

Article

Hydrochemical and Isotopic Characterization of the Impact of Water Diversion on Water in Drainage Channels, Groundwater, and Lake Ulansuhai in China

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Abstract: Lakes are important natural water reservoirs that connect other water bodies and play essential roles in water supply, ecological preservation, and climate regulation. Because of global climate change and human activities, many lakes worldwide are facing severe challenges, such as ecological degradation and reductions in their water storage, levels, surface areas, and quality. Water diversion into lakes is considered an effective measure to address these challenges and has attracted much attention. Water has been diverted into Lake Ulansuhai through drainage channels from the Yellow River since 2013. This shallow lake is located in arid northern China and is greatly affected by high salinity and eutrophication. The lake is the lowest area in the Hetao basin and is a sink for terrestrial water in this region. High salinity in lake water, drainage channels, and groundwater caused by NaCl is an ongoing problem; however, water diversion has played an important role in dilution. The main hydrochemical type in the lake water is $\text{Cl}\cdot\text{HCO}_3\text{--Na}\cdot\text{Mg}$, while those in the drainage channels and the groundwater show more diversity because of spatial differences. The main source of water in the lake (52–60%) is that diverted through six drainage channels on the west bank, followed by meteoric precipitation (36–38%). Groundwater recharge to the lake is minimal (west bank: 2–7%, and east bank: 1–5%). Extensive evaporation occurs in the lake before the lake water is discharged into the Yellow River through a waste canal. The hydrochemical evolution and salinization of the lake are dominated by the six drainage channels, followed by evaporation from the lake surface. Thus, resolution of soil salinization in the Hetao irrigation area is key to addressing salinity issues in the lake. This study will be helpful for the planning of future water diversion and ecological restoration.



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Keywords: hydrochemistry; stable isotope; water cycle; water diversion; Lake Ulansuhai

1. Introduction

Lakes are an important part of the terrestrial hydrological system [1]. They play a key role in regulating river runoff and regional hydrological cycles [2], and in sustaining ecosystems [3]. In recent years, with the intensification of human activities and climate change, many lakes around the world have been facing severe challenges such as reduced water storage [4,5], falling water levels, shrinking water surface areas, deterioration of water quality, and ecological degradation [6,7]. These issues are especially apparent in arid and semi-arid areas where a lack of natural meteoric precipitation is accompanied by extensive evaporation, resulting in water resource shortages, decreases in the areas of lakes and wetlands, poor self-recovery of ecosystems, and serious declines in ecological function [8]. One of the fastest and most effective measures to deal with these challenges is water diversion. The impact of water diversion on regional water resources and the

aqueous environment has attracted much attention [4,9]. After a lake is replenished by water diversion, hydrochemical indices and the water cycle will be affected and change to a certain extent. An understanding of the water cycle is required to solve ecological problems in lakes. This knowledge could provide a basis for sustainable development of lake water resources and ecosystem management [10]. Therefore, the impact of water diversion on the water cycle needs to be evaluated.

Many studies around the world have investigated the water cycle. Environmental isotopic and hydrochemical methods are the most common ones used to analyze the characteristics, transformation processes, and relationships between atmospheric precipitation, surface water, and groundwater [11]. These techniques have played an important role in clarifying the mechanisms of the water cycle [12,13]. The hydrochemical composition of a water body records migration information of the water [14–17]. The relationship between surface water and groundwater can be evaluated by using the hydrogeochemical tracing method [18]. In the course of migration, water will dissolve various water-soluble salts, which will change its chemical composition [19]. Stable isotopes of hydrogen and oxygen in water molecules are not disturbed by processes other than evaporation and fractionation, which is convenient to obtain more accurate data [20], and they have good application potential for tracing the water cycle [21]. Increasingly, studies have combined hydrochemical characteristic and isotope analysis to identify the sources of recharge of groundwater and river water in different geomorphic areas [22], the interaction between surface water and groundwater [23], and the water movement mechanism in each link of the water cycle [24].

Lake Ulansuhai in China is a typical eutrophic lake in a semi-arid area [25]. It has important hydrological and ecological functions because of its unique geographical location in the Yellow River Basin. However, in the past few decades, the water level and area of the lake have decreased, conflict about water resources has intensified near the lake, and ecological deterioration around the lake has occurred [26]. To promote ecological restoration of the lake and increase the water volume, 200–300 million cubic meters of water have been directly supplied to the lake from the Yellow River every year through a main channel since 2013. Moreover, this water diversion has increased to approximately 600 million cubic meters since 2018 [27]. Many studies have been performed on the lake, mainly focusing on evaluation of the quality of the lake water [27–29], eutrophication [25], and vegetation and ecological evolution [30]. Few studies have systematically investigated changes in the hydrochemical characteristic, isotopes, and water cycle in different linked water bodies in the basin after water diversion.

The objectives of this study were to characterize the impact of the water diversion from the Yellow River on the water in drainage channels, groundwater, and Lake Ulansuhai in China from the perspectives of hydrochemical characteristics and isotopes, and to subsequently establish a new local water cycle model involving this impact.

2. Study Area

Lake Ulansuhai is located in Urad Front Banner, Bayannur, Inner Mongolia, China, and its geographic coordinates are 108°43′–108°57′ E and 40°36′–41°03′ N (Figure 1). The lake is 35–40 km long from north to south and 5–10 km wide from east to west, with an existing water area of 298 km² and 130 km of shoreline. For most of the lake, the water depth is 0.5–3 m. The deepest water of the lake reaches 4 m, and the average water depth is 1 m [27]. The lake is located in an arid area where the climate is classed as temperate continental monsoon. It is cold and dry in winter, and hot with little rain in summer. There is a large temperature difference between day and night, and the average annual temperature is 7.2 °C. There is little meteoric precipitation (annual precipitation of 217.1 mm) and extensive evaporation (annual evaporation of 1900–3000 mm) [31].

The study area was located at the end of the Hetao Plain. The site was bounded by Langshan Mountain in the Yinshan mountain range to the north, Wula Mountain to the southeast, the Yellow River alluvial plain (Hetao Plain) to the west, and the piedmont

alluvial plain to the east. The terrain in this area slopes from northeast to southwest. Lake Ulansuhai receives farmland drainage water from the Hetao irrigation area through channels linked with the west bank, and discharges into the Yellow River through a southern channel. The lake not only plays an important role in drainage of the Hetao irrigation area and control of farmland salinization but is also important for the local regional economy and its ecological value [32].

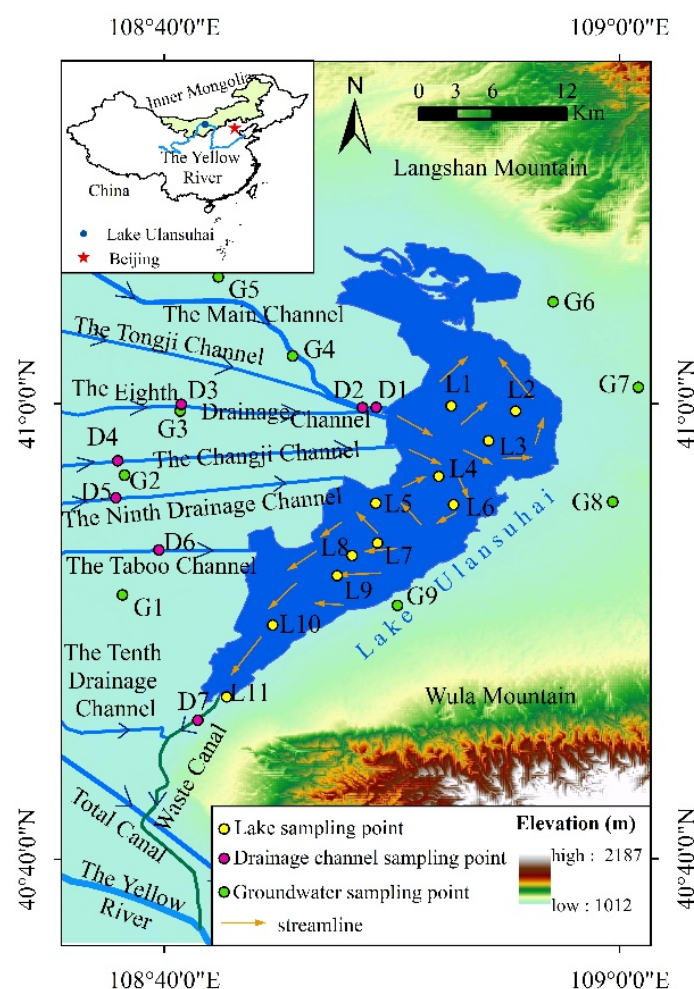


Figure 1. Location of the study area and the sampling sites.

3. Materials and Methods

3.1. Sampling and Measurements

3.1.1. Sampling and Conservation

Samples of water from the lake ($n = 11$, L1–L11), the drainage channels ($n = 8$, D1–D8), and the groundwater near the lake ($n = 10$, G1–G10) in the study area (Figure 1) were collected in April 2021. The lake water sampling points were selected to cover the surface of the whole lake evenly. The groundwater samples were collected from existing monitoring wells and village pumping wells in the irrigation area. The drainage channel water sampling points were located near the lake inlet. The lake water and drainage channel water were collected 15–30 cm below the water surface. All samples were collected into sampling bottles, which were sealed well, transported to the laboratory immediately, and stored at 4 °C.

3.1.2. Measurements and Analysis

The pH, temperature, oxidation–reduction potential (ORP), and total dissolved solids (TDS) concentration of each water sample were measured in the field by use of a calibrated

portable multiparameter for rapid water quality analysis (HI9828, Hanna Instruments, Shanghai, China) (Table S1 in the Supplementary Materials). Further analysis of the water samples was performed in the laboratory. Ion chromatography (ICS-2100, ThermoFisher Scientific, Shanghai, China) was used for analysis of four cations (K^+ , Na^+ , Ca^{2+} , and Mg^{2+}) and two anions (Cl^- and SO_4^{2-}). HCO_3^- concentration was measured by use of acid–base titration, NH_4^+ –N concentration was measured by use of Nessler’s reagent spectrophotometry (Spectrophotometer UV1102, Techcomp, Shanghai, China), and NO_3^- –N concentration was measured by use of UV spectrophotometry (Spectrophotometer UV1102, Techcomp, Shanghai, China). All the analytical procedures met the relevant quality requirements. The error was less than 5% and the pass rate was 100%.

The stable isotope ratios ^2H (D) and ^{18}O of water molecules in the samples were measured by use of a liquid water isotope analyzer (Picaro L2140-I, Exponent, Guangzhou, China). Each sample was analyzed six times. To reduce the memory effect, the results of the first two analyses were discarded. The measured results were part per thousand deviations from Vienna Standard Mean Ocean Water, and the measurement accuracies for δD and $\delta^{18}O$ were 0.50‰ and 0.15‰, respectively.

3.2. Study Method

The study objectives were realized by use of multiple methods. The general hydrochemical characteristic analyses were realized by use of the statistical method with box plots, and the spatial distributions of the hydrochemical compositions were realized by use of ArcGIS 10.2.2 histograms and Kriging interpolation. The hydrochemical classifications were determined by use of the three-line Piper diagrams.

The contribution ratios of the different recharge sources of the lake were determined using the end-member mixing model according to the principle of isotope mass balance [33,34].

$$\begin{cases} \delta_L = f_P \delta_P + f_D \delta_D + f_G \delta_G \\ f_P + f_D + f_G = 1 \end{cases} \quad (1)$$

where δ_L is the δ_D value of the lake (‰); δ_P is the δ_D value of local meteoric precipitation (‰); δ_D is the δ_D value of the drainage channel water (‰); δ_G is the δ_D value of the groundwater (‰); f_P is the contribution ratio of meteoric precipitation; f_D is the contribution ratio of the drainage channel water; and f_G is the contribution ratio of the groundwater. The contribution ratio calculations were completed using IsoSource software.

4. Results and Discussion

4.1. Hydrochemical Characteristic

4.1.1. General Characteristics in 2021

The pH of the lake water ranged from 8.27 to 8.78 with a mean of 8.51 (Figure 2), the pH of the drainage channel water ranged from 8.23 to 8.74 with a mean of 8.54, and the pH of the groundwater ranged from 7.53 to 8.59 with a mean of 8.02. These results indicated that water in the region was nearly alkaline. The TDS concentration of the lake water ranged from 1370 mg/L to 2416 mg/L with a mean of 1724 mg/L. This range was small, indicating weak mineralization ($1000 \text{ mg/L} < \text{TDS} < 3000 \text{ mg/L}$). The TDS of the drainage channel water ranged from 642 mg/L to 6770 mg/L with a mean of 2890 mg/L. This range was large and indicated weak mineralization ($1000 \text{ mg/L} < \text{TDS} < 3000 \text{ mg/L}$) and medium mineralization ($3000 \text{ mg/L} < \text{TDS} < 10,000 \text{ mg/L}$). The TDS of the groundwater ranged from 1125 mg/L to 6970 mg/L with a mean of 4367 mg/L, indicating weak mineralization ($1000 \text{ mg/L} < \text{TDS} < 3000 \text{ mg/L}$) and moderate mineralization ($3000 \text{ mg/L} < \text{TDS} < 10,000 \text{ mg/L}$).

For the three water bodies, we measured the mass concentrations of the main cations (K^+ , Na^+ , Ca^{2+} , and Mg^{2+}). The mass concentrations of the cations varied greatly, with Na^+ having the highest values and K^+ the lowest. The average concentrations of K^+ , Na^+ , Ca^{2+} , and Mg^{2+} in the lake water were 6.5, 359.2, 77.36, and 83.5 mg/L, respectively. The corresponding values in the drainage channel water were 5.43, 645.82, 102.28, and 140.87 mg/L, and those in the groundwater were 12.21, 981.74, 190.5, and 159.74 mg/L.

The average concentrations of the main cations were highest in the groundwater, followed by the drainage channel, and then the lake water.

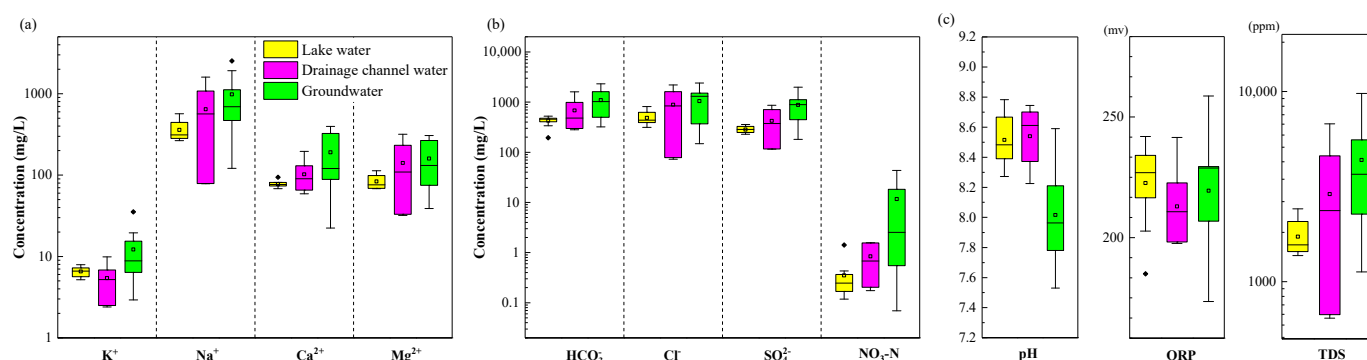


Figure 2. Boxplot of the hydrochemical indices ((a): K⁺, Na⁺, Ca²⁺, and Mg²⁺; (b): HCO₃⁻, Cl⁻, SO₄²⁻ and NO₃⁻-N; (c) pH, ORP and TDS) of the three water bodies (lake water, drainage channel water and groundwater).

We also measured the concentrations of the three main anions (HCO₃⁻, Cl⁻, and SO₄²⁻) in the different water bodies. The average data of HCO₃⁻, Cl⁻, and SO₄²⁻ in the lake water were 427.56, 485.9, and 283.88 mg/L, respectively. The corresponding values in the drainage channel water were 683.39, 889.33, and 423.17, and those in the groundwater were 1094.53, 1050.73, and 877.42 mg/L. The average concentrations of the main anions were highest in the groundwater, followed by the drainage channel water, and then the lake water. This order was consistent with that for the four cations.

The NO₃⁻-N concentrations in the lake water and drainage channel water were relatively low (<1.6 mg/L). There were two groundwater samples with high NO₃⁻-N values (43.6 mg/L and 34.8 mg/L). The average NO₃⁻-N concentrations were highest in the groundwater (11.68 mg/L), followed by the drainage channel water (0.84 mg/L), and then the lake water (0.35 mg/L). This order was consistent with those for the four cations and three main anions.

4.1.2. Spatial Distributions in 2021

The indices with the highest concentrations in all three water bodies were Na⁺, Cl⁻, and TDS. The spatial distributions of these three indices in the lake water were even, while those in the drainage channel water and the groundwater were markedly uneven (Figure 3). For the drainage channel water, this uneven distribution was possibly because the sampling points were located in different drainage channels. The results for sample D4 (Changji channel) and D6 (Taboo channel) were notably lower than those in the other drainage channels. Sample D5 (Ninth drainage channel) had the highest concentrations of Na⁺ (1596.3 mg/L), Cl⁻ (2192.5 mg/L), and TDS (6769.9 mg/L). For the groundwater, uneven distributions were observed along the east and west banks of the lake. The index concentrations in the groundwater on the west bank were higher than those on the east bank. The average concentrations of Na⁺, Cl⁻, and TDS in the groundwater on the west bank were 1445.39, 1473.64, and 6028.62 mg/L, respectively, and those on the east bank were 402.17, 522.1, and 2289.7 mg/L, respectively. The salinity of the groundwater on the west bank was much higher than that on the east bank. In addition, the index concentrations in the groundwater on the west bank also varied, first decreasing and then increasing, from south to the north. The northernmost sample (G5) had the highest concentrations. By contrast, no such variation in the results was observed on the east bank.

According to the distribution of the sampling points, three approximately parallel lines were drawn along the west–east direction to divide the lake into three sections (northern section: line I–I', middle section: II–II', and southern section: III–III'; Figure 3d). These lines linked groundwater and lake water samples for linear distribution analysis. Along the line I–I' (Figure 4a), the Na⁺ and SO₄²⁻ concentrations in the groundwater on both banks were higher than those in the lake. For the K⁺, Ca²⁺, Mg²⁺, Cl⁻, and NO₃⁻-N concentrations,

the order was west bank groundwater < lake water < east bank groundwater, while for the HCO_3^- concentrations the order was west bank groundwater > lake water > east bank groundwater.

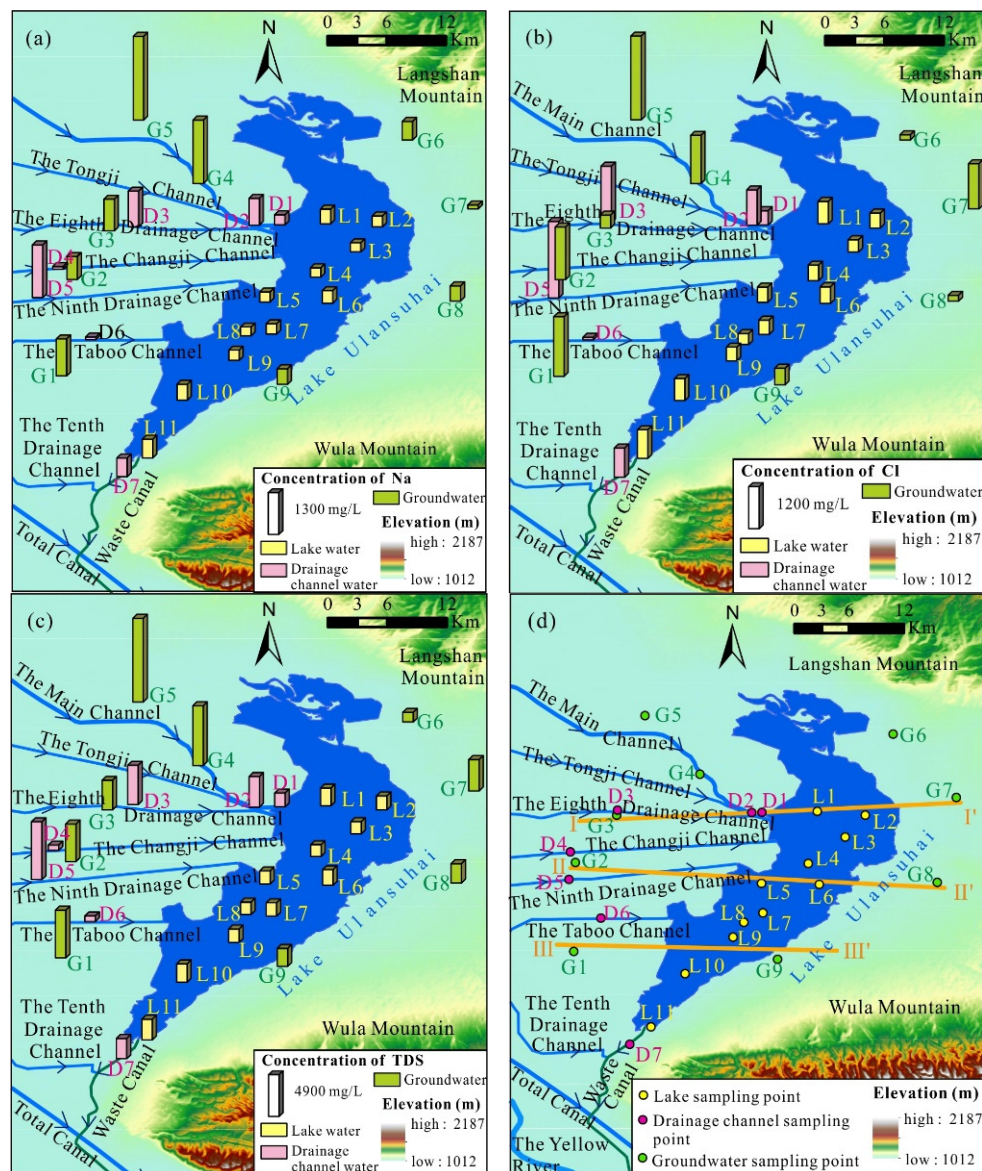


Figure 3. Spatial distributions of (a) Na^+ , (b) Cl^- , and (c) TDS in the three water bodies and (d) three section lines.

Along the line II–II' (Figure 4b), the Na^+ , HCO_3^- and SO_4^{2-} concentrations in the groundwater on both banks were higher than those in the lake. For the K^+ , Ca^{2+} , and Mg^{2+} concentrations, the concentrations in the groundwater on the west bank were greater than those in the lake water, while on the east bank, the groundwater and lake water concentrations were similar. The highest Cl^- concentration in the groundwater on the west bank was 1509 mg/L, and that on the east bank was 167.8 mg/L. The mean Cl^- concentration in the lake water was 456.6 mg/L. The NO_3^- -N concentrations in the groundwater on the east and west banks were 43.6 and 34.8 mg/L, respectively, and these values were higher than those in the lake water (<1 mg/L).

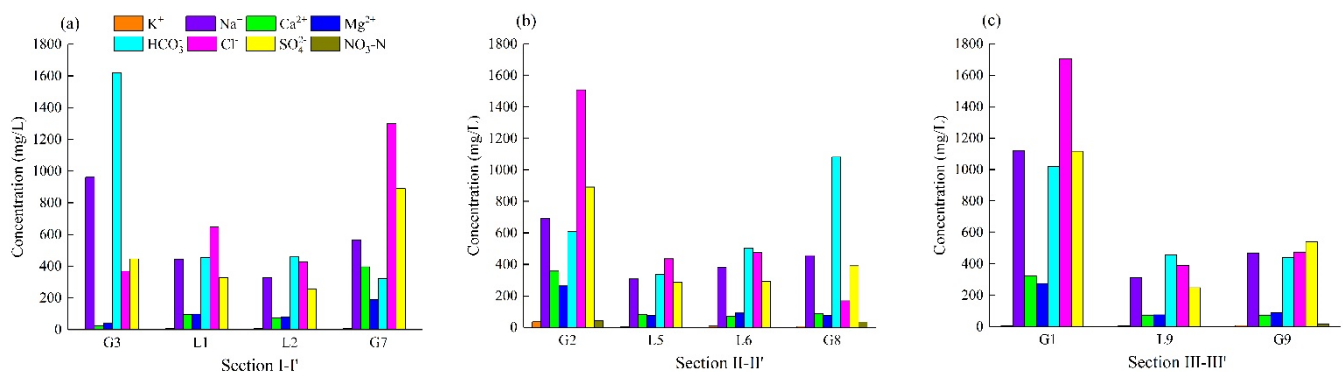


Figure 4. Linear distributions of hydrochemical indices along the three section lines (a) Section I–I', (b) Section II–II' and (c) Section III–III' linking the groundwater (represented by points beginning with G) and lake water (represented by points named beginning with L). The direction from left to right in this figure represents west to east. The locations of the three lines are shown in Figure 3d.

Along the line III–III' (Figure 4c), the Na^+ , Cl^- , and SO_4^{2-} concentrations in the groundwater on both banks were higher than those in the lake. In addition, the concentrations in the groundwater on the west bank were higher than those in groundwater on the east bank. The K^+ concentration showed little variation among the different samples. The Ca^{2+} , Mg^{2+} and HCO_3^- concentrations in the groundwater on the west bank were higher than those in the lake, while those in the groundwater on the east bank were similar to those in the lake. The NO_3^- –N concentrations in the groundwater on the west bank and the lake were very low at 1.35 and 0.15 mg/L, respectively. By contrast, the NO_3^- –N concentration in the groundwater on the east bank was 18.26 mg/L.

Generally, the index concentrations in groundwater on the east and west banks of the lake in all three sections (north, central, and south) were higher than those in the lake. In addition, there were large differences in the index concentrations in the groundwater between the east and west banks of the lake. In the middle (line II–II') and southern (line III–III') sections of the study area, the concentrations of some indices on the east bank differed slightly from those in the lake water.

For the entire lake surface (Figure 5), the TDS concentration of the lake water ranged from 1000 to 1900 mg/L, which classified it as brackish water (1000–3000 mg/L). The TDS concentrations were slightly higher at the mouths of the drainage channels than in the rest of the lake. Among the channels, the concentrations at the mouth of the main, Tongji, Eighth, and Taboo channels were higher than those at the mouths of the Changji and Ninth channels. The main channel is responsible for 88% of the drainage in the irrigation area, and the remaining drainage channels carry only small volumes of water into the lake. The mouths of the Tongji and Eighth drainage channels are very close to that of the main channel, which would contribute to the high TDS concentrations measured at the mouths of these drainage channels. Although the Taboo channel carries only a small volume of water, it is the southernmost drainage channel, and the overall flow direction of the lake from north to south causes TDS to accumulate near its mouth. The TDS concentration in the lake water gradually increased from the center of the lake to the north and south. There were two areas with lower TDS concentrations near the center of the lake. In the north of the lake, there is an area of dense reeds where water exchange is weak [25]. This means that water flow in this area is slow, water exchange is not active, and the lake water TDS concentration increases. The high TDS concentration in the south of the lake was likely caused by the accumulation of salt in the downstream direction and narrowing of the lake surface.

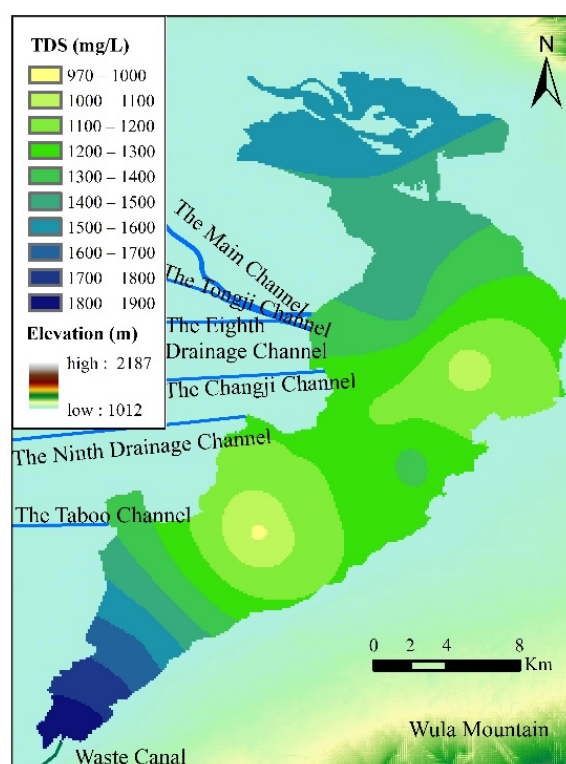


Figure 5. Spatial distribution of TDS in the lake water.

4.1.3. Temporal Evolution

Every year since 2013, water has been supplied directly to the lake from the Yellow River through the main channel. This water diversion has been used to improve the lake ecological conditions and maintain the water volume. We compared averaged data for hydrochemical indices in 2011 [35] and 2012 [36] before this diversion and in 2019 [31,37] and 2021 after the diversion (Figure 6). We found that the K^+ , Na^+ , Mg^{2+} , Cl^- , and SO_4^{2-} concentrations in the lake water and the Na^+ , Mg^{2+} , and SO_4^{2-} concentrations in the groundwater decreased significantly after the diversion. In addition, the HCO_3^- concentrations in the lake water increased considerably, while the Ca^{2+} concentrations in the lake and K^+ , Ca^{2+} , and Cl^- concentrations in the groundwater fluctuated slightly. Before the water diversion, the Cl^- concentration in the lake water exceeded the standard by up to 3.9 times, and lake water salinization was serious [35]. After the water diversion, the concentrations of most of the main ions in the lake water decreased, the salinization of the lake was controlled, and the water quality improved. By contrast, no notable hydrochemical changes were observed in the groundwater before and after implementation of the water diversion.

The historical data showed that the highest TDS concentration in the lake water appeared in 1975 (8000 mg/L). The TDS concentration then dropped sharply to 1090 mg/L in 1986, and then gradually increased and remained relatively stable, reaching 2890 mg/L in 2008 [38]. These changes were mainly related to the water diversion from the Yellow River into the lake, and the drainage channel system in the irrigation area. Between 2010 and 2014, the maximum TDS concentration in the lake water was 3000 mg/L, and the annual average was 1600 mg/L [39]. In 2021, the TDS concentration of the lake water stabilized below 2000 mg/L, and lake water salinization had improved. These results show that the water diversion project helped suppress salinization of the lake and stabilize the lake ecosystem.

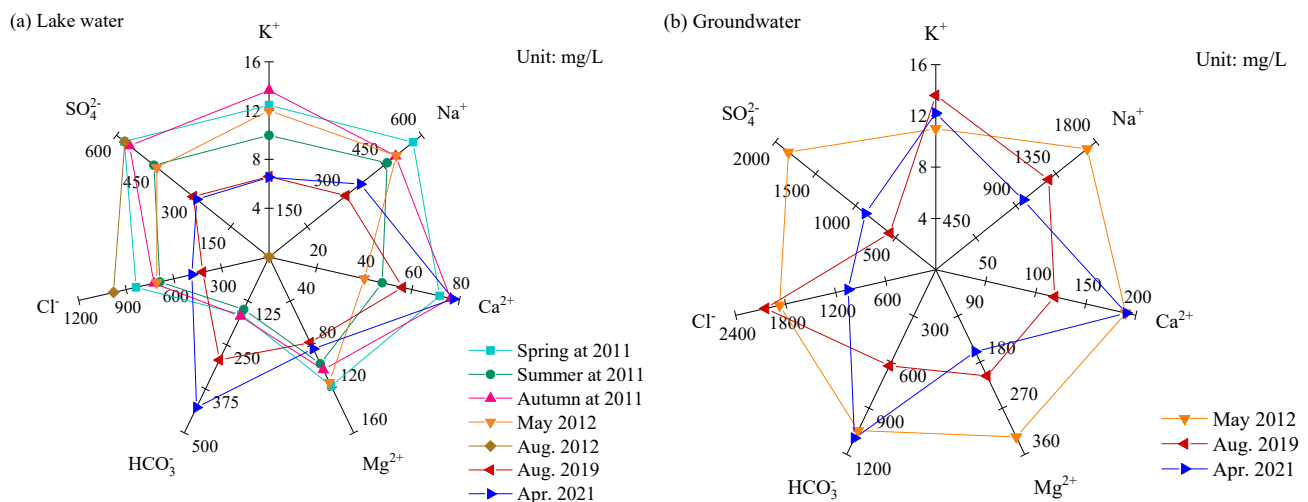


Figure 6. Temporal changes in the hydrochemical indices in (a) lake water and (b) groundwater before and after the water diversion. The 2011 data are from [35]; the 2012 data are from [36]; and the 2019 data are from [31,37].

4.2. Characterization of the Hydrochemical Types

4.2.1. General Characteristics in 2021

There were notable differences in the hydrochemical types in the lake water, drainage channel water, and groundwater (Figure 7). When plotted, the lake water data were concentrated on the right, the drainage channel water data were divided into two groups on the left and right, and the groundwater data were scattered. The hydrochemical types in the lake water were relatively consistent. The main type was $\text{Cl}\cdot\text{HCO}_3\text{--Na}\cdot\text{Mg}$, but this changed to $\text{Cl}\cdot\text{Na}\cdot\text{Mg}$ near the mouth of the main channel into the lake (L1) and $\text{Cl}\cdot\text{Na}$ near the outlet of the waste canal (L11). A small amount of $\text{Cl}\cdot\text{SO}_4\text{--Na}\cdot\text{Mg}$ was also observed in the lake. There were some differences in the hydrochemical types observed in the drainage channels. The following five hydrochemical types were observed for the six drainage channels and one waste canal: $\text{Cl}\cdot\text{HCO}_3\text{--Na}\cdot\text{Mg}$, $\text{Cl}\cdot\text{SO}_4\text{--Na}\cdot\text{Mg}$, $\text{Cl}\cdot\text{Na}\cdot\text{Mg}$, $\text{HCO}_3\cdot\text{SO}_4\text{--Na}\cdot\text{Ca}\cdot\text{Mg}$, and $\text{Cl}\cdot\text{Na}$. The hydrochemical type in the main channel was $\text{Cl}\cdot\text{HCO}_3\text{--Na}\cdot\text{Mg}$, which was consistent with that in the lake water. This indicated that the main channel had a large impact on the lake water. The hydrochemical types in the groundwater were diverse with five types ($\text{Cl}\cdot\text{SO}_4\text{--Na}\cdot\text{Mg}$, $\text{Cl}\cdot\text{SO}_4\text{--Na}\cdot\text{Mg}\cdot\text{Ca}$, $\text{Cl}\cdot\text{Na}$, $\text{Cl}\cdot\text{HCO}_3\cdot\text{SO}_4\text{--Na}$, and $\text{Cl}\cdot\text{SO}_4\cdot\text{HCO}_3\text{--Na}$) on the west bank, and four types ($\text{SO}_4\text{--Ca}\cdot\text{Mg}\cdot\text{Na}$, $\text{Cl}\cdot\text{Ca}\cdot\text{Mg}\cdot\text{Na}$, $\text{HCO}_3\cdot\text{SO}_4\text{--Na}$, and $\text{Cl}\cdot\text{SO}_4\text{--Na}$) on the east bank. The hydrochemical type at each sampling point differed from the others. Although there were differences in the chemical compositions of the three water bodies, generally, Na^+ was the major cation and Cl^- was the major anion. These results indicated that this area was strongly affected by salinization.

The groundwater sampling points G6 and G7 on the east bank showed uniform cation distributions. At G7, Ca^{2+} was the dominant cation over Na^+ . There were significant differences in the hydrochemical types in the east bank groundwater, the lake water, and the west bank groundwater. We speculated that there was little hydraulic connection between groundwater on the east bank and the lake water, and that the sources of the groundwater on the east and west banks were different. For example, runoff from Wula Mountain can replenish the east bank groundwater, which would make the hydrochemical characteristics of this groundwater markedly different from that of the Yellow River irrigation water [32].

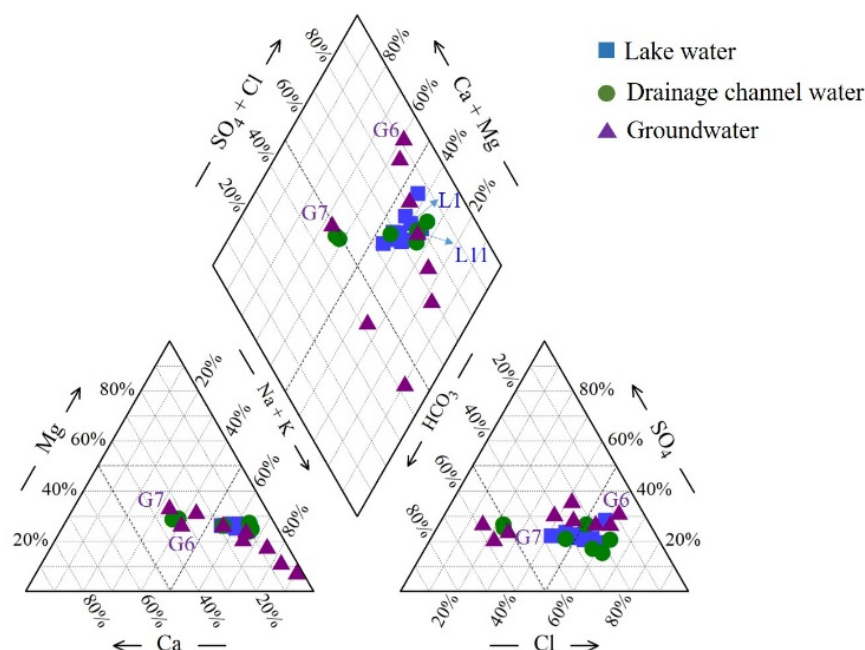


Figure 7. Piper diagram showing the hydrochemical types in the three water bodies.

4.2.2. Temporal Evolution

Analysis of the water bodies in the study area before the water diversion showed that the lake water was mainly of the $\text{Cl}\cdot\text{SO}_4\text{--Na}\cdot\text{Mg}$ type, which is relatively simple. The west bank groundwater contained $\text{HCO}_3\text{--Na}\cdot\text{Mg}$ and $\text{Cl}\cdot\text{HCO}_3\cdot\text{SO}_4\text{--Mg}\cdot\text{Na}\cdot\text{Ca}$ types, and the east bank groundwater contained $\text{HCO}_3\cdot\text{Cl}\cdot\text{SO}_4\text{--Na}\cdot\text{Ca}\cdot\text{Mg}$ and $\text{Cl}\cdot\text{HCO}_3\cdot\text{SO}_4\text{--Mg}\cdot\text{Na}$ types [32]. After the water diversion, Na^+ and Cl^- were still the main ions in the water bodies, and other dominant ions did not show regular changes. These results show that the area has been strongly affected by salinization, and that the influence of water diversion on the hydrochemical types is not as great as that on the concentrations of the hydrochemical indices.

4.3. Stable Isotope Characterization

4.3.1. Water Exchange

The relationship between δD and $\delta^{18}\text{O}$ (Figure 8) showed that almost all of the water sampling points were located to the lower right of the global meteoric water line and the local meteoric water line (LMWL). For the lake water, the δD ranged from -62.89‰ to -53.59‰ (mean: -58.8‰) and the $\delta^{18}\text{O}$ from -8.21‰ to -6.47‰ (mean: -7.46‰). For the drainage channel water, the δD ranged from -74.14‰ to -56.17‰ (mean: -64.57‰) and the $\delta^{18}\text{O}$ from -10.24‰ to -6.92‰ (mean: -8.32‰). For groundwater on the west bank, the ranges were -71.94‰ to -61.28‰ (mean: -67.47‰) for δD and -9.74‰ to -8.66‰ (mean: -8.99‰) for $\delta^{18}\text{O}$. For groundwater on the east bank, the ranges were -78.84‰ to -70.62‰ (mean: -74.75‰) for δD and -10.57‰ to -9.57‰ (mean: -74.75‰ and -10.13‰) for $\delta^{18}\text{O}$. The δD and $\delta^{18}\text{O}$ values in the drainage channel water varied greatly, which was related to the differences in the water in the channels. The δD and $\delta^{18}\text{O}$ values in the lake water and the groundwater showed small changes, with the groundwater on the east bank having the smallest changes. This is because the study area is located in arid northwestern China, and the different water bodies are affected by meteoric precipitation, temperature, recharge sources, and other factors, resulting in different degrees of water isotope fractionation [40,41]. The stable isotope values in the lake water were significantly higher than those in the drainage channel water and the groundwater, reflecting extensive evaporation and concentration of the lake water, leading to stronger isotope enrichment.

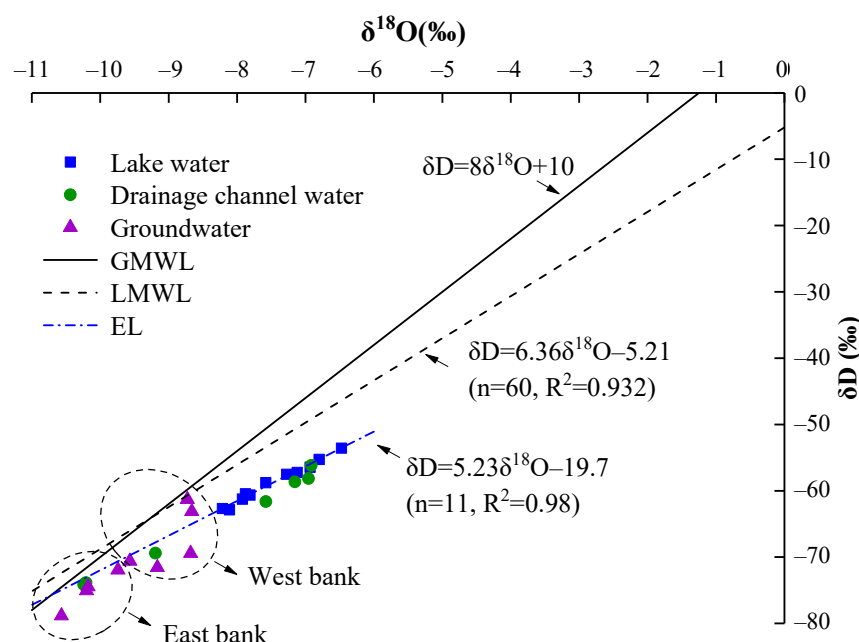


Figure 8. Comparison of the deuterium and ^{18}O ratios of water molecules in the three water bodies. GMWL: the global meteoric water line [42]. LMWL: the local meteoric water line (data from the Baotou Station of the Global Network of Isotopes in Precipitation collected from 1986 to 1993). EL: the lake water evaporation line (data from the lake water samples in this study).

The isotope values of the lake water were more negative than those of meteoric precipitation, which indicated that the lake water was not greatly affected by atmospheric water. Therefore, meteoric precipitation is not the main source of the lake water. The lake water generally flows from north to south. Because of extensive evaporation, the lake water as a whole is gradually enriched in heavy isotopes from north to south. Although the Eighth, Ninth, Tongji, and Taboo channels also drain into the lake, most (88%) of the water entering the lake comes through the main channel to the north. This means that even if there are differences between the channels, they have almost no effect on the isotope composition of the lake water. Closer inspection of the data shows there is a strong hydraulic connection between the drainage channel water and the lake water, which confirms that the drainage channel water is the main source of water for the lake.

The groundwater data could be divided into two groups (east bank and west bank) according to the sampling locations. The groundwater on the west bank was markedly richer in heavy isotopes than that on the east bank. This may be because of the shallower depth of the groundwater table on the west bank than on the east bank, because the former experienced strong evaporation and fractionation. The absence of surface water irrigation on the east bank and groundwater exploitation mean that the groundwater table is deeper on the east bank. The groundwater samples on the east bank were located at the lower right of the lake water evaporation line. The isotope values in this location were significantly lower than those of the lake water, and the degree of deviation was greater. These results indicated that there was a poor hydraulic connection between the east bank groundwater and the lake water. When studying the stable isotope relationship around the lake, other scientists have proposed that because the east bank of the lake is on a geological fault, it is unlikely that groundwater on the east bank will flow into the lake. Combined with experimental results from installed pressure gauges, it is believed that the interaction between groundwater and the lake on the east bank will be almost zero [32]. In addition, the weak hydraulic connection may be related to spatial differences in deposited silt stratification at the bottom of the lake [43]. The average thickness of silt stratification is 0.5 m, and the maximum thickness can reach more than 0.9 m [29]. This aquitard may weaken the interaction between the lake water and the groundwater.

The stable isotope ratios of the groundwater in the study area were all located at the lower right of the LMWL, and most of them deviated greatly. Therefore, meteoric precipitation is not the main source of water recharging the groundwater. The groundwater is partly recharged from bedrock fissure water in the northern mountainous area [44]. The TDS concentration of the west bank groundwater was equal to or even higher than that of the drainage channel water. In combination with the stable isotope ratios, these results indicate that most of the west bank groundwater comes from the infiltration of water from the Hetao irrigation area, which is irrigated by the Yellow River. Although there was some degree of deviation between the isotope ratios of the drainage channel water and the surrounding groundwater, this may be the result of fractionation of the drainage channel water with evaporation. The isotope ratios of the individual groundwater samples in the northwestern region fell between the LMWL and lake water evaporation line, indicating that the groundwater in the northwestern region may be affected by the infiltration of water from floods in the mountain.

4.3.2. Stable Isotope Ratios for Water Exchange

The stable isotope ratios of meteoric precipitation, the drainage channel water, and the groundwater were calculated by use of Equation (1). A value of -48.2‰ was assigned to δ_P [45]. The values for δ_L , δ_D , and δ_G on the west bank, and δ_G on the east bank were -58.8‰ , -65.65‰ , -67.47‰ , and -74.7‰ , respectively. Because there were many unknown end elements, 133 possible results were obtained (Table S2 in the Supplementary Materials). For the water entering the lake from the drainage channels, the obvious unreasonable results were eliminated and only results from parts with drainage channel water contributions of $>50\%$ were used. The contributions of meteoric precipitation, the drainage channel water, the west bank groundwater, and the east bank groundwater were 36–38%, 52–60%, 2–7%, and 1–5%, respectively. These values show that the lake water is mainly recharged by the drainage channel water followed by meteoric precipitation. Recharge from groundwater on both banks is minimal, which indicates that there is a weak hydraulic connection between the lake and the surrounding groundwater.

4.4. The Regional Water Cycle

4.4.1. The Hydrological Cycle

With Lake Ulansuhai at the center, the hydrochemical and isotopic characterization results were used to establish a quantitative regional hydrological cycle model (Figure 9). Approximately 52–60% of water entering the lake comes from the six drainage channels on the west bank. The water in these channels is a mixture of water diverted from the Yellow River, farmland drainage from the Hetao irrigation area, and local industrial and domestic wastewater. Approximately 36–38% of water entering the lake comes from meteoric precipitation. The remaining recharge comes from the surrounding groundwater (west bank: 2–7%, and east bank: 1–5%) and floods in the northern mountainous area, but these inputs are generally minimal. After extensive evaporation from the lake surface, the lake water is discharged into the Yellow River through a waste canal at the southern end. Water exchange on the east bank of the lake is generally minimal.

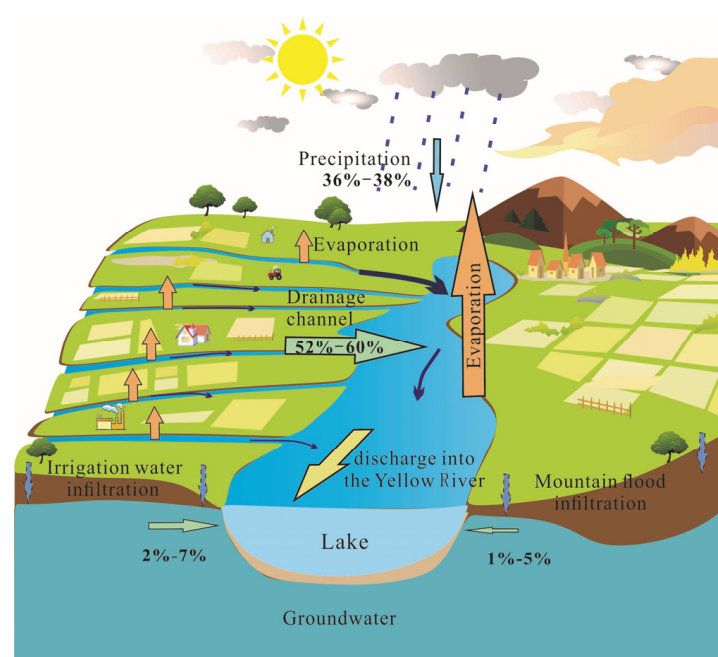


Figure 9. Model characterizing the regional hydrological cycle in the study area established using hydrochemical and isotopic analysis results.

4.4.2. The Hydrochemical Cycle

On the basis of the regional hydrological cycle and water exchanges among the different bodies mentioned above, we can infer that hydrochemical evolution (i.e., salinization and eutrophication) of Lake Ulansuhai is dominated by water from the drainage channels on the west bank of the lake, followed by the evaporation of water from the lake surface. It should be noted that 88% of the drainage water input comes from the main drainage channel in the north [27]. Meteoric precipitation, the surrounding groundwater, and the possible water exchange on the east bank of the lake generally have minimal impacts on salinization and eutrophication, so they will not be effective for addressing remediation. Although water diversion has increased the volume of water stored in the lake, raised the water level, expanded the water surface area, and slowed down salinization and eutrophication, there are still serious aquatic ecological issues affecting the species in the lake and the hydrochemical composition of the lake water. The main contributor to the water quality issues is the diverted water. Although this water comes from the Yellow River, which has a low salt content, the channels that carry the water receive large volumes of farmland drainage with a high salt content as they pass through the Hetao irrigation area. In other words, solving soil salinization issues in the Hetao irrigation area is key to addressing the water quality in Lake Ulansuhai.

5. Conclusions

Lake Ulansuhai is located in the middle of Inner Mongolia, China, and near the Yellow River. It is the lowest area in the Hetao basin and therefore the sink for the terrestrial water in this region. Water was diverted from the Yellow River from 2013 to 2021 to increase the volume of water stored in the lake and decrease the salinity. After water diversion, the concentrations of hydrochemical indices showed large differences among the lake, the drainage channels, and the surrounding groundwater. High salinity dominated by NaCl was problematic in all the three water bodies. The stable isotope values in the lake water are much higher than those in the drainage channel water and the groundwater, reflecting that the evaporation and concentration of the lake water lead to stronger isotope enrichment. The main hydrochemical type in the lake water was $\text{Cl}\cdot\text{HCO}_3\text{--Na}\cdot\text{Mg}$. Because of spatial differences, the hydrochemical types in the drainage channel water and the groundwater

were different. The six drainage channels on the west bank and evaporation of water from the lake surface were dominant contributors to the hydrochemical evolution and salinization of the lake. A new model reflecting the local water cycle in this area was established considering the impact of the water diversion in recent years. Approximately 52–60% of water entering the lake comes from six drainage channels on the west bank, in which the water is a mixture of that diverted from the Yellow River, farmland drainage from the Hetao irrigation area, and local industrial and domestic wastewater. Approximately 36–38% of the of the remaining water entering the lake is from meteoric precipitation. Recharge of groundwater to the lake is generally minimal. Extensive evaporation occurs in the lake. Discharge of lake water into the Yellow River occurs through a waste canal at the southern end of the lake. Water exchange on the east bank of the lake can be neglected. Generally speaking, the key to solving issues with the lake is to rectify soil salinization in the Hetao irrigation area.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/w13213033/s1>, Table S1. Measurement methods and detection limits for the monitoring of hydrochemical indices, Table S2. The contribution rate of different water bodies to lake water based on IsoSource software.

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References

1. Lin, S.; Shen, S.; Zhou, A.; Lyu, H. Assessment and management of lake eutrophication: A case study in lake Erhai, China. *Sci. Total Environ.* **2021**, *751*, 141618. [\[CrossRef\]](#)
2. Tao, S.; Fang, J.; Ma, S.; Cai, Q.; Xiong, X.; Tian, D.; Zhao, X.; Fang, L.; Zhang, H.; Zhu, J.; et al. Changes in China's lakes: Climate and human impacts. *Natl. Sci. Rev.* **2020**, *7*, 132–140. [\[CrossRef\]](#) [\[PubMed\]](#)
3. Liu, H.; Liu, G.; Xing, W. Functional traits of submerged macrophytes in eutrophic shallow lakes affect their ecological functions. *Sci. Total Environ.* **2021**, *760*, 143332. [\[CrossRef\]](#)
4. Miller, C.; Null, S.; DeRose, R.; Wilcock, P.; Wurtsbaugh, W.; Null, S.; DeRose, R.; Hahnenberger, M.; Howe, F.; Moore, J. Decline of the world's saline lakes. *Nat. Geosci.* **2017**, *10*, 816–821.
5. Wang, S.; Wei, S.; Liang, H.; Zheng, W.; Li, X.; Hu, C.; Currell, M.; Zhou, F.; Min, L. Nitrogen stock and leaching rates in a thick vadose zone below areas of long-term nitrogen fertilizer application in the North China Plain: A future groundwater quality threat. *J. Hydrol.* **2019**, *576*, 28–40. [\[CrossRef\]](#)
6. Cui, S.; Hough, R.; Yates, K.; Osprey, M.; Kerr, C.; Cooper, P.; Coull, M.; Zhang, Z. Effects of season and sediment-water exchange processes on the partitioning of pesticides in the catchment environment: Implications for pesticides monitoring. *Sci. Total Environ.* **2020**, *698*, 134228. [\[CrossRef\]](#)
7. Zhang, Q.; Liu, Y.; Yao, J.; Lai, X.; Li, X.; Wu, G.; Huang, Q.; Sun, Z.; Zhang, D.; Li, Y.; et al. Lake hydrology in China: Advances and prospects. *J. Lake Sci.* **2020**, *32*, 1360–1379. (In Chinese with English abstract)
8. Wang, Y.; Duan, L.; Liu, T.; Li, J.; Feng, P. A non-stationary standardized streamflow index for hydrological drought using climate and human-induced indices as covariates. *Sci. Total Environ.* **2020**, *699*, 134278. [\[CrossRef\]](#)

9. Xu, R.; Pang, Y.; Hu, Z.; Zhu, T.; Kaisam, J. Influence of water diversion on spatial and temporal distribution of flow field and total phosphorus (TP) concentration field in Taihu Lake. *Water Sci. Technol.* **2020**, *20*, 1059–1071. [\[CrossRef\]](#)
10. Dittmar, T.; Kothawala, D.; Tranvik, L.; Kellerman, A.; Kothawala, D.; Tranvik, L. Chemodiversity of dissolved organic matter in lakes driven by climate and hydrology. *Nat. Commun.* **2014**, *5*, 3804.
11. Zhu, Y.; Zhai, Y.; Teng, Y.; Wang, G.; Du, Q.; Wang, J.; Yang, G. Water supply safety of riverbank filtration wells under the impact of surface water-groundwater interaction: Evidence from long-term field pumping tests. *Sci. Total Environ.* **2020**, *711*, 135141. [\[CrossRef\]](#)
12. Zhai, Y.; Xia, X.; Yang, G.; Lu, H.; Ma, G.; Wang, G.; Teng, Y.; Yuan, W.; Shrestha, S. Trend, seasonality and relationships of aquatic environmental quality indicators and implications: An experience from Songhua River, NE China. *Ecol. Eng.* **2020**, *145*, 105706. [\[CrossRef\]](#)
13. Heydarizad, M.; Minaei, M.; Ichiyanagi, K.; Sori, R. The effects of local and regional parameters on the $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of precipitation and surface water resources in the Middle East. *J. Hydrol.* **2021**, *600*, 126485. [\[CrossRef\]](#)
14. Cui, R.; Ye, X.; Du, X. Coupled effects of bacteria and suspended solids on clogging during managed aquifer recharge. *J. Hydrol.* **2021**, *600*, 126543. [\[CrossRef\]](#)
15. Li, D.; Zhai, Y.; Lei, Y.; Li, J.; Teng, Y.; Lu, H.; Xia, X.; Yue, W.; Yang, J. Spatiotemporal evolution of groundwater nitrate nitrogen levels and potential human health risks in the Songnen Plain, Northeast China. *Ecotox. Environ. Saf.* **2021**, *208*, 111524. [\[CrossRef\]](#)
16. Zhai, Y.; Zheng, F.; Zhao, X.; Xia, X.; Teng, Y. Identification of hydrochemical genesis and screening of typical groundwater pollutants impacting human health: A case study in Northeast China. *Environ. Pollut.* **2019**, *252*, 1202–1215. [\[CrossRef\]](#)
17. Zheng, F.; Zhai, Y.; Xia, X.; Yin, Z.; Du, Q.; Zuo, R.; Wang, J.; Teng, Y.; Xu, M. Simulation of trinitrogen migration and transformation in the unsaturated zone at a desert contaminant site (NW China) using HYDRUS-2D. *Water* **2018**, *10*, 1363. [\[CrossRef\]](#)
18. Wannous, M.; Jahnke, C.; Troeger, U.; Falk, M.; Bauer, F. Hydrochemistry and environmental isotopes (^{18}O , ^2H , ^3H , $^3\text{He}/^4\text{He}$) of groundwater and floodwater in the great area of Hurgada, eastern desert of Egypt. *Environ. Earth Sci.* **2021**, *80*, 407. [\[CrossRef\]](#)
19. Jia, Y.; Guo, H.; Jiang, Y.; Wu, Y.; Zhou, Y. Hydrogeochemical zonation and its implication for arsenic mobilization in deep groundwaters near alluvial fans in the Hetao Basin, Inner Mongolia. *J. Hydrol.* **2014**, *518*, 410–420. [\[CrossRef\]](#)
20. Yang, J.; Dudley, B.; Montgomery, K.; Hodgetts, W. Characterizing spatial and temporal variation in ^{18}O and ^2H content of New Zealand river water for better understanding of hydrologic processes. *Hydrol. Process.* **2020**, *34*, 5474–5488. [\[CrossRef\]](#)
21. Sprenger, M.; Leistert, H.; Gimbel, K.; Weiler, M. Illuminating hydrological processes at the soil-vegetation-atmosphere interface with water stable isotopes. *Rev. Geophys.* **2016**, *54*, 674–704. [\[CrossRef\]](#)
22. Liu, Y.; Yamanaka, T. Tracing groundwater recharge sources in a mountain-plain transitional area using stable isotopes and hydrochemistry. *J. Hydrol.* **2012**, *464*, 116–126. [\[CrossRef\]](#)
23. Qin, W.; Han, D.; Song, X.; Liu, S. Environmental isotopes ($\delta^{18}\text{O}$, $\delta^2\text{H}$, ^{222}Rn) and hydrochemical evidence for understanding rainfall-surface water-groundwater transformations in a polluted karst area. *J. Hydrol.* **2021**, *592*, 125748. [\[CrossRef\]](#)
24. Liu, Y.; Yamanaka, T.; Zhou, X.; Tian, F.; Ma, W. Combined use of tracer approach and numerical simulation to estimate groundwater recharge in an alluvial aquifer system: A case study of Nasunogahara area, central Japan. *J. Hydrol.* **2014**, *519*, 833–847. [\[CrossRef\]](#)
25. Sun, H.; Lu, X.; Yu, R.; Yang, J.; Liu, X.; Cao, Z.; Zhang, Z.; Li, M.; Geng, Y. Eutrophication decreased CO_2 but increased CH_4 emissions from lake: A case study of a shallow lake Ulansuhai. *Water Res.* **2021**, *201*, 117363. [\[CrossRef\]](#)
26. Wang, G.; Shi, H.; Li, X.; Yan, J.; Miao, Q.; Li, Z.; Akai, T. A study on water and salt transport, and balance analysis in sand dune-wasteland-lake systems of Hetao Oases, upper reaches of the Yellow River Basin. *Water* **2020**, *12*, 3454. [\[CrossRef\]](#)
27. Zhang, Q.; Yu, R.; Jin, Y.; Zhang, Z.; Liu, X.; Xue, H.; Hao, Y.; Wang, L. Temporal and spatial variation trends in water quality based on the WPI index in the shallow lake of an arid area: A case study of Lake Ulansuhai, China. *Water* **2019**, *11*, 1410. [\[CrossRef\]](#)
28. Shi, R.; Zhao, J.; Shi, W.; Song, S.; Wang, C. Comprehensive assessment of water quality and pollution source apportionment in Wuliangsuhai Lake, Inner Mongolia, China. *Int. J. Environ. Res. Public Health* **2020**, *17*, 5054. [\[CrossRef\]](#)
29. Tian, W.; Pei, G.; Zhao, S.; Shi, X.; Zhang, H.; Sun, B.; Song, S.; Sun, C.; Ma, H. Seasonal varieties and influential factors of heavy metals in sediments of Wuliangsuhai Lake. *Water Sci. Technol.-Water Supply* **2020**, *20*, 3779–3790. [\[CrossRef\]](#)
30. Chen, Q.; Yu, R.; Hao, Y.; Wu, L.; Zhang, W.; Chen, Q.; Zhang, Q.; Bu, X. A new method for mapping aquatic vegetation especially underwater vegetation in lake Ulansuhai using GF-1 satellite data. *Remote Sens.* **2018**, *10*, 1279. [\[CrossRef\]](#)
31. Ma, M.; Dong, S.; Zhang, W.; Hou, Q.; Zhao, Z. Hydrochemical characteristics and genesis of groundwater in Wuliangsuhai lake area. *Earth Environ.* **2021**, *49*, 472–479. (In Chinese with English abstract)
32. Zhu, D.; Ryan, M.; Sun, B.; Li, C. The influence of irrigation and Wuliangsuhai Lake on groundwater quality in eastern Hetao basin, Inner Mongolia, China. *Hydrogeol. J.* **2014**, *22*, 1101–1114. [\[CrossRef\]](#)
33. Donald, L.; Jillian, W.G. Source partitioning using stable isotopes: Coping with too many sources. *Oecologia* **2003**, *136*, 261–269.
34. Yan, X.; Dong, W.; An, Y.; Lu, W. A Bayesian-based integrated approach for identifying groundwater contamination sources. *J. Hydrol.* **2019**, *579*, 124160. [\[CrossRef\]](#)
35. Cui, F.; Li, C.; Shi, X.; Shi, Y.; Fu, X. Seasonal changing characteristics of the major ions in the Lake Wuliangsuhai. *J. Arid Land Resour. Environ.* **2013**, *27*, 137–142. (In Chinese with English abstract)

-
36. Du, D.; He, J.; Lv, C.; Bai, S.; Xie, Z.; Hou, D.; Wang, J. Water quality chemistry of several main anions in the Lake Ulansuhai and the Lake Daihai water environment. In Proceedings of the Agricultural Environment and Ecological Security—The Fifth National Symposium on Agricultural Environmental Science, Nanjing, China, 19–22 April 2013.
 37. Hou, Q.; Dong, S.; Gao, D.; Ma, M.; Chen, Y. Hydrogeochemical evolution and water and salt migration in the Wuliangsuhai Watershed. *Environ. Sci. Technol.* **2021**, *44*, 108–114. (In Chinese with English abstract)
 38. Wang, J.; Wu, J.; Zeng, H.; Ma, L. Analysis on water resources and their changes of main lakes in Inner Mongolia. *Arid Zone Res.* **2015**, *32*, 7–14. (In Chinese with English abstract)
 39. Li, C.; Yang, F.; Shi, X.; Sun, B.; Zhao, S.; Cen, R.; Fan, C. Impact of seasonal ice cover on nutrient distribution in Ulansuhai Lake. *J. Hydroelectr. Eng.* **2016**, *35*, 1–8. (In Chinese with English abstract)
 40. Feng, S.; Liu, X.; Li, H. Spatial variations of δD and $\delta^{18}O$ in lake water of western China and their controlling factors. *J. Lake Sci.* **2020**, *32*, 1199–1211. (In Chinese with English abstract)
 41. Liu, J.; Song, X.; Sun, X.; Yuan, G.; Liu, X.; Wang, S. Isotopic composition of precipitation over arid northwestern China and its implications for the water vapor origin. *J. Geogr. Sci.* **2009**, *19*, 164–174. [[CrossRef](#)]
 42. Craig, H. Isotopic variations in meteoric waters. *Science* **1961**, *133*, 1702–1703. [[CrossRef](#)] [[PubMed](#)]
 43. Gu, H.; Lan, S.; Zhang, H.; Wang, M.; Chi, B.; Sauter, M. Water level response in wells to dynamic shaking in confined unconsolidated sediments: A laboratory study. *J. Hydrol.* **2021**, *597*, 126150. [[CrossRef](#)]
 44. Chen, J.; Zhang, Z.; Liu, Z.; Ji, B. Isotopic study on water supply relationship in Ulansuhai and its surrounding areas. *Water Resour. Prot.* **2013**, *29*, 12–18. (In Chinese with English abstract)
 45. Liu, J.; Guo, H.; Liu, F.; Wei, W.; Zhang, L.; Zhang, X. The variations of stable isotopes (δD and $\delta^{18}O$) in the precipitation in Baotou area. *J. Arid Land Resour. Environ.* **2013**, *27*, 157–162. (In Chinese with English abstract)