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River–Lake System Connectivity Effectively Reduced the Salinity of Lake Water in Bosten Lake, Northwest China

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Abstract: High salinity in water constitutes a serious problem for the aquatic environment management of Bosten Lake. Weak water exchange and water movement are the essential factors for the high total dissolved solids (TDS) content of lake water. To improve the water quality of Bosten Lake, a river–lake system connectivity project (water diversion) was introduced starting at the end of 2018, which diverted fresh water from the Kaidu River and the Huangshuigou River to Bosten Lake. In this study, the effect and its mechanism of water diversion on the TDS content of Bosten Lake were evaluated using continuous-field monitoring data. The results showed that the water diversion effectively reduced the TDS content of the lake water and changed Bosten Lake from a brackish lake back to a freshwater lake. Water diversion also improved the spatial distribution of TDS content. One year, two years, and three years after the implementation of the water diversion project, the TDS content of northern, southern, and eastern lake water significantly decreased by more than 20%, 25%, and 30%, respectively. Our study demonstrated that water diversion significantly increased the annual endogenous TDS pollutant amount discharged from the lake and reduced and homogenized the TDS content of the whole lake. TDS content reduction of the lake was realized by water diversion accelerating water movement and water exchange in the lake, especially for the northern, southern, and eastern waters. Therefore, water diversion could be used as an effective measure for water quality improvement in semi-closed inland lakes in arid areas.

Keywords: salinity; endogenous pollutants; water quality improvement; water diversion; Bosten Lake

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Citation: Zhou, H.; Chen, Y.; Ye, Z.; Li, Y.; Zhu, C. River–Lake System Connectivity Effectively Reduced the Salinity of Lake Water in Bosten Lake, Northwest China. *Water* **2022**, *14*, 4002. https://doi.org/10.3390/w14244002

Academic Editors: Glen R. Walker and Junhong Bai

Received: 4 October 2022
Accepted: 6 December 2022
Published: 8 December 2022

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1. Introduction

As an important carrier of freshwater resources, lakes play a critical role in water resource allocation, ecosystem balance, and social and economic development [1]. With the rapid development of human activities and climate changes, the water environment of lakes has deteriorated significantly [2]. Most lakes have suffered water contamination resulting from eutrophication or salinity, and diminishing lake water quality may become an increasingly dire issue globally [3–6]. Many biological, chemical, and physical measures exist for improving the water quality of lakes [7–10]. Presently, river–lake system connectivity (water diversion), an important physical method for lake water quality improvement, has received significant interest from scientists and lake administrations [2,11,12]. Theoretically, the implementation of water diversion, in which large amounts of low-saline and low-nutrient water are diverted from a river into a lake, could not only dilute pollution in the lake to improve water quality and mitigate the urgent lake water environmental crisis, but also shorten water renewal time by accelerating water exchange to eliminate dead water zones in the lake [2,12,13]. Moreover, compared with other measures, water diversion projects are low-cost and easy to conduct [11]. Therefore, water diversion projects have been increasingly applied to many lakes worldwide, such as Taihu Lake in China [10,14], Moses Lake and Green Lake in the USA [15], Tega Lake in Japan [16], etc.

Under the dual stresses of lack of precipitation and strong evaporation, lakes in arid and semi-arid regions suffer from increasing salinization [17]. In fact, salinization has become one of the major water quality crises for lakes [3,18]. Bosten Lake is the largest inland freshwater lake in China, and it plays a central role in the livelihoods of the surrounding 1,280,000 residents, their economy, and ecosystems. As a semi-closed lake in an arid region, however, Bosten Lake has gradually become a brackish lake since the 1970s due to human activities and climate changes [6,19]. Brackish water weakens the important ecological–economic functions of the lake and gradually threatens the drinking-water quality, agricultural irrigation, and aquatic organisms that rely on the lake. This leads to agricultural output reduction, wetland degradation, and biological diversity decreases around the lake [5,18,20]. Indeed, brackish water is destroying the aquatic ecosystem and constraining social and economic development in the Bosten Lake Basin. Over the past 40 years, although the local government implemented a series of measures to limit sewage release into the lake to improve the water environment of Bosten Lake, the total dissolved solids (TDS) content of the lake water did not show a significant improvement [5,21–23]. Therefore, determination of how to effectively reduce TDS content to return the lake to a freshwater lake and to improve water quality has constituted an urgent and challenging task for the water resource management of Bosten Lake. This issue is also equally important for all lakes in arid and semi-arid regions that are facing increasing salinization.

In this study, we analyzed the historical TDS content change of Bosten Lake and introduced the justifications for water diversion implementation in Bosten Lake to improve the water environment. Then, we evaluated the improvement effects of water diversion on TDS content using continuous-field monitoring data and discussed the impact mechanism of water diversion on water quality in Bosten Lake. This study aimed to elucidate the effectiveness of water diversion in reducing the TDS content of lake water and attempted to provide a valid engineering measure for improving the water quality of semi-closed inland lakes generally, which could benefit the sustainable management of lake-water environments in arid and semi-arid areas.

2. Study Area and Methods

2.1. Study Area

Bosten Lake, located between 86°19′~87°28′ E and 41°46′~42°08′ N in arid Central Asia, is the biggest freshwater inland lake in China. It also acts as a crucial, central water control and allocation facility in Xinjiang Province. It regulates droughts and floods, and provides irrigation, drinking, and ecological water to the Bosten Lake Basin. Bosten Lake is also an important fishery and the source of reeds for Xinjiang Province. Bosten Lake is a semi-closed shallow lake with a surface area of 1002.4 km^2 and a mean depth of 8.8 m. It is also the tail of the Kaidu River and the source of the Konqi River. Its contributing rivers include the perennial Kaidu River and the seasonal Huangshuigou River, Qingshui Rivers, Quhuigou River, and Wushitala River (Figure 1). There is no flow from the Qingshui Rivers, Quhuigou River, or Wushitala River into Bosten Lake because their lower reaches have been dried up since 2008. Due to increasing agricultural water demand in the upper reaches, the flow from the Huangshuigou River entering Bosten Lake has been decreasing since 2000, and the west branch of the Huangshuigou River gradually desiccated. In recent years, most of the lake water has been supplied by the Kaidu River, and another small portion of the lake water has come from the east Huangshuigou River. Bosten Lake discharges to the Konqi River through a pump, and the discharge amount is manually controlled.

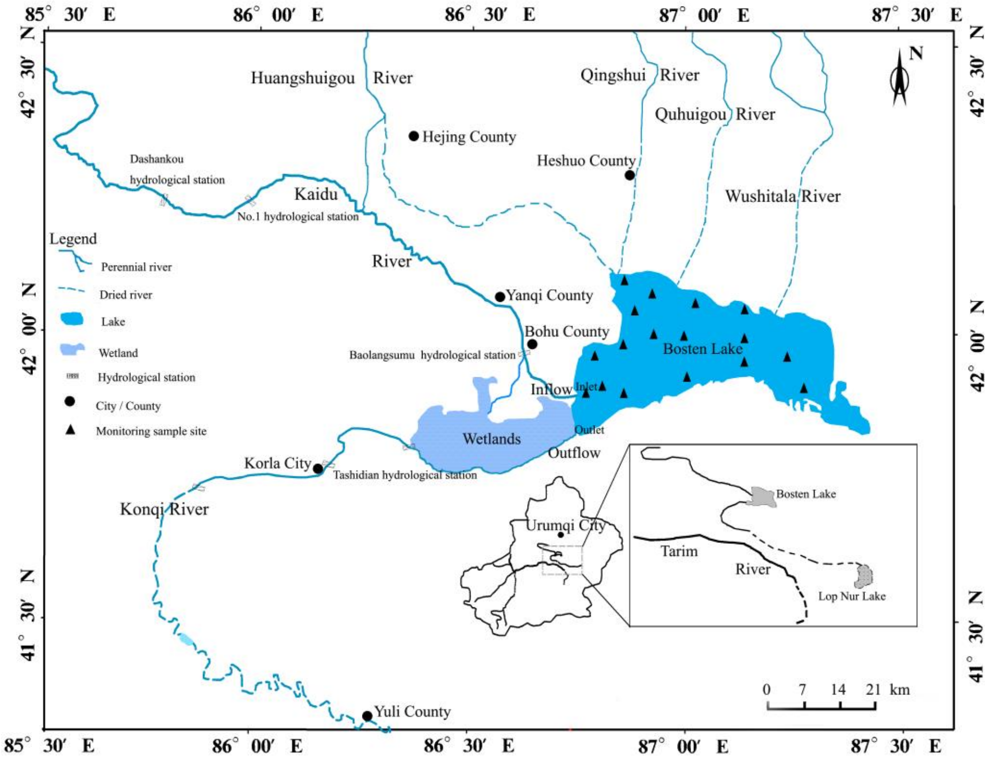

Figure 1. Illustration of the study area.

2.2. Material and Methods

2.2.1. TDS Content Data Monitoring

In order to continuously monitor the total dissolved solids (TDS) content changes in Bosten Lake, 17 long-term fixed-monitoring points have been established since 2000 (Figure 1). These monitoring points essentially covered the whole lake space, so that the monitoring data could comprehensively represent the water quality of the entire lake. The TDS content of water samples at these monitoring points was measured monthly from April to November (Bosten Lake is frozen from December to February of the next year) in 2000–2021. The water samples were collected from the 0–50 cm water layer at every monitoring site using a speedboat. The TDS content was measured using a smart, portable, multi-parameter water quality analyzer (YSI ProPlus, YSI Environmental, Inc., Yellow Springs, OH, USA). A widely used classification standard for fresh water and salt water was adopted to assess the salinity of the water in Bosten Lake (Table 1).

Table 1. Classification standard of water salinity.

Classification Standard	Fresh Water	Brackish Water	Salt Water	Brine	Bittern
TDS (g/L)	<1.0	1 ~ < 3.0	3 ~ < 10.0	10 ~ < 50.0	≥50.0

Note: Data came from the National Standards of the People's Republic of China: Classification of Groundwater Resources (GB/T15218-2021).

Data of annual average TDS content of the lake water from 1958 to 1999 were collected from the Bayinguoleng Water Resources Management Department of the Xinjiang Tarim River Basin Authority. Data of annual average TDS content of the lake were calculated from monthly monitoring of TDS content at 17 monitoring sites in 2000–2021 in the study.

2.2.2. Pollutants Amount Calculation

There are two ways that allochthonous pollutants enter Bosten Lake: exogenous pollutants from the sewage of surrounding drainage channels and exogenous pollutants with the inflow from the Kaidu River and the Huangshuigou River entering the lake. Considering that a large amount of outflow from the lake can take away pollutants from the lake, the total amount of exogenous pollutants retained in the lake was calculated using following formula:

$$W_{TDS} = C_{WT} \times V + C_{IT} \times R_{inflow} - C_{OT} \times R_{outflow} \quad (1)$$

where W_{TDS} is the total amount of allochthonous TDS retained in the lake; C_{WT} is the TDS content of wastewater entering the lake from the drainage channel; V is the quantity of wastewater entering the lake from the drainage channel; C_{IT} is the TDS content of inflow entering the lake; R_{inflow} is the inflow amount entering Bosten Lake from the Kaidu River and the Huangshuigou River; C_{OT} is the TDS content of the outflow; and $R_{outflow}$is the outflow amount from Bosten Lake.

Data of inflow (including water diversion amount) entering the lake, outflow from the lake, water level of the lake, and sewage discharge entering the lake, as well as TDS content of inflow, outflow, and sewage, were obtained from the Bazhou Hydrology and Water Resources Survey Bureau. Monthly data of wind directions from 1960 to 2021 were obtained from the Yanqi National Ground Exchange Station of the Meteorological Bureau.

2.3. Statistical Analysis

Monthly wind directions were categorized as mean values for spring (March–May), summer (June–August), autumn (September–November), and winter (December–February). Correlational relationships between TDS content and water level, TDS amount into the lake, TDS amount out of the lake, and TDS amount retained in the lake were derived using the Pearson correlation. The correlation heatmap was conducted with Excel software. The differences between TDS content, inflow, and outflow of the lake before and after water diversion were determined using an independent t-test. Data of TDS content from the monitoring sites in the lake conformed to a normal distribution. Spatial interpolation was conducted by the Ordinary Kriging method. Statistical analyses were performed using SPSS 13.0 (International Business Machines Corporation (IBM), Armonk, NY, USA), and plots were conducted with ArcGIS 8.0 (Environmental Systems Research Institute, Inc. (ESRI), Redlands, CA, USA) and SigmaPlot 12.0 (Systat Software Inc., San Jose, CA, USA).

3. Results and Discussions

3.1. Historical Water Quality Problems of Bosten Lake

TDS content changes of Bosten Lake water in 1958–2018 are shown in Figure 2. Bosten Lake was a typical freshwater lake prior to 1970, in which the average TDS content was below 1 g/L. Since 1970, Bosten Lake has been suffering from a severe salinity issue; the highest TDS content in the 1980s was up to 1.87 g/L, which caused Bosten Lake to become a brackish lake. Numerous studies indicated that discharged sewage entering the lake, especially agricultural sewage, was the main factor in the increasing TDS content because the secondary salinization degree of farmland soil in Xinjiang was usually very high [24–26]. In order to reduce the TDS content of the lake water, the local government introduced legislation and regulations to limit sewage entering the lake and implemented a series of sewage-treatment projects costing 1.17 billion RMB [23]. Through these measures, exogenous pollutants entering the lake were effectively controlled, which resulted in the TDS content of the lake water decreasing in 1990–2000 (Figure 2), although the lake was still categorized as brackish water, as shown in Table 1.

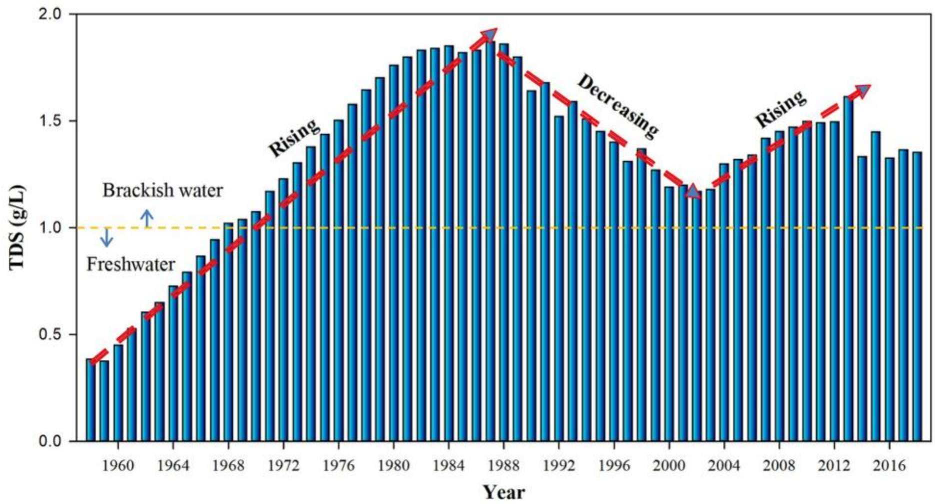

Figure 2. Annual average TDS content of Bosten Lake in 1958–2018. (Red arrow line is a trend line; Yellow line is the critical line of brackish water and fresh water).

Generally, water quality is closely related to pollutant amount into and out of a lake. Surprisingly, although the TDS amount entering and remaining in the lake significantly decreased in 2000–2018 (Figure 3), continuous-field monitoring data revealed that the TDS content of the lake water exhibited an increasing trend in 2000–2013, and the highest value in 2013 was up to 1.61 g/L (Figure 2). This might be because the annual TDS pollutant amount retained in the lake was continuously accumulating in the lake, which resulted in an increasing endogenous TDS pollutant amount. The increasing endogenous TDS pollution in successive years finally led to the increase of TDS content. Compared with 2013, the TDS content decreased from 2014–2018, but it still fluctuated between 1.32 g/L and 1.45 g/L, which was higher than that in 1995–2000 (Figure 2). Consequently, the high TDS content of lake water has become the key challenge to improve water quality and mitigate the urgent water crisis in Bosten Lake.

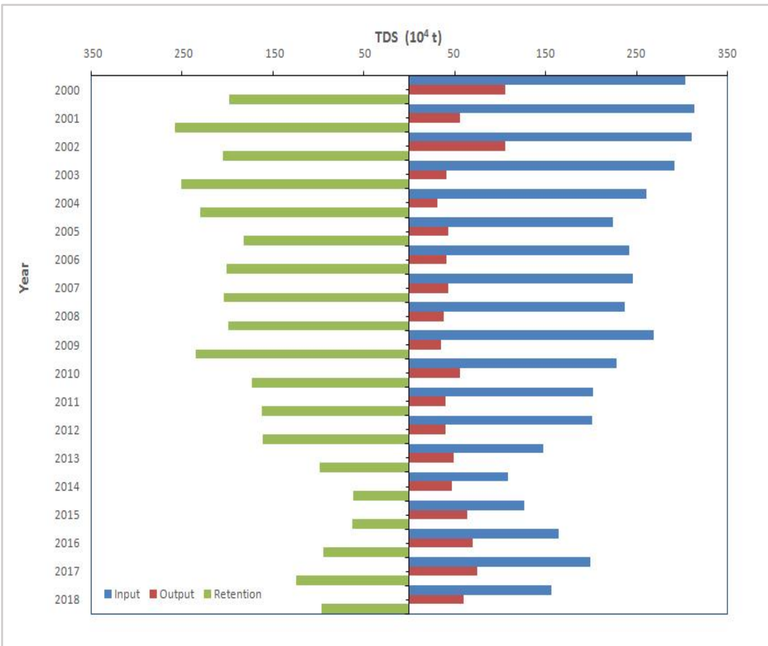

Figure 3. Butterfly chart of TDS amount entering the lake (Input), TDS amount discharged from the lake (Output), and TDS amount retained (Retention) in the lake in 2000–2018.

3.2. Background of the River–Lake System Connectivity Implementation

The annual total TDS amount entering and remaining in Bosten Lake was positively correlated with the TDS content of the lake water (Figure 4), but the correlations did not reach a significant level ($p > 0.05$, Figure 4). However, the annual total TDS amount exiting Bosten Lake was significantly negatively correlated with the TDS content of the lake water ($p < 0.05$, Figures 3 and 4). This suggests that the TDS content of Bosten Lake is mainly affected by the total TDS amount discharged from the lake. Extant literature also indicated that endogenous pollutants that are continuously accumulated in the lake might be key factors leading to high TDS content [17,27]. Therefore, increasing the TDS amount discharged from the lake might effectively reduce the TDS content of the lake water. As a semi-closed lake, both too-high and too-low water levels are not conducive to the ecological and economic functions of Bosten Lake [19]. To maintain a suitable water level for the normal ecological and socioeconomic functions of Bosten Lake, the annual outflow amount discharged from the lake was strictly controlled by the pump. Under the limited outflow from the lake, the only way to increase the total TDS amount discharged from the lake was to increase the TDS content of outflow water through accelerating water exchange and mixture in the whole lake.

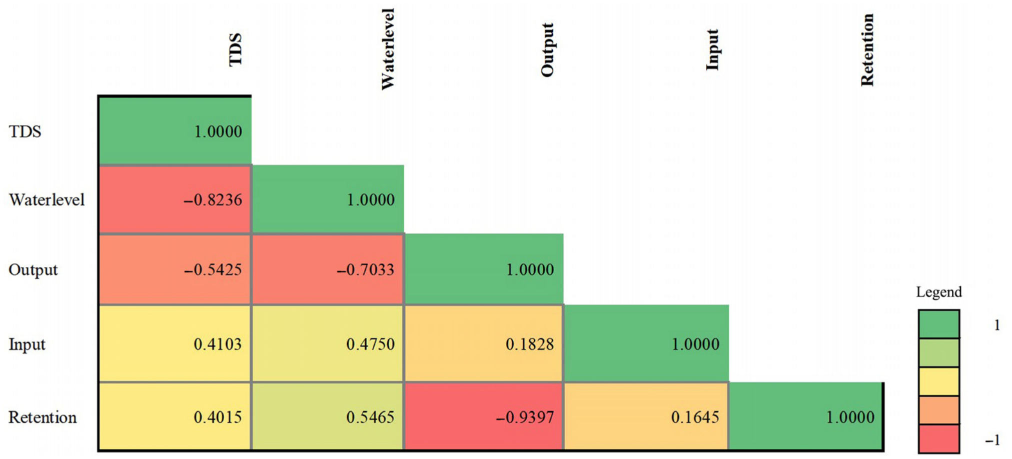

Figure 4. Correlation heatmap between TDS content (TDS) and water level, TDS amount into the lake (Input), TDS amount out of the lake (Output), and TDS amount retained in the lake (Retention).

In fact, water movement and water exchange have always been weak in Bosten Lake. The outlet of outflow is close to the inlet of inflow in Bosten Lake, which causes fresh water from the inlet to be rapidly discharged from the outlet under the tensile action of outflow (Figure 5). This hinders the effective mixture and dilution of fresh water with the other water in the lake, especially for the northern, southern, and eastern waters. In addition, wind is one of the main factors leading to the large-scale movement of lake water [2]. The wind directions of the Bosten Lake Basin are mainly southwesterly in spring, autumn, and winter, and primarily northwesterly in summer (Figure 6). This further weakens water movement and water exchange in northern, southern, and eastern Bosten Lake (Figure 5). These phenomena resulted in the formation of dead water zones in the northern, southern, and eastern Bosten Lake, which ultimately caused high TDS content in the northern, southern, and eastern lake water (Figure 7). Based on these results, it can be concluded that the essential reason for the high TDS content of Bosten Lake is weak water exchange and slow water circulation.

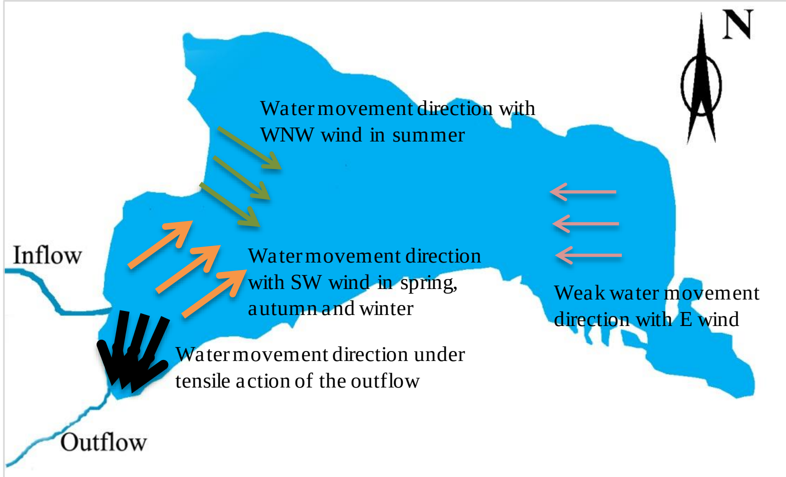

Figure 5. Water movement and water exchange in Bosten Lake.

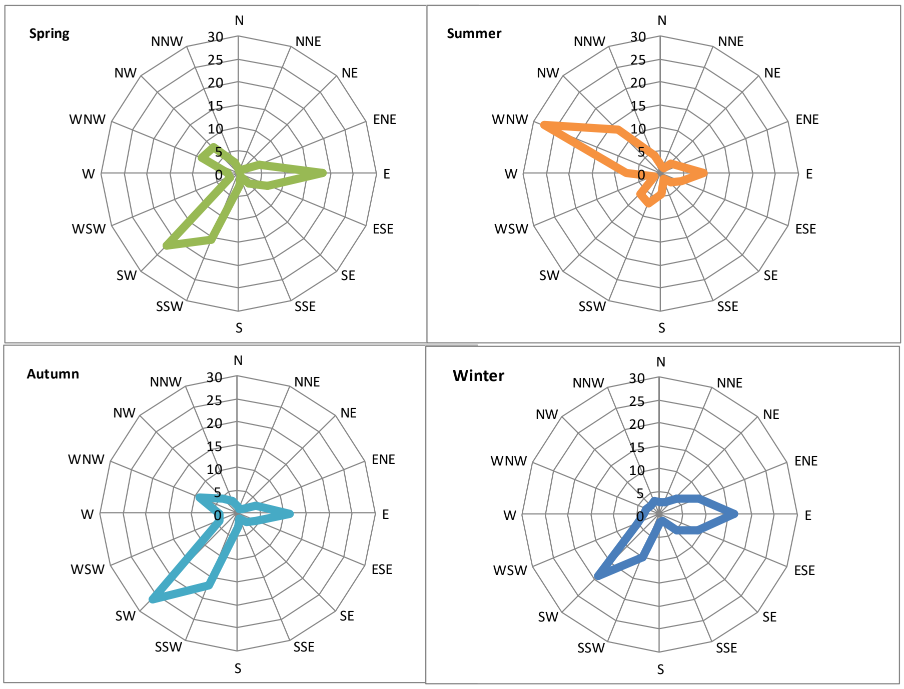

Figure 6. Rose diagrams of wind direction frequencies of the Bosten Lake Basin.

Many model simulation results have shown that water division might be an effective measure for improving lake water quality by increasing circulation and water exchange ability [1,28,29]. Moreover, water division projects were widely implemented for many lakes; these projects included diverting water from the Columbia River to Moses Lake [30], from the Mississippi River to Lake Pontchartrain [31], from the Red Deer River to Alix Lake [32], from the Yangtze River to Taihu [12], from the Yangtze River to Wanghu Lake [2], and from the Qiantang River to Xihu Lake [11]. Consequently, the local government implemented a river–lake system connectivity project (water diversion) at the end of 2018. To minimize the investment cost, the river–lake system connectivity project diverted fresh water from the Kaidu River and the Huangshuigou River to the northwestern Bosten Lake along the original dried river course of the eastern branches of the Huangshuigou River (Figure 8). The local government hoped that the water diversion project could accelerate the exchange of the northern, southern, and eastern waters of, and thereby eliminate the dead water zones from, Bosten Lake.

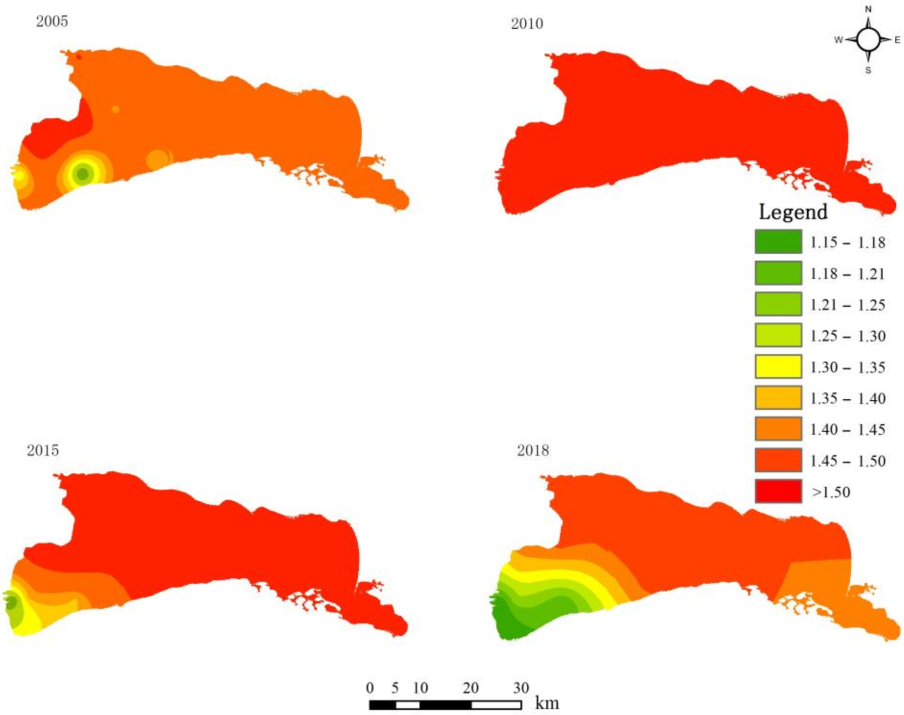

Figure 7. Spatial distribution of TDS content of Bosten Lake water in 2005, 2010, 2015, and 2018.

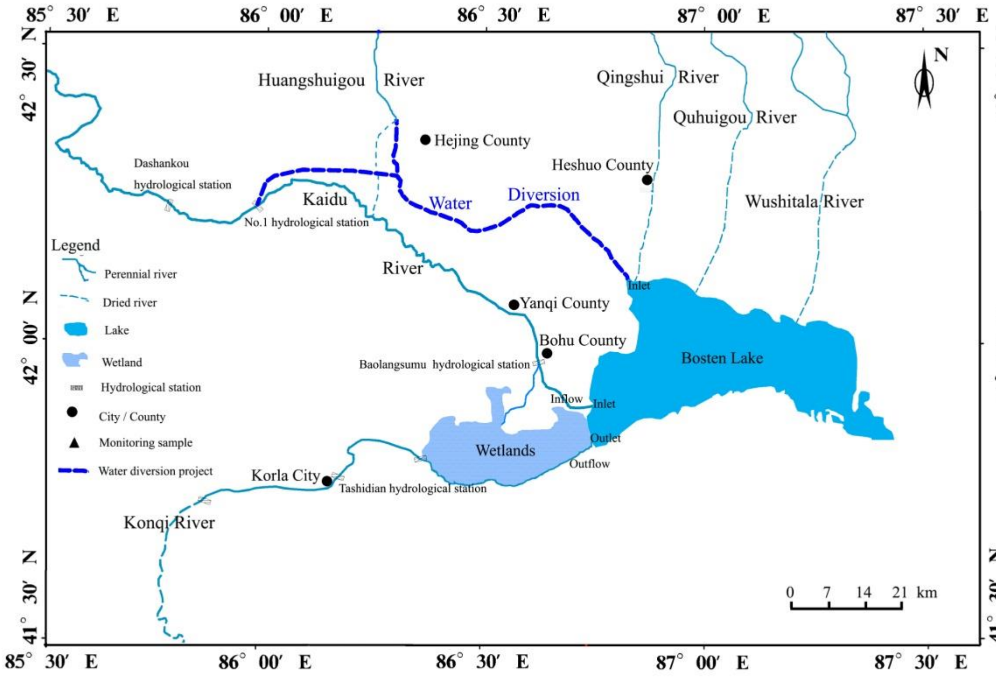

Figure 8. The route of the river–lake system connectivity project (water diversion) in Bosten Lake.

3.3. Improvement Evaluation of River–Lake System Connectivity on TDS Content

3.3.1. Improvement in the Temporal Change of TDS Content

Water quality monitoring data lasting three years after the water diversion implementation confirmed that water diversion significantly reduced the annual average TDS content of Bosten Lake (Figure 9). The average TDS content of 2019, 2020, and 2021 decreased by 18.35%, 23.94%, and 30.14%, respectively, compared to before the water diversion implementation (2018); they decreased by 18.42%, 24.01%, and 30.21%, respectively, compared with the average TDS content in 2000–2018. These reductions also reached a significant level (independent-sample t-test, $p < 0.05$). After three years of water diversion, the average TDS content of lake water dropped to 0.82 g/L, which denotes fresh water. Based on these data, the water diversion project made Bosten Lake become a freshwater lake again.

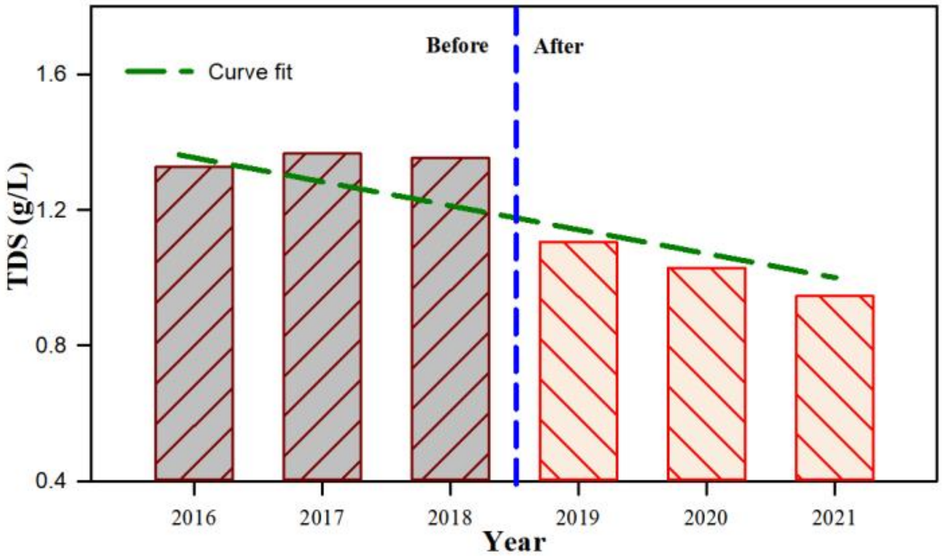

Figure 9. Changes in average annual TDS content of lake water before and after water diversion implementation in Bosten Lake.

3.3.2. Improvement in the Spatial Change of TDS Content

Water diversion also significantly improved the spatial distribution of the TDS content of Bosten Lake (Figure 10). One year after water diversion implementation (2019), the areas with the largest TDS decrease were in the north and south, with an improvement rate of more than 20%. The improvement rate was 15–20% in the southeastern and northwestern lake regions, and the improvement rate was lowest, 5–10%, in the southwest corner near the outlet of the lake. Two years after water diversion implementation (2020), both the TDS content improvement rate and the improvement areas expanded further, and the improvement rate of TDS content reached more than 20%, except for the area near the outlet. Three years after water diversion implementation (2021), the TDS content improvement rate of the whole lake reached more than 25%, and it was more than 30% in the northern and eastern lake regions.

Compared with the spatiotemporal changes of TDS content before and after the water diversion project implementation, the TDS content of the whole lake was effectively reduced and homogenized under water diversion.

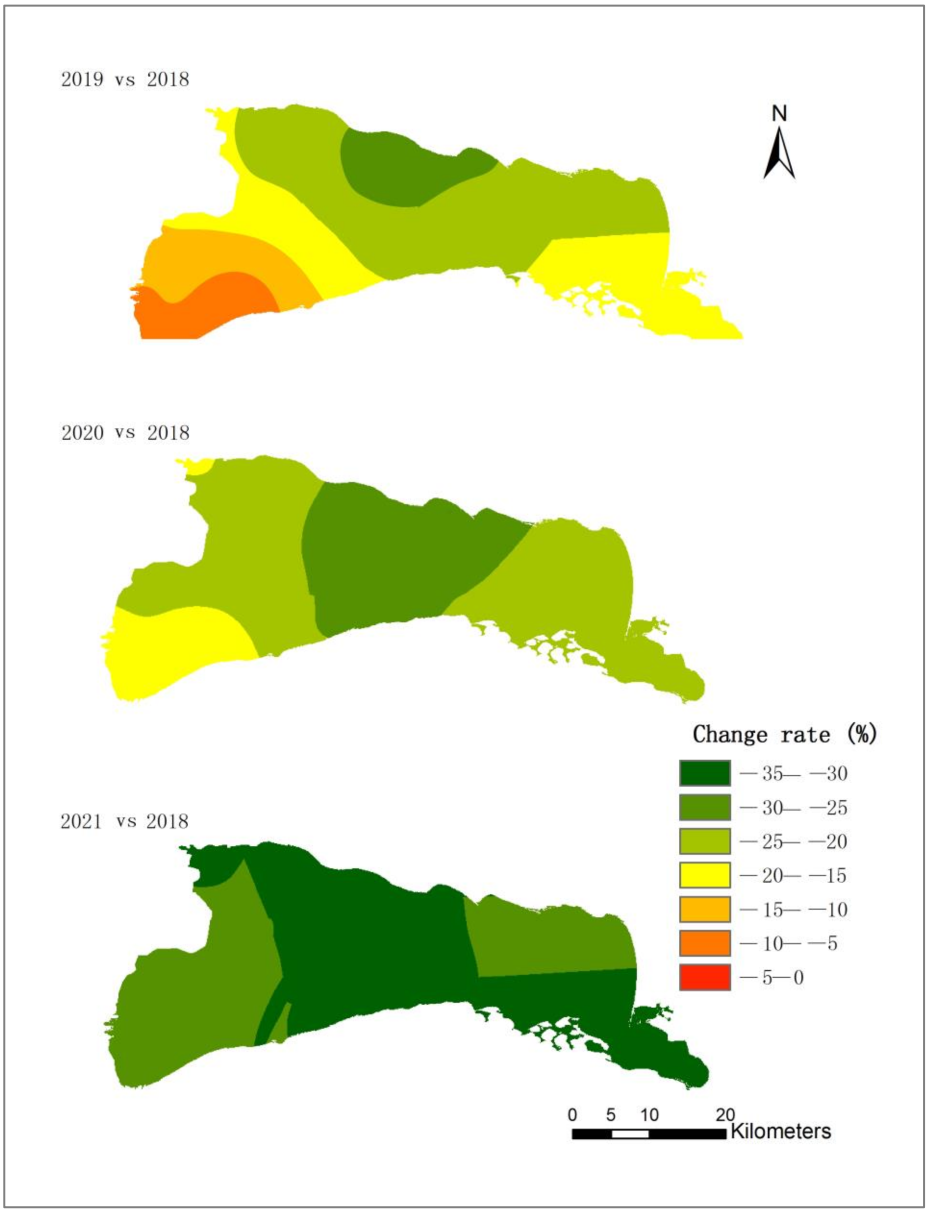

Figure 10. Improvement rate of TDS content in Bosten Lake in 2019, 2020, and 2021, compared to prior to the water diversion implementation (2018).

3.4. Improvement Mechanism of River–Lake System Connectivity on Water Quality

Although river–lake system connectivity has been applied in many lakes, some studies reported that water diversion did not effectively stop or reverse water quality deterioration in certain lakes, and even that lake water quality diminished further because the process increased the external loading of pollutant into the lakes [2,10,33,34]. However, most of these investigations were conducted by a virtual simulation using models [1,2,29], and their results might be limited due to the lack of comparison analysis and verification using continuous-field monitoring data before and after water diversion implementation [2,35]. Our monitoring data showed that the annual total TDS amount entering the lake was significantly less than the amount discharged from the lake, and the annual total TDS amount discharged from the lake increased after water diversion (Figure 11). This indicated that endogenous TDS pollution was gradually discharging from the lake. Therefore, water diversion not only pushed the annual external TDS loading entering the lake out of the lake, but also pushed a part of the annual internal TDS loading in the lake out of the lake, which finally resulted in the continuous decline of TDS content in 2019–2021 (Figure 8).

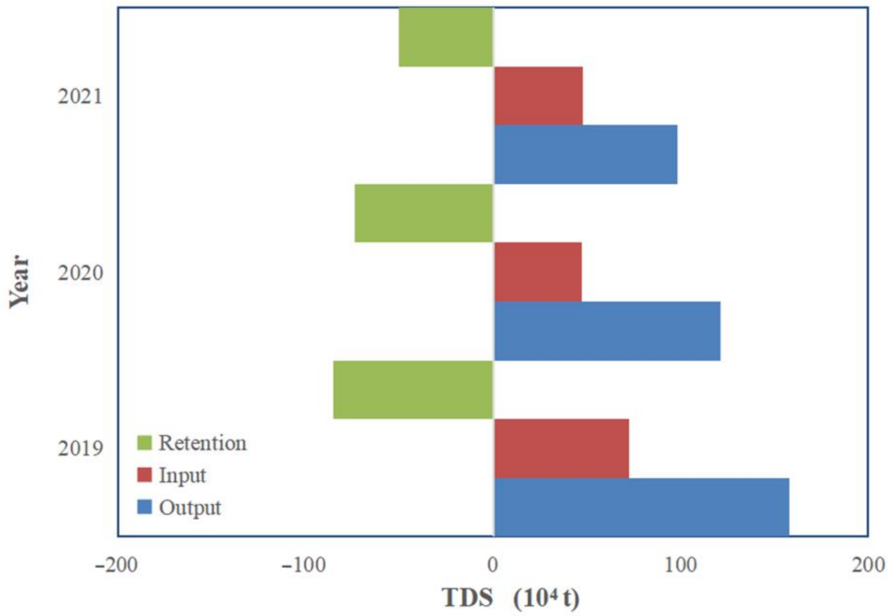

Figure 11. Butterfly chart of TDS amount entering the lake (Input), TDS amount discharged from the lake (Output), and TDS amount retained (Retention) in the lake in 2019–2021.

Spatially, the river–lake system connectivity diverted a large volume of low TDS content water from the Kaidu River and the Huangshuigou River to the northwestern Bosten Lake, which accelerated the exchange between high TDS content water in the northern, southern, and eastern lake regions and fresh water entering the lake from southwestern and northwestern inlets (Figure 12). Therefore, under the double actions of inflow force and wind force, fresh water entering the lake could fully mix and dilute the high TDS content water in the northern, eastern, and southern lake regions (Figure 12). Subsequently, fully mixed water with higher TDS content would be discharged from the lake under tensile action of the outflow (Figure 12). This was proven by the TDS content change after water diversion. One year, two years, and three years after the implementation of the water diversion project, the TDS content in the northern, southern, and eastern waters significantly decreased by more than 20%, 25%, and 30%, respectively (Figure 10). Furthermore, compared with the inflow amount entering the lake before (2016–2018) and after water diversion (2019–2021), through an independent t-test, the inflow into the lake did not exhibit a significant difference ($F = 5.122$, $p > 0.05$). Similarly, the outflow amount discharged from the lake before and after water diversion did not show a significant difference ($F = 0.137$, $p > 0.05$), either. This indicated that the water diversion did not change the inflow and outflow amount but significantly accelerated water movement and water exchange, especially for the northern, southern, and eastern water in the lake. The fully mixed water with higher TDS content discharged from the lake increased the total TDS amount discharged from the lake and reduced the endogenous pollutants in the lake to significantly mitigate the high TDS content crisis (Figure 11). Based on our continuous monitoring, water diversion could be used as an effective measure for water quality improvement in semi-closed inland lakes in arid and semi-arid regions.

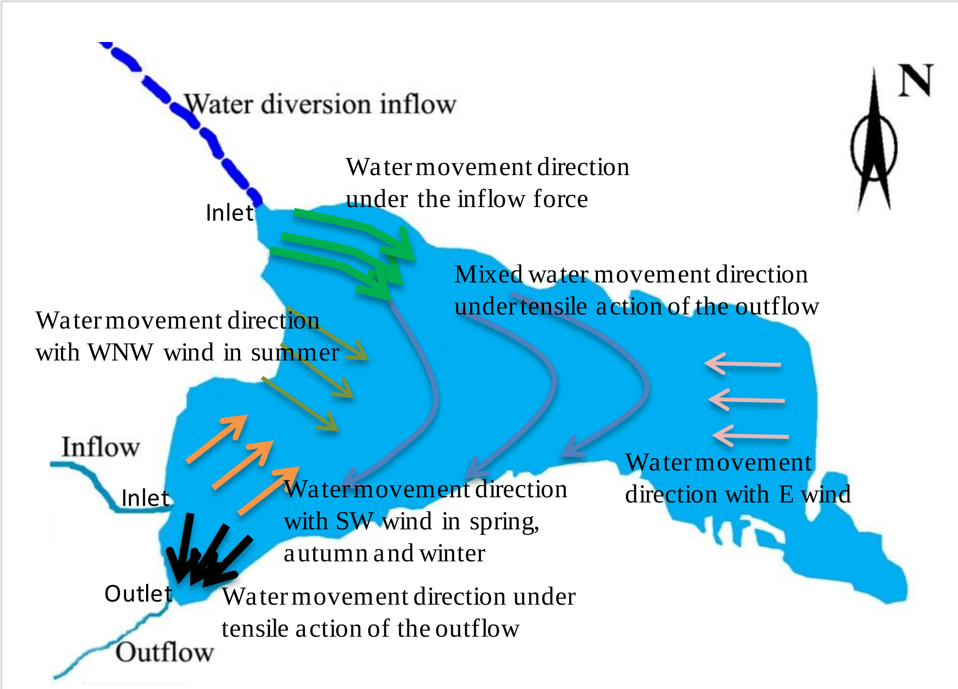

Figure 12. Water movement and water exchange after water diversion in Bosten Lake.

4. Conclusions

Bosten Lake is a typical semi-closed lake in an arid area and the biggest freshwater inland lake in China. With human activities and climate changes occurring over the past decades, the water quality of Bosten Lake has been deteriorating markedly, turning it into a brackish water lake. The key reason for the high TDS content of the lake water was weak water exchange and water movement. To improve water quality, the local government implemented river–lake system connectivity (water diversion) at the end of 2018, which diverted fresh water from the Kaidu River and the Huangshuigou River to the northwestern Bosten Lake. The field monitoring data indicated that the water diversion significantly improved the water quality of Bosten Lake. It continuously reduced the TDS content of the lake water, and the average TDS content decreased to 0.82 g/L in 2021, which made Bosten Lake become a freshwater lake again. Water diversion also significantly improved the spatial distribution of TDS content in the lake water. The TDS content in the northern, southern, and eastern waters significantly decreased by more than 20%, 25%, and 30%, in 2019, 2020, and 2021, respectively (Figure 9). The TDS content of the entire lake was reduced and homogenized by accelerating water exchange and water movement resulting from the water diversion.

The inflow amount entering Bosten Lake is affected by both human activities and climate changes, and climate changes will increase the uncertainty of the inflow amount entering the lake [36]. Meanwhile, the evaporation loss of lake water is enormous [19]. In the future, we will continue to monitor the changes in water quality in Bosten Lake after the implementation of water diversion and will attempt to build models based on these monitoring data to calculate an appropriate inflow and outflow amount of Bosten Lake to ensure the maintenance of the freshwater lake and its normal ecological and economic functions. It is expected that our research will provide more detailed support for the water resource management of Bosten Lake.

Author Contributions: H.Z. analyzed the data and wrote the first draft; Y.C. proposed the main structure of this study; C.Z. made the plots; Z.Y. and Y.L. collected the data; all authors contributed to the final manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Key Program of the Natural Science Foundation of Xinjiang Province, China (grant No. 2021D01D01), and the Youth Innovative Research Team of Xinjiang Institute of Ecology and Geography, Chi-nese Academy of Sciences (grant No. Y970000384).

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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