Postprint: Analysis of Water Quality and Eutrophication Changes in Hulun Lake, 2011–2020

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Date: 2021-12-12T00:00:00+00:00

Abstract

This study takes Hulun Lake as the research object, selecting long-term measured water quality indicators from 2011 to 2020 to analyze the interannual variations of salinity (S), electrical conductivity (EC), total dissolved solids (TDS), pH, transparency (SD), chlorophyll a (Chl.a), dissolved oxygen (DO), chemical oxygen demand (COD), total nitrogen (TN), and total phosphorus (TP). Based on the grey pattern recognition model and comprehensive trophic level index method, the water quality and eutrophication degree of Hulun Lake from 2011 to 2020 were evaluated. Combined with the actual conditions of Hulun Lake, water quality and eutrophication degree were analyzed from both external input and meteorological conditions. The results show: (1) From 2011 to 2020, S, TDS, and EC all decreased, indicating improvement in water salinization; pH ranged between 8.86 and 9.37, showing weakly alkaline conditions; except for TP, both TN and COD decreased. The Grey pattern comprehensive index (GC) indicates that the year with optimal water quality in the past decade was 2012, while the worst was 2011. Overall, GC decreased from 4.01 in 2011 to 3.35 in 2020, demonstrating a trend of water quality improvement. (2) The Trophic Level Index (TLI) shows that from 2011 to 2020, the water body underwent a transition process of moderate eutrophication—heavy eutrophication—moderate eutrophication. TLI first increased then decreased, rising from 61.837 in 2011 to 71.815 in 2016, then falling to 61.535 in 2020. Meanwhile, wind speed (WS) and water depth (H) are driving factors of water eutrophication in Hulun Lake. Currently, water pollution in Hulun Lake is primarily dominated by nitrogen, phosphorus, and organic pollution. Controlling upstream sewage and wastewater discharge, strictly managing grass-livestock balance, and improving the water quality of replenishment sources are important measures for improving Hulun Lake' s water quality.

Full Text

Analysis of Water Quality and Eutrophication Changes in Hulun Lake from 2011 to 2020

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Abstract

This study examined Hulun Lake using long-term measured water quality data from 2011 to 2020. Interannual variations in salinity (S), electrical conductivity (EC), total dissolved solids (TDS), pH, transparency (SD), chlorophyll a (Chl.a), dissolved oxygen (DO), chemical oxygen demand (COD), total nitrogen (TN), and total phosphorus (TP) were analyzed. Water quality and eutrophication levels were evaluated using the grey pattern recognition model and comprehensive trophic level index (TLI) method. Based on actual conditions in Hulun Lake, water quality and eutrophication were analyzed from two perspectives: external source inputs and meteorological conditions. Results showed that S, TDS, and EC all decreased from 2011 to 2020, indicating improved water salinization. pH ranged between 8.86 and 9.37, reflecting weakly alkaline conditions. TN and COD decreased, while TP showed no significant decline. The Grey Pattern Composite Index (GC) identified 2012 as the year with optimal water quality and 2011 as the worst. Overall, GC decreased from 4.01 in 2011 to 3.35 in 2020, demonstrating improving water quality trends. The TLI revealed that Hulun Lake experienced moderate eutrophication, severe eutrophication, and then returned to moderate eutrophication from 2011 to 2020. TLI initially increased then decreased, rising from 61.837 in 2011 to 71.815 in 2016 before declining to 61.535 in 2020. Wind speed and water depth were identified as driving factors of eutrophication in Hulun Lake. Current pollution is dominated by nitrogen, phosphorus, and organic contaminants. Key measures for improving water quality include controlling upstream sewage discharge, strictly regulating grass-livestock balance, and enhancing the quality of water supply sources.

Keywords: Hulun Lake; eutrophication; grey pattern recognition model; comprehensive trophic level index method

Introduction

In recent years, rapid socioeconomic development, population growth, and unsustainable water resource utilization have led to increasingly severe water quality deterioration in rivers, lakes, and reservoirs across China. Lakes in the

Mongolian-Xinjiang Plateau region are particularly vulnerable due to their location in cold, arid zones where annual precipitation is far less than evaporation. Insufficient water supply leads to declining water levels and concentration of lake water, gradually transforming them toward salt lakes. Overgrazing, grassland-livestock imbalance, and soil erosion cause surface runoff to carry large amounts of nutrients into lakes. Additionally, increased water demand for industrial, agricultural, and domestic use has resulted in dramatic increases in wastewater discharge, making lake eutrophication particularly prominent.

Hulun Lake is the largest lake in Inner Mongolia and the largest grassland-type lake at the same latitude in inland areas, playing a crucial role in maintaining biodiversity and abundant flora and fauna resources on the Hulunbuir Grassland. As an extremely important ecological barrier in northern China, Hulun Lake holds great significance for regional economic development and ecological construction, and was listed in the "International Important Wetlands Directory" in 2002. However, years of pollution from surrounding residential sewage, industrial wastewater, and livestock operations have severely damaged the lake' s aquatic ecosystem. While numerous scholars have studied Hulun Lake' s water quality, water quantity, and sediments, most research has been based on short time series for status analysis and evaluation, with few long-term sequence studies. Since the implementation of the "River-to-Lake" water diversion project in 2009, the water circulation structure of Hulun Lake has changed, and pollution structures and control mechanisms from surrounding residential, industrial, and livestock sources have also evolved significantly. Therefore, long-term sequence analysis of water quality and eutrophication changes in Hulun Lake is particularly important for understanding the process of ecological environment deterioration and for water quality pollution control.

This study utilized measured water quality data from Hulun Lake from 2011 to 2020 to evaluate water quality and trophic status based on interannual variations in water quality indicators, the grey pattern recognition model, and the comprehensive trophic level index method. Combined with actual conditions in Hulun Lake, this research analyzed interannual variation trends and driving factors of water quality and eutrophication over the past decade, providing data support and scientific basis for controlling water pollution and eutrophication in Hulun Lake.

1. Study Area Overview

Hulun Lake (116°58 ~117°48 E, 48°33 ~49°20 N) is located between Manzhouli City and the Xin Barag Left and Right Banners in Inner Mongolia, within a temperate continental climate zone. The lake has an average temperature of -0.7~1.1°C, an irregular oblique rectangular shape with an average length of 93 km and average width of 32 km, a water area of 2339 km^2, and a storage capacity of approximately 138.5$\times$10^{8}$ m^3. The multi-year average precipitation is 264.3 mm, and the multi-year average evaporation is 1411 mm. The lake has an average depth of 5.75 m, with spring being hot and dry and winter being cold and long. The ice-bound period lasts about 6 months. In addition to atmospheric and groundwater recharge, the Hailar River, Kherlen River, and Ursun River are the main water supply sources for Hulun Lake. The Xinkai River in the north is a throughput-type river—when the Hailar River has high flow, water is injected into Hulun Lake through the Xinkai River; when Hulun Lake has high water volume, water flows out through the Xinkai River into the Erguna Wetland.

2. Materials and Methods

2.1 Data Sources Based on actual conditions, 10 representative monitoring sites were established in Hulun Lake [Figure 1: see original paper]. The research team conducted sampling during the non-ice-bound period (May to September). Compared with southern lakes, Hulun Lake as a cold-arid region grassland lake shows large seasonal differences. May to September is the key period when pollutant concentrations easily increase and algae blooms are prone to occur, making it particularly important for lake pollution control. Therefore, water quality indicator data measured during these months from 2011 to 2020 were selected for analysis.

2.2 Water Quality Monitoring Methods Water sample collection followed the technical guidance for lake and reservoir sampling (GB/T 14581-1993). At each sampling point, a Swiss Mettler water quality parameter detector was used to measure salinity, total dissolved solids (TDS), and electrical conductivity (EC) on-site. Transparency (SD) was measured using a Secchi disk. Water samples were collected 0.5 m below the surface using a water sampler, with three parallel samples taken and stored in polyethylene bottles (acid-washed and sterilized with alcohol) in a 4°C incubator for transport to the laboratory. Some samples were acidified with sulfuric acid and analyzed for total nitrogen (TN) using alkaline potassium persulfate digestion-ultraviolet spectrophotometry (GB 11894-1989) and for total phosphorus (TP) using potassium persulfate digestion-ammonium molybdate spectrophotometry (GB 11893-1989). Other samples were filtered through 0.45 m membranes and analyzed for chlorophyll a (Chl.a) using acetone extraction spectrophotometry (SL 88-1994) and for chemical oxygen demand (COD) using the potassium dichromate method (GB 11914-1989). The relative deviation of parallel measurement results was required to be less than 10%; otherwise, measurements were repeated and the average value was taken as the monitoring value. Wind speed data were obtained from the National Meteorological Science Data Center (http://data.cma.cn, hydrological station numbers: V01301, V04001, V04002).

2.3 Grey Pattern Recognition Model A grey pattern recognition model matrix was established: Let there be n water quality monitoring samples to be graded, each with i measured pollutant indicator values C. Based on the Environmental Quality Standards for Surface Water (GB 3838-2002), i pollutant indicators were divided into k evaluation grades with standard concentration values S, yielding the pollutant indicator measured concentration matrix (Cij) and pollutant indicator standard concentration matrix (Sik).

Data normalization: Since different indicators have different units, the measured concentration matrix and standard concentration matrix were normalized to become grey fuzzy matrices with all elements within [0,1]. It was stipulated that Class I water (best quality) in the standard concentration matrix is 0 and Class k water (worst quality) is 1. For indicators where higher concentration indicates more severe pollution, normalization was performed using formula (2). For indicators where higher concentration indicates lighter pollution, normalization was performed using formula (3).

Calculation of correlation degree and correlation dispersion: In the normalized measured concentration matrix, CCin (n=1,2,···,t,···,k) serves as the sub-sequence. The correlation coefficient between the nth measured concentration sample and the tth grade standard concentration for the mth indicator is calculated using formula (4), where is the resolution coefficient (typically [0,1]). The correlation degree is obtained by weighted summation using formula (5), where λm represents the weight of the mth water quality indicator. In practical problems, all indicators are considered to have equal weight.

Since correlation degree alone provides low resolution for water quality classification, correlation dispersion formula (6) is used to highlight sequence differences.

Calculation of membership degree: Membership degree measures the degree to which a sample belongs to a certain category and can be viewed as a weight concept in fuzzy sets. The difference between water sample measured concentration n and water quality standard t is expressed by weighted correlation dispersion. The optimal classification membership degree matrix is used to calculate membership degree unt using formula (7).

Grey pattern recognition composite index: To evaluate water quality more accurately, the Grey Pattern Composite Index (GC) is introduced. The composite index GC(n) is obtained by weighting the water quality category t with its corresponding membership degree unt, as shown in formula (8), where t represents the water quality standard grade.

2.4 Eutrophication Evaluation Model The comprehensive trophic level index method was used to evaluate the eutrophication status of Hulun Lake. Using chlorophyll as the baseline parameter, weights for other water quality parameters were determined and the comprehensive trophic level index was obtained through weighted summation using formula (9), where TLI(Σ) is the comprehensive trophic level index, Wj is the weight of the jth water quality parameter, TLI(j) is the trophic level index of the jth parameter, and m is the number of parameters involved in the evaluation.

The calculation formulas for each water quality parameter' s trophic level index are: - TLI(Chl.a) = 10(2.5 + 1.086 ln Chl.a) - TLI(TP) = 10(9.436 + 1.624 ln

TP) - TLI(TN) = 10(5.453 + 1.694 ln TN) - TLI(SD) = 10(5.118 - 1.94 ln SD)

Since Hulun Lake suffers from severe organic pollution and permanganate index (CODmn) is only suitable for relatively clean surface water, chemical oxygen demand (CODcr) was selected to characterize organic pollution levels. Therefore, CODmn was excluded from the eutrophication evaluation indicators, and all Chl.a mentioned in this paper represents chemical oxygen demand (CODcr). Evaluation results use continuous numbers from 0-100 to classify trophic states: oligotrophic (TLI(Σ)<30), mesotrophic (30≤TLI(Σ)$ 50), *lighteutrophic*(50 < *TLI*(Σ) 60), *moderateeutrophic*(60 < *TLI*(Σ) $70), and severe eutrophic (TLI(Σ)>70). Within the same trophic state, higher values indicate more severe eutrophication.

Parameter weights were normalized using the correlation coefficients between Chl.a and other parameters .

2.5 Data Analysis and Processing Data analysis and mapping were performed using Excel 2018, SPSS 22.0, ArcGIS 10.7, and Origin 2019b.

3. Results

3.1 Interannual Variation of Water Quality Indicators Analysis of measured physicochemical indicators from Hulun Lake during 2011-2020 showed varying degrees of fluctuation [Figure 2: see original paper]. Salinity ranged from 0.73 to 2.08 psu, with a multi-year average of 1.08 psu, decreasing annually to 0.78 psu in 2016 before increasing slightly to 0.98 psu in 2020. Electrical conductivity fluctuated between 1.46 and 3.79 $\text{mS} \cdot \text{cm}^{-1}$, with a multi-year average of 2.06 $\text{mS} \cdot \text{cm}^{-1}$, showing a dramatic increase as an outlier in 2016. Total dissolved solids ranged from 0.73 to 1.97 $\text{g} \cdot \text{L}^{-1}$, with a multi-year average of 1.07 $\text{g} \cdot \text{L}^{-1}$, indicating weakly alkaline water. pH fluctuated between 8.86 and 9.37, with the minimum in 2011 and maximum in 2016. Transparency ranged from 0.21 to 0.43 m, with the minimum in 2011 and maximum in 2016.

Chlorophyll a concentration, an important indicator of water self-purification capacity crucial for maintaining aquatic environmental balance and health, fluctuated between 5.09 and 8.99 $\text{mg} \cdot \text{m}^{-3}$, with a multi-year average of 7.51 $\text{mg} \cdot \text{m}^{-3}$. The lowest value appeared in 2012 and the highest in 2011. Overall, Chl.a concentrations remained at relatively high levels, with all years except 2012 exceeding Class V water standards (GB3838-2002). Dissolved oxygen concentrations fluctuated between 3.05 and 16.15 $\text{mg} \cdot \text{L}^{-1}$, with a multi-year average of 8.91 $\text{mg} \cdot \text{L}^{-1}$, decreasing by 43.34% from 2011 to 2020 [Figure 3: see original paper].

Chemical oxygen demand, which measures organic and inorganic reducing substances in water, is a critical indicator of organic pollution severity. COD concentrations in Hulun Lake fluctuated between 51.19 and 122.72 $\text{mg} \cdot \text{L}^{-1}$, with a multi-year average of 71.90 $\text{mg} \cdot \text{L}^{-1}$. Despite decreasing from 82.36 $\text{mg} \cdot \text{L}^{-1}$

in 2011 to 71.90 mg $\cdot$ L^{-1} in 2020, water quality remained classified as inferior Class V, indicating extremely severe organic pollution.

Total nitrogen, a key factor causing eutrophication, showed significant interannual variation ranging from 1.81 to 9.79 mg $\cdot$ L^{-1}, with a multi-year average of 4.02 mg $\cdot$ L^{-1}. TN concentration increased dramatically to 9.79 mg $\cdot$ L^{-1} in 2016 (exceeding Class V standards) before decreasing to 4.02 mg $\cdot$ L^{-1} in 2020, representing a 22.6% reduction and indicating improved pollution conditions returning to pre-2016 levels.

Total phosphorus, another critical factor causing eutrophication and the limiting element in Hulun Lake, originates primarily from sewage discharge from surrounding mines and factories, as well as phosphorus-containing pesticide use. TP fluctuated between 0.13 and 0.60 mg $\cdot$ L^{-1}, with a multi-year average of 0.29 mg $\cdot$ L^{-1}. The concentration increased from 0.27 mg $\cdot$ L^{-1} in 2011 to 0.60 mg $\cdot$ L^{-1} in 2016 (exceeding Class V standards) before decreasing to 0.22 mg $\cdot$ L^{-1} in 2020, slightly lower than the 2011 level.

3.2 Comprehensive Water Quality Assessment Based on water quality monitoring data from 2011 to 2020, the grey pattern recognition model was used for comprehensive evaluation. The measured concentration matrix and standard concentration matrix of pollution indicators (4$×$10) were normalized using formulas (2) and (3). Correlation coefficients were calculated using formula (4), and correlation dispersion was computed using formula (5) to weight the correlation coefficients and obtain correlation degrees, yielding the correlation dispersion of water quality to various standards from 2011 to 2020 .

The membership degree matrix was calculated using formula (7), and the Grey Pattern Composite Index (GC) was obtained by weighting membership degree elements with corresponding water quality categories. When using the grey pattern recognition model, GC values range from 1 to 5. When all indicators meet Class I standards, GC=1; when all indicators meet Class V standards, GC=5. The GC values from 2011 to 2020 ranged from 3.35 to 4.01, indicating the lake was at Class IV water quality standards. Water quality experienced two improvement phases in 2012 and 2020. The minimum GC value (3.35) appeared in 2012 (optimal water quality), while the maximum (4.01) occurred in 2011 (worst water quality). Overall, GC decreased from 4.01 in 2011 to 3.35 in 2020, showing improving water quality trends [Figure 4: see original paper].

3.3 Eutrophication Status Evaluation The comprehensive trophic level index method was used to evaluate eutrophication status from 2011 to 2020. Results showed that Hulun Lake exhibited varying degrees of eutrophication over the years . The lake experienced a transition from moderate eutrophication to severe eutrophication and back to moderate eutrophication. TLI(Σ) initially increased then decreased, rising from 61.837 in 2011 to 71.815 in 2016 (the most severe eutrophication year) before declining to 61.535 in 2020, indicating slight improvement in eutrophication.

4. Discussion

4.1 Relationship between GC, TLI and Environmental Factors To explore the relationship between GC, TLI and environmental factors in Hulun Lake, Pearson correlation analysis was performed on GC, TLI(Σ) and 10 environmental factors using SPSS 22.0. Results showed that GC was extremely significantly positively correlated with Chl.a and significantly positively correlated with TP, with correlation coefficients of 0.854 and 0.673, respectively. While Chl.a is a manifestation and result of eutrophication rather than a driving factor, TP directly changes nutrient concentrations in Hulun Lake. GC was extremely significantly positively correlated with wind speed and significantly negatively correlated with water depth, with correlation coefficients of 0.891 and -0.723, respectively. Changes in water depth affect nutrient and organic concentrations, and depth-induced velocity gradients accelerate water circulation, promoting pollutant migration and transformation. Water exchange with external water bodies through lake discharge greatly reduces pollutant accumulation within the lake.

TLI(Σ) was extremely significantly positively correlated with Chl.a and TP, with correlation coefficients of 0.934 and 0.812, respectively. Chl.a regulates the release of nitrogen and phosphorus nutrients from sediments, thereby affecting water column concentrations. TLI(Σ) was significantly positively correlated with wind speed and significantly negatively correlated with water depth, with correlation coefficients of 0.845 and -0.689, respectively. pH affects algal photosynthesis—Hulun Lake' s weakly alkaline environment facilitates algae' s capture of CO_2 for photosynthesis. Within a certain range, algal density typically increases with rising pH, thereby increasing Chl.a concentration.

4.2 Influencing Factors of Hulun Lake Water Quality Analysis of interannual water quality indicators, comprehensive water quality assessment, and eutrophication status evaluation results from 2011 to 2020 revealed varying degrees of fluctuation in all parameters. TN, TP, and COD showed an initial increase followed by a decrease, rising from 2011 to 2016 then declining to 2020. Based on actual conditions in Hulun Lake, the main factors affecting water quality and trophic status include:

4.2.1 External Source Input

In addition to atmospheric and groundwater recharge, Hulun Lake' s main supply rivers are the Hailar River, Kherlen River, and Ursun River. Since the "River-to-Lake" project implementation in 2009, the Hailar River has become the primary water source, with diversion volumes exceeding the sum of the other two rivers. The Hailar River receives domestic and industrial wastewater from Hailar District and Yakeshi City, maintaining high pollutant concentrations. The Kherlen River and Ursun River are impacted by livestock operations, with total nitrogen and phosphorus losses of 1.75 $mg \cdot L^{-1}$ and 0.63 $mg \cdot L^{-1}$ from traditional pastures, 1.6 $mg \cdot L^{-1}$ and 0.68 $mg \cdot L^{-1}$ from fenced pastures, and

0.89 $mg \cdot L^{-1}$ and 0.45 $mg \cdot L^{-1}$ from non-grazed pastures. The Zhalainuoer District near the lake has rapidly developing mining operations, with nitrogen and phosphorus pollutants entering water bodies through atmospheric deposition and surface runoff during coal extraction. Dry grass residues around the lake are also easily carried into the water, where microbial decomposition increases nitrogen and phosphorus concentrations after decomposition.

Analysis of pollutant concentrations at river inlets from 2011 to 2020 showed that TN, TP, and COD at the Hailar River inlet (A10) ranged from 1.64-11.50 $mg \cdot L^{-1}$, 0.07-0.46 $mg \cdot L^{-1}$, and 6.12-8.23 $mg \cdot L^{-1}$, respectively, all far exceeding Class V surface water environmental quality standards (2 $mg \cdot L^{-1}$ for TN and 0.2 $mg \cdot L^{-1}$ for TP). At the Ursun River inlet (A7), TN, TP, and COD ranged from 3.98-7.82 $mg \cdot L^{-1}$, 0.26-0.45 $mg \cdot L^{-1}$, and 0.70-3.98 $mg \cdot L^{-1}$, respectively, also exceeding standards. At the Kherlen River inlet (A1), concentrations remained relatively low but increased in 2019-2020. Such highly polluted inflow inevitably causes water quality deterioration and eutrophication.

4.2.2 Meteorological Conditions

Hulun Lake is located between Manzhouli City and the Xin Barag Left and Right Banners. Wind speed significantly influences the degree of atmospheric deposition and dry grass residue input. The flat terrain and vast grasslands around the lake mean that higher wind speeds facilitate atmospheric deposition and dry grass input. External disturbances enhance sediment resuspension, making sediments a "source" of nutrient pollution. Temperature and other factors promote nutrient release from sediments to the water column. Precipitation is also an important factor affecting nitrogen and phosphorus concentrations. Hulun Lake receives an average annual dust input of 6440$\times10^{4}$ t, with annual dry grass input of 1.58$\times10^{4}$ t during the ice-bound period and 2.1$\times10^{4}$ t during the non-ice-bound period, corresponding to nitrogen inputs of 6.28$\times10^{4}$ t and 2.3$\times10^{4}$ t, and phosphorus inputs of 176.8$\times10^{4}$ t and 0.97$\times10^{4}$ t, respectively, demonstrating substantial pollution impact.

Analysis of average precipitation and wind speed in Manzhouli City and the Xin Barag Left and Right Banners from 2011 to 2020 showed a gradual increasing trend in wind speed, maintaining relatively high levels of 4.30 $m \cdot s^{-1}$ and 4.13 $m \cdot s^{-1}$ in 2019-2020 before decreasing slightly. As precipitation increased, water recharge became more abundant, water depth and area increased, and pollutant concentrations were diluted, reducing TN and TP concentrations. Conversely, decreased precipitation led to concentration increases. In 2011, precipitation was minimal at only 8.3 mm, combined with high pollutant concentrations from the three inflow rivers, resulting in high pollutant concentrations in Hulun Lake. Although precipitation fluctuated, the overall trend was upward, while TN and TP concentrations gradually decreased, consistent with the water quality grade change trend shown in [Figure 4: see original paper].

5. Conclusions

(1) From 2011 to 2020, water quality indicators in Hulun Lake showed interannual variations: S, EC, TDS, TN, and COD decreased, while pH, SD, and TP increased. Chl.a concentrations decreased by 43.34%.

(2) Grey pattern recognition model evaluation indicated that Hulun Lake' s optimal water quality year was 2012 and the worst was 2011. Overall, GC decreased from 4.01 to 3.35, indicating improving water quality.

(3) Comprehensive trophic level index evaluation revealed that Hulun Lake experienced moderate eutrophication, severe eutrophication, and then returned to moderate eutrophication from 2011 to 2020. TLI initially increased then decreased, rising from 61.837 in 2011 to 71.815 in 2016 before declining to 61.535 in 2020, showing slight eutrophication improvement.

(4) Correlation analysis showed that GC was extremely significantly positively correlated with Chl.a and TP, and significantly positively correlated with wind speed but significantly negatively correlated with water depth. TLI(Σ) was extremely significantly positively correlated with Chl.a and TP, significantly positively correlated with wind speed, and significantly negatively correlated with water depth.

(5) Nitrogen, phosphorus, and organic pollution remain the main causes of water pollution in Hulun Lake. To ensure healthy water quality development, emphasis should be placed on source control: improving wastewater discharge standards for upstream industrial parks; strictly controlling livestock development by converting traditional grazing to rotational systems, rationally utilizing livestock manure, ensuring grassland carrying capacity, and reducing soil erosion; enhancing water quality monitoring of inflow rivers; and improving water quality of supply sources while maintaining adequate water recharge.

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