumqi 830052, Xinjiang, China;
2. Xinjiang Hydrology and Water Resources Engineering Research Center, Urumqi 830052, Xinjiang, China;
3. Xinjiang Key Laboratory of Hydraulic Engineering Security and Water Disasters Prevention, Urumqi 830052, Xinjiang, China;
4. Bosten Lake Scientific Research Institute, Bayingol Mongolian Autonomous Prefecture in Xinjiang, Korla 841000, Xinjiang, China)

Abstract: To explore the interactive driving mechanism of natural and human factors on surface water quality, this study takes Bosten Lake and its inflow and outflow rivers as the object, uses the Nemerow index method to evaluate water quality, and combines grey correlation analysis, spatial autocorrelation, and optimal parameter geographic detector model to identify the correlation characteristics, spatial clustering, and factor interaction of water quality indicators. The results show that: (1) The source of the Kongque River is Class II water quality, and the rest of the rivers are Class I. The lake water is mainly Class II (59.3%), and the water quality of the river is better than that of the lake. (2) The average TDS of lake water (819.49 mg · L−1) was significantly higher than that of rivers, and the correlation with river transport was weak. (3) CODMn, F−, pH, and TDS showed significant spatial aggregation characteristics. (4) Annual precipitation (natural factor) is the main driving factor, followed by the distance from the main road (human factor), and the overall influence of natural factors is stronger. The interaction of any two factors showed a two-factor enhancement effect, and the explanatory power was higher than that of the single factor. This study reveals the complex mechanism of the synergistic effect of natural-anthropogenic factors on lake water quality in arid areas, highlights the nonlinear response of river-lake system under the influence of climate and human activities, and provides a scientific basis for the sustainable management of lake-watershed in arid areas of Northwest China.

Keywords: grey correlation; spatial autocorrelation; optimal parameter geographical detector (OPGD); driving mechanism; Bosten Lake

Note: Figure translations are in progress. See original paper for figures.

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