Analyzing the Vertical Recharge Mechanism of Groundwater Using Ion Characteristics and Water Quality Indexes in Lake Hulun

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Abstract: The water level of Lake Hulun has changed dramatically in recent years. The interannual interaction between groundwater and lake water is an important factor affecting Lake Hulun’s water level. Vertical recharge between groundwater and the lake is particularly important. Based on an analysis of differences between the hydrogeochemical and water quality characteristics of the spring water, the lake water, and the surrounding groundwater, the source and recharge mechanism of the spring water in the vertical recharge lake are determined. The results show that spring water is exposed at the bottom of Lake Hulun, and there are obvious differences between spring water and lake water in lake ice thickness, ion characteristics, and water quality characteristics. For example, the ice thickness at the spring site is only 6.8% of the average ice thickness of the lake, and there is a triangular area directly above the spring water area that is not covered by ice; the ion contents of the spring water at the lake bottom were less than 50% of those in the lake water; and the NH4+-N content of the spring water at the lake bottom was only 3.0% of the mean content of the lake water. In addition, the total nitrogen (TN), dissolved oxygen (DO), and NH4+-N contents of the spring water at the lake bottom all fall outside the range of contents of the surrounding groundwater. In general, the source of the spring water at the lake bottom is not recharged by the infiltration recharge of the phreatic aquifer but by the vertical recharge of the confined aquifer. Additionally, the Lake Hulun basin may be supplied with confined water through basalt channels while it is frozen. The vertical groundwater recharge mechanism may be that spring water at the lake bottom is first supplied by the deep, confined aquifer flowing through the fault zone to the loose-sediment phreatic aquifer under the lake, and finally interacts with the lake water through the phreatic aquifer.

Keywords: hydrochemistry; groundwater; spring; hydraulic relationship; Lake Hulun

1. Introduction

Lakes are important carriers of the Earth’s water resources and have played a critical role in the history of human development [1]. Lake Hulun is the fifth-largest lake in China. Its water storage capacity is 10.66 km³, accounting for more than 0.06‰ of the total water storage capacity of lakes worldwide [2]. Therefore, changes in the water volume of Lake Hulun are crucial for the water storage capacity of lakes worldwide. Over the past 60 years, Lake Hulun has mainly depended on groundwater recharge as its water supply source. However, the amount of groundwater available to recharge the lake water varies greatly from year to year, and the recharge amount is not stable. In 2013, the lake even discharged 1.86 km³ of water into the groundwater [3]. The water balance of Lake Hulun is mainly affected by lake surface evaporation, seepage, atmospheric precipitation, river runoff, slope runoff in the lake area, and underground runoff. However, water balance simulations show that there are other water bodies with large water volumes that interact with the lake [4–6]. According to an analysis of the lakeshore landform and the lake’s flow...
characteristics, some studies concluded that the outcropping of spring water at the bottom of Lake Hulun plays an obvious role in the formation of the lake’s local flow and indicated that the spring at the lake bottom is one of the water supply sources of Lake Hulun, whose annual maximum water supply can reach 0.3–0.4 km³ [7].

The hydrochemical characteristics of water bodies are often used to analyze hydraulic connections between water bodies. This study analyzes various water bodies that recharge Lake Hulun to determine the reason for the change in the lake’s water level [8] and explore the source of the bottom spring [9]. There are many methods of studying the characteristics and development of groundwater, including hydrochemical analysis methods such as Piper diagrams, Gibbs diagrams, ion proportion diagrams, dispersion point diagrams, and hydrogeochemical simulations [10–12]. The main methods of research into the mechanisms of groundwater formation include principal component analyses, the positive definite matrix factor method, and the environmental isotope method [13–15]. In this present study, the Durov method and ion ratio method are adopted to investigate the material sources of different types of groundwater and spring water.

Lake eutrophication has recently intensified under the influence of climate change and human activities [16]. Water quality analyses of the various water bodies that recharge Lake Hulun are also effective measures for exploring the source of the lake’s bottom spring [17]. Therefore, the water quality of the lake water, groundwater, and spring water is analyzed to investigate the role of the bottom spring in the change in the water quality of the lake. Among commonly used water quality evaluation methods, single-factor evaluation methods, artificial neural network evaluation methods, fuzzy mathematics, and the comprehensive water quality index (WQI) have their own advantages [18–20]. The WQI method is currently widely used in the Hetao Irrigation Area [21], Panyang Lake [22], and other rivers, lakes, and reservoirs. In the present study, the WQI method was used to assess water quality.

This study aimed to investigate the degree of influence of the bottom spring on the lake water and the bottom spring supply channel. The main objectives of the present study were to (1) evaluate the hydraulic connection between the lake water, groundwater, and spring water based on ion characteristics and water quality index data; (2) analyze the source of the bottom spring in the lake based on the ion characteristics of each water bodies; (3) determine the degree of influence of the spring water on the lake water based on the water quality index of each water body; and (4) analyze the reason for the large difference in the interaction between groundwater and lake water volume of the water balance of Lake Hulun over a long time period.

2. Methods and Materials

2.1. Study Region

Lake Hulun (117°00′–117°45′ E, 48°30′–49°20′ N) is located in the western part of the Hulunbuir Grassland, Inner Mongolia (Figure 1). The lake is shaped like an irregular, oblique rectangle with a long axis extending from north to south. It is approximately 93 km long, 41 km wide, 480 km in circumference, and has an area of 2037.3 km² [23]. There are fault zones on the east and west sides of the lake basin that strike in line with the long axis of the lake. The Xishan Fault on the west side of the lake basin and the Cuogang Fault on the east side of the lake basin were both formed in the late Cenozoic Upper Pleistocene (Qp3) period, and the two faults are parallel. The lake basin forms a graben basin in the west and a gentle basin in the east under the joint control of the two fault zones. The basin is low-lying and recharged by surface rivers to form Lake Hulun [24]. This lake is classified as a tectonic lake formed by crustal movement, with a water surface area of 2037.3 km² and an average water depth of 5.7 m. The average water depth of Lake Hulun is 5.7 m, and the total frozen period of lake ice is 155 d; the lake ice lasts for 193 days, and the thickness of the lake ice can reach 1.3 m [25].
2.2. Spring at Lake Bottom

The emergence of groundwater is related to a fault. There are a total of 26 springs in the area, most of which are distributed on or near the fault line. Among the ten known springs outcropping from Lake Hulun, five are associated with the large NNE fault on the west bank of Lake Hulun [26].

Through a field investigation, one of the known springs related to the Xishan Fault was identified in the southwest region of Lake Hulun. The Xishan Fault in this spring point area is controlled by the Derbugan Fault, which is exposed along the west bank of the lake and forms a steep lakeshore cliff [27]. The characteristics of this spring point are consistent with the characteristics of extremely weak lake ice caused by abnormal hydrodynamic conditions. Combined with the characteristic of lake ice in this area for many years, this area is determined to be the area at which the bottom spring is located, which is called “Qingyan” by local herdsmen. In this study, we took the Xishan Fault with a NE40° strike as an axis, made a vertical line passing through the position of the spring at the lake bottom, and set up lake-water-sampling points at 50 m, 100 m, 150 m, 300 m, −100 m, and −200 m from the spring point on the northwest and southeast sides of the axis to explore the characteristics of the bottom spring and the influence of the bottom spring on the lake water. Among these sampling points, “50 m” indicates a point 50 m from the northwest side of the bottom spring, and “−100 m” indicates a point 100 m from the southeast side of the bottom spring. As the lake ice at the spring is weak and the depth of the lake is 3.50 m, it was difficult to sample the spring water. In this study, the chosen method of sampling the lake bottom spring water was to throw a sampling bottle 1.50 m from the spring point and obtain a water sample at a water depth of 3.30 m at the spring hole. Because the lake water was mobile, the spring water sample taken was a mixed sample of the lake water and the bottom spring water, and the mixing ratio was unknown.
2.3. Sample and Methods

To examine water within the scope of the Lake Hulun basin, we collected lake water, groundwater, spring water from near the lakeshore, and spring water from the lake bottom. The water samples were collected during the frozen period in 2022 (January). We collected 13 groups of lake water, 10 samples of groundwater, 1 sample of spring water near the lakeshore, 1 sample of spring water at the lake bottom, and 6 samples of surrounding lake water. The groundwater was collected in a submersible well used by herdsmen; the well depth was less than 80 m, and collection was carried out after 5 min of flushing the well. We used 1 L polyvinyl chloride bottles to collect the water samples and stored the samples at a low temperature of 4 °C. In order to reduce systematic error, the samples were divided into two parts for determination, and a blank control group was established. Physical indicators were measured on-site using a portable multi-parameter water quality analyzer (YSI); these indicators included pH, dissolved oxygen (DO), temperature (T), total dissolved solids (TDSs), and the thickness of the lake ice. Ion indicators and water quality indicators were measured in a laboratory. The chemical oxygen demand (CODcr) and total phosphorus (TP), total nitrogen (TN), and ammonia–nitrogen (NH₄⁺-N) indexes were, respectively, determined using alkaline potassium persulfate digestion, UV spectrophotometry, referring to the “HJ 636-2012” standard [28], ammonium–molybdate spectrophotometry, referring to the “GB/T 11893-1989” standard [29], fast-digestion spectrophotometry, referring to the “HJ/T 399-2007” standard [30], and Nessler’s reagent spectrophotometry, referring to the “DZ/T 0064.57-2021” standard [31]. Ion contents included Na⁺, K⁺, Ca²⁺, Mg²⁺, Cl⁻, SO₄²⁻, and NO₃⁻ and were determined using the “GB/T 5750.3-2023” standard [32]. A phenolphthalein/methyl orange indicator titration method was used to determine HCO₃⁻ and CO₃²⁻.

2.4. Water Quality Evaluation Method

The WQI can effectively and accurately evaluate lake water quality [33]. In this study, we used an improved method by Liu and Zhang [34] to evaluate the water quality of Lake Hulun:

\[
WQI = X_1 \times X_2 = \sum_{i=1}^{n} \omega_i \times Q_i
\]

\[
\omega_i = \frac{P_i}{\sum_{i=1}^{n} P_i}
\]

where \(X_1\times X_2\) represents the integer bit and the first decimal of the comprehensive water quality index; \(X_1\) is the comprehensive water quality classification of the water body; \(X_2\) is the position of the comprehensive water quality in the water quality variation interval of classification \(X_1\); \(n\) is the number of single factors for calculating the WQI; \(Q_i\) is the single-factor water quality index of the \(i\)th water quality factor, which is calculated by comparing water quality monitoring data with the standard “GB 3838-2002” [33]; \(w_i\) is the relative weight of the \(i\)th water quality factor; and \(P_i\) is the weight value of the water quality factor based on its importance to organisms, and its value ranges from 1 to 4 [35–37].

Table 1 shows the weight value of the single water quality factor and the classification of the comprehensive water quality index of Lake Hulun. In this study, we used the TP, TN, DO, COD, and NH₄⁺-N contents as factors in the water quality evaluation index. Refer to Table 1 for WQI values and the water quality classification of the lake water [38].
Table 1. Weight values of single water quality factor and quality classification of comprehensive water quality index.

<table>
<thead>
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<th>Factor</th>
<th>P_i</th>
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<th>Quality Classification</th>
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<td>1</td>
<td>2.0 &gt;= X1·X2 &gt; 1.0</td>
<td>I</td>
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</tr>
<tr>
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<td>4</td>
<td>4.0 &gt;= X1·X2 &gt; 3.0</td>
<td>III</td>
</tr>
<tr>
<td>COD</td>
<td>3</td>
<td>5.0 &gt;= X1·X2 &gt; 4.0</td>
<td>IV</td>
</tr>
<tr>
<td>NH4+-N</td>
<td>3</td>
<td>6.0 &gt;= X1·X2 &gt; 5.0</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.0 &gt;= X1·X2 &gt; 6.0</td>
<td>V+</td>
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<tr>
<td></td>
<td></td>
<td>X1·X2 &gt; 7.0</td>
<td>V++</td>
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3. Results

3.1. Hydrochemical Composition

In the process of field sampling, we found that the ice thickness at the bottom of the lake spring was unusually small, only 5 cm thick, which was 6.8% of the average ice thickness of Lake Hulun at that time. As shown in Figure 2, the lake surface features in this area were abnormal and visible to the naked eye. The lake ice was raised up in an elliptical shape directly above the spring, with a radius of 0.7 m. The triangular area in the central area, which had a length of 0.35 m and a width of 0.1 m, was not covered by ice, showing an open state.

![Figure 2](image-url)

Figure 2. Analysis of ion characteristics in water: (A) Durov diagram for various water bodies; (B) ion characteristics of spring in lake bottom and lake water on section line; (C) section line of spring in lake bottom; and (D,E) real picture of spring at lake bottom.

The difference in TDS content between the bottom spring point and the surrounding lake water was small, and the difference was only 12% of the lake water. The contents of HCO₃⁻, Cl⁻, SO₄²⁻, Na⁺, K⁺, Mg²⁺, and Ca²⁺ ions in the springs at the bottom of the lake were all less than 50% of those in the lake water, indicating that there were a large number of other ions in the springs at the bottom of the lake compared to the lake water and that there were great differences between the springs at the bottom of the lake and the surrounding lake water. While the ion concentration of the bottom spring water was different from that of the lake water, their ion concentrations showed similar trends. The anion
trend appeared as $\text{HCO}_3^- > \text{Cl}^- > \text{SO}_4^{2-}$, and the cation trend appeared as $(\text{Na}^+ + \text{K}^+) > \text{Mg}^{2+} > \text{Ca}^{2+}$. The contents of $\text{Ca}^{2+}$ and $\text{Mg}^{2+}$ in the lake water and bottom spring water were smaller, and the concentration difference was not large.

Through a Durov analysis of water samples from Lake Hulun, the hydrochemical types of each water body were identified [39]. The hydrochemical type of the lake water was $\text{HCO}_3^-\text{Cl}^-\text{Na}$, the hydrochemical type of groundwater was diverse, the hydrochemical type of the lakeshore spring water was $\text{HCO}_3^-\text{Na}\text{Mg}$, and the hydrochemical type of the lake bottom spring water was $\text{HCO}_3^-\text{Na}$. The contents of all major ions in the bottom spring water were lower than those in the lake water, but the percentages of $\text{Mg}^{2+}$ and $\text{SO}_4^{2-}$ mg equivalent in the bottom spring water were higher than those in the lake water and similar to those in a spring near the lakeshore. The main cation in the lake water was $\text{K}^+ + \text{Na}^+$, and its cation percentage was $68.51 \pm 0.60\%$. The $\text{K}^+\text{Na}^+$ cation percentage of the bottom spring water was $66.87\%$, which is slightly lower than that of lake water, while the $\text{K}^+ + \text{Na}^+$ ion percentage in the spring near the lakeshore was only $38\%$ of that of the lake water. The ion percentage of its main cation, $\text{Ca}^{2+}$, was up to $48.94\%$.

3.2. Characteristics of Water Quality Variables

As shown in Figure 3, the ANOVA method was adapted to the monitoring data from 2022 to identify the spatial distribution of the water quality variables of the groundwater and lake water in Lake Hulun and the characteristics of the water quality variables of its spring water. There were significant differences in the $\text{NH}_4^+\text{N}$ and $\text{DO}$ indexes among the lake water samples, while there were significant differences in all indexes except $\text{NH}_4^+\text{N}$ among the groundwater samples.

There were great differences between the bottom spring and lake water in all water quality indexes. The $\text{DO}$ and $\text{COD}_\text{cr}$ contents of the bottom spring were $19.2 \text{mg/L}$ and $58.3 \text{mg/L}$, which were higher than those of the lake water, which had mean values of $14.6$
mg/L and 51.1 mg/L. The contents of TP and TN in the bottom spring were 0.13 mg/L and 1.30 mg/L, which were lower than the values of 0.15 mg/L and 1.63 mg/L found in the lake water. The most significant difference between the bottom spring and the lake water index was the content of NH$_4^+$-N: the content of NH$_4^+$-N in the bottom spring was 0.09 mg/L, which was significantly lower than the mean value of the lake water NH$_4^+$-N content at 3.03 mg/L. The contents of TN, DO, and NH$_4^+$-N in the bottom springs were all outside the range of the groundwater, indicating that the bottom springs have different sources than the groundwater [40].

The contents of TP, DO, COD, and TDS in the lakeshore spring water were outside the range of the groundwater. The index content of NH$_4^+$-N in the lakeshore spring water was close to that of the lake bottom spring water (0.24 mg/L), which was much lower than the lake water value and close to the G16 groundwater value. The TN index content of the lakeshore spring water was higher than that of the lake water and bottom spring water and was similar to that of the G16 groundwater. However, the G16 groundwater points, lakeshore spring points, and lake bottom spring points are all located above the Xishan Fault, indicating that the initial water sources of these three water bodies may be related to the Xishan Fault and then undergo different hydraulic exchanges [41] which cause the water quality and ion characteristics of the water bodies to change.

The water quality evaluation results are shown in Figure 4. The single-factor index evaluation of the TN and NH$_4^+$-N contents as well as the comprehensive index evaluation method showed significant differences between the bottom spring water and the lake water. In the single-factor water quality evaluation taking TN as the index, the TN content of the groundwater varied greatly, ranging from 1.38 to 31.89 mg/L, and the single-factor water quality evaluation results ranged from 4.8 to 8.0, with an average of 7.0. The TN content of the lakeshore spring water was 5.10 mg/L, and the single-factor water quality evaluation result was 7.6. The difference in TN content among groundwater sampled from the Lake Hulun basin was as much as 2300%. This is because the groundwater in some areas is seriously polluted by point sources, and the degree of point source pollution in lakeside springs is relatively light. The single-factor water quality evaluation using NH$_4^+$-N as an index showed that the bottom spring water quality was the best. The comprehensive water quality evaluation results showed that the water quality index of the lakeshore spring was 2.9, which was the best water quality score achieved. The water quality index of the spring water at the bottom of the lake was 3.1, which was better than that of the groundwater. The mean value of the groundwater quality index was 3.8, and the mean value of the lake water quality index was 4.3. The water quality of the lake water was worse than that of the groundwater and spring water, and the water quality of the groundwater and lake water in different regions varied greatly [42].

Figure 4. Water quality assessments: (A) factor—TN; (B) factor—NH$_4^+$-N; and (C) comprehensive factors.
4. Discussion

4.1. Mechanism of Ion Transformation in Groundwater

The groundwater in the Lake Hulun basin is not directly supplied by precipitation, so the groundwater is affected relatively little by precipitation; instead, its ion composition is mainly affected by strong rock dissolution and filtration, and its hydrochemical evolution is mainly controlled by water–rock interactions [43]. As shown in Figure 5, the ratios of major ions can be used to determine the factors influencing various water bodies’ chemical evolution [44]. As shown in Figure 5a, lake water and groundwater are mainly affected by evaporite and silicate rock, and spring water is more affected by silicate rock than groundwater.

![Figure 5. Ratios of major ions: (A) Ca²⁺/Na⁺; (B) Cl⁻; (C) HCO₃⁻ + SO₄²⁻; (D) SO₄²⁻; (E) Ca²⁺ + Mg²⁺ + Na⁺ + K⁺; and (F) Na⁺ + K⁺.](image)

The ratio of the Na⁺/Cl⁻ concentration (mg equivalent ratio, the same as below) can explain evaporite dissolution, and it is usually an important parameter when characterizing the sources of Na⁺ and K⁺ [45]. Because Cl⁻ is highly soluble and does not precipitate easily, it is relatively stable in groundwater, and its main source is the dissolution of rock minerals in the aquifer. As can be seen from Figure 5b, the Na⁺/Cl⁻ ratios of the groundwater and spring water are higher than 1, indicating that the Na⁺ and Cl⁻ are not all derived from rock salt dissolution [46]. The chemical composition of the groundwater in the Lake Hulun basin is mainly affected by the efflorescence and dissolution of silicate rocks.

Together, the ratio of the (Ca²⁺ + Mg²⁺)/SO₄²⁻ concentration and (Ca²⁺ + Mg²⁺)/(HCO₃⁻ + SO₄²⁻) reflect the dissolution of carbonate and aluminosilicate minerals in the subsurface water body [47], as shown in Figure 5c,d. The effect of aluminosilicate mineral dissolution on the bottom spring is very similar to the effect on the shore spring and the G16 groundwater point. The ratio relationships among Ca²⁺, Mg²⁺, Na⁺, and K⁺ are used jointly to explain the influence of various minerals on water bodies during the evolution of their hydrochemical components [48], as shown in Figure 5e,f. The groundwater is mainly affected by the dissolution of calcium plagioclase and olivine. The bottom spring water is affected...
by various mineral interactions to a similar extent to the lakeshore spring water, and the G16 groundwater point is similar to the spring water in its properties.

An analysis of the main ion relationships shows that feldspar mineral dissolution is the main factor affecting the hydrochemical evolution of the groundwater, and silicate rock dissolution has a greater impact on the spring water than on the groundwater. The bottom springs in the lake show water–rock interaction properties similar to those of the shore springs and some of the groundwater. Combining this information with the structure of Lake Hulun [49], it was determined that the spring water at the bottom of the lake may be affected by the Xishan Fault. The spring water is first supplied by a deep, confined aquifer under the lake through the fault zone, and it then interacts with the lake water through the phreatic aquifer. This is proved by the fact that the hydrochemical properties of the bottom spring water lie between those of the groundwater and deep confined water.

4.2. The Channel through Which the Spring Supplies Lake Hulun

Ice crevasses are external manifestations of stress in an ice body. In a lake, ice will generate cracks in areas with relatively thin layers of ice due to the thermal expansion and contraction of the ice itself and the top supporting layer of water under the ice. After the water overflows the water surface, the upper part of the ice body freezes again to form ice cracks [50]. Differing from the area of weak lake ice caused by the bottom spring in Lake Hulun, the dynamic and potential pressure caused by the spring inflow and the pressure difference caused by evaporation on the lake surface generate the lake flow force, which forces the lake water to flow from the recharge spring point to the evaporation surface [51]. The temperature difference between the lake water and the spring water is also a main factor in the generation of lake flow dynamics. During the ice-sealing period, the temperature of the spring water is relatively high, 2.6 °C more than the lake water, and it flows along the upper surface layer after entering the lake, which makes the lake ice in the spring point area weak [52]. In addition, the difference in ice thickness between the widely distributed ice fissure area and the spring point area is significant. The upper part of the ice body in the ice fissure area has a clear linear dividing line (commonly known as a “green ditch”), and the ice thickness decreases in a fault-like manner. However, the upper part of the ice in the spring point area has no obvious characteristics, and the ice thickness grows slowly in a certain range [41]. Therefore, considering the significant ion difference and water quality difference between the bottom spring water and the lake water, it can be concluded that the lake water is recharged directly by the spring at the bottom of the lake during the frozen period.

In order to clarify the source of the bottom spring water, the bottom spring water is compared with the groundwater in the Lake Hulun basin and the lakeshore spring water, and the hydraulic relationship between these water bodies is explored through their hydrogeochemical characteristics and water quality index values. The contents of TN, DO, and NH₄⁻N in the bottom springs are all outside the ranges of the contents in groundwater, and the dissolution of alumino-silicate minerals in the bottom springs is very similar to that in the lakeshore springs and the G16 groundwater points. For example, the NH₄⁻N and TN contents of the bottom spring are similar to those of the lakeshore spring and the G16 groundwater. The replenishment source for the bottom spring water is not the infiltration of the diving aquifer but the confined aquifer. The lake bottom spring water, lakeshore spring water, and G16 groundwater water have some similar characteristics, and the lake bottom spring water, lakeshore spring water, and G16 groundwater point are all located just above the Xishan Fault, indicating that the initial water source of these three water bodies may be related to the Xishan Fault, and the supply source may come from the confined aquifer in the same period. Afterward, the water quality and ionic characteristics change due to different hydraulic exchanges.

In addition to the hydrogeological cycle, there is also a deep cycle in which groundwater transfers water across basins for a long period through a water conduction channel
in the middle crust or upper mantle lithosphere which was formed by shrinkage cracks generated as volcanic lava cools [53]. The formation of Lake Hulun iwas related to volcanic eruption and magmatic activity. Severe magmatic activity occurred in the Hulun Buir area during the Cenozoic period [54]. With the continuous compression of the Earth’s crust at the end of the Tertiary period of the Cenozoic period, the Cretaceous Damoguaihe Formation stratum (K1d2), with a roof buried depth of 441 m and an aquifer thickness of 8 m, underwent hydraulic exchange with phreatic water and lake water through the Xishan Fault zone, which was generated by a crust fault and produced different spatio-temporal responses in different periods [55]. This mode of hydraulic exchange is similar to the discontinuous permafrost zones of the Qinghai–Tibet Plateau [56]. As shown in Figure 6, the Lake Hulun basin may receive an exogenous confined water inflow through the basalt channel during the period of freezing [57–59]. In the process of recharging with confined water, the spring water at the bottom of the lake is first supplied from the deep, confined aquifer to the loose-sediment phreatic aquifer under the lake through the fault zone; it then interacts with the lake water through the phreatic aquifer and soon mixes with the lake water after entering the lake. The water characteristics of the spring point are similar to those of the lake water.

![Figure 6. Channel through which spring in lake bottom supplies Lake Hulun.](image)

From 1963 to 2016, the annual average groundwater recharge of Lake Hulun was 0.43 km³/a [56]. Over those fifty-four years, the water exchange between Lake Hulun and the groundwater fluctuated greatly; the regularity was not significant, but the overall conclusion was that Lake Hulun was mainly supplied by groundwater, and the average annual amount of groundwater recharge accounted for more than 20% of the total annual water inflow into the lake; in only a few years, especially in the lake’s water level recovery period, the lake water was mainly supplied by groundwater [60]. For example, in 1998, the lake discharged 0.82 km³ into underground runoff, accounting for −25.52% of the lake’s water supply source. In 2000, groundwater runoff supplied 0.88 km³ of the lake’s water, accounting for 59.60% of the lake’s water supply. In 2013, the lake discharged 1.86 km³ into underground runoff, accounting for −41.87% of the lake’s water supply source [61]. The interaction between lake water and groundwater is large and very complex. The recharge of Lake Hulun with bottom spring water is another main means of interaction between the lake and the groundwater. According to records, the spring water gushing out of the bottom of the lake is one of Lake Hulun’s water supply sources, and the annual maximum supply of water can reach 0.3–0.4 km³ [62]. The long-term variation in water recharge from the bottom spring may have caused the interannual difference in the interaction between groundwater and lake water in Lake Hulun.
5. Conclusions

In this study, we analyzed the difference between the spring water in a lake bottom and lake water through a comparison of their hydrogeochemical characteristics and water quality evaluation parameters and explained the mechanism of lake ice weakness in the bottom spring area through an analysis of lake flow dynamics. We then compared ion and water quality characteristics between the bottom spring, the surrounding groundwater, and the spring near the lakeshore to determine the source of the bottom spring. Finally, we analyzed the channel supplying the spring at the lake bottom to Lake Hulun in combination with the topographic characteristics of Lake Hulun. The main conclusions are as follows:

(1) There is an outcrop of spring water at the bottom of Lake Hulun which is related to the large NNE Fault on the west bank of Lake Hulun. There are obvious differences between spring water at the lake bottom and lake water regarding lake ice thickness, ion characteristics, and water quality characteristics.

(2) The source replenishing the spring water at the lake bottom is not the infiltration recharge of the phreatic aquifer but the vertical recharge of the confined aquifer due to the influence of the Xishan Fault zone.

(3) The Lake Hulun basin may receive a confined water supply through basalt channels during the frozen period. The spring water at the lake bottom is first supplied from the deep, confined aquifer to the loose-sediment phreatic aquifer under the lake through the fault zone, and it then interacts with the lake water through the phreatic aquifer.

This study improves our understanding of the control cycle of lake groundwater systems in cold and arid regions. However, research on the location of the bottom spring in Lake Hulun was not carried out. In addition, the interannual interaction between the vertical groundwater and the lake and its proportion in the lake water supply source are not clear.

Author Contributions: H.G.: conceptualization, investigation, methodology, writing—original draft, and writing—review and editing; S.Z.: formal analysis, project administration, and writing—review and editing; W.L.: formal analysis, project administration, writing—review and editing; Y.T.: writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Natural Science Foundation of China under contracts No. 52160021 and 51669021, by the Natural Science Foundation of Inner Mongolia under contract No. 2021MS05043, by the Major Science and Technology Projects in the Inner Mongolia Autonomous Region (2020GG0009), and by the National Basic Research Program of China under contract No. 2019YFC0409205.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

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

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