Abstract: As the main scavenge port of groundwater in the karst water system, most of the karst springs affected by human activities experienced discharge attenuation phenomenon in the north of China. Whilst artificial replenishment measures have been taken to keep water spewing, the results are not ideal in many karst springs. This is mainly because of poor understanding about the recharging water sources. This paper used the Jinan Spring region as an example to discuss about different spring water supply sources. Based on a wide range of methods (e.g., dynamic observation of spring water level, real-time monitoring of water temperature and electrical conductivity (EC), tracer test, and frequency analysis), this study obtained several findings. First, the maximum karst-fractured water proportion that Cambrian Zhangxia Formation contribute to the Zhenzhu Spring is 57–59%, and the Heihu Spring only recharges 25–31%. Second, the proportion of fracture-karst water to the Heihu Spring from the Fengshan Formation to the Sanshanzi Formation of the Ordovician is 69–75%, while the proportion of the Tanxi spring is 15–17%. Third, the Baotu Spring and Heihu Spring mainly receive karst-fractured water from the Cambrian Zhangxia Formation and fracture-karst water from the Cambrian Fengshan Formation to the Ordovician Sanshanzi Formation. The supply sources of the Zhenzhu Spring and Tanxi Spring are more diverse, including karst-fractured water of the Cambrian Zhangxia Formation and fracture-karst water of the Cambrian Fengshan Formation to the Ordovician Sanshanzi Formation, as well as a small amount of pore water and fissure water, artificial recharge water supply. Fourth, the frequency analysis of spring water temperature indicated that the Zhenzhu Spring and Tanxi Spring are mainly in deep circulation, while the Baotu Spring and Heihu Spring are predominantly in shallow circulation. The differences in the sources of the four largest spring groups suggest that the karst water movement in Jinan has heterogeneous characteristics. The determination of the mixing ratio of the sources of spring water supplies provides a scientific basis for the protection of spring water, and the implementation of artificial recharge projects.

Keywords: CFD; recharging source; karst water; karst spring; Jinan

1. Introduction

Karst areas are widely distributed worldwide with various forms which are valuable tourism resources [1]. They often develop underground karst holes and karst fissures, which create a
concentrated drainage area of karst water-bearing system; and form large karst springs and water resources [2]. However, these karst areas are also considered as vulnerable area of geological environment. Specifically, the highly anisotropic and heterogeneity of karst development makes it difficult to control when hydrogeological problems occur in these karst areas [3].

Detailed description about groundwater circulation conditions is always a challenge in the research of karst water system. To calculate the replenishment of karst water system, numerous methods can be employed, such as the hydrogeological condition analysis method [4–6], hydrochemical method [7–9], isotope method [10–13], and the consequences have been acquired by utilizing the comprehensive analysis of methods mentioned above [14,15]. On the macroscopic scale, groundwater recharge sources mainly include the atmospheric precipitation, surface water, condensed water, and etc. For the small-scale local aquifers, there may be lateral runoff recharge, vertical leakage recharge, and artificial recharge [16]. The atmospheric precipitation infiltration is complex process, because the total annual precipitation, precipitation characteristics, lithology and thickness of the aerated zone, topography, and vegetation influence the amount of groundwater recharge from precipitation infiltration [17]. Aiming at the impact of the dynamic changes of the surface environment, Daniel Bittner [18] and Chloé Ollivier [19] proposed a new semi-distributed model to discuss the impact of heterogeneity at different degrees on aquifer flow and proved this method has wide adoptability, but it did not refer to the recharge ratio of different karst aquifers. For the karst water-containing media, the infiltration mechanism is more complex. There are piston type infiltration and short circuit type infiltration. Typical karst carbonate aquifers contain a series of funnels, sinkholes and shafts leading to the groundwater surface, as well as impervious areas with poor permeability. Thus, it is difficult to accurately obtain the precipitation infiltration coefficient. The underground runoff is often calculated using the Darcy formula. Unfortunately, the karst aquifers have great heterogeneity, including large-scale karst channels, very small cracks and even pores. Due to the coexistence of laminar and turbulent flows [20], the uniform hydraulic connections and local hydraulic connections are poor [21]. Therefore, it is difficult to accurately calculate the cross-sectional flow of karst aquifers using the Darcy formula. In addition, isotopes are constrained by distance scales, pollutants released by human activities and hydrogeochemistry. Hence, the calculation of recharge sources for the karst water systems containing multiple aquifers is also limited.

Whilst the medium field and hydrodynamic field of a karst water system are highly complex, a typical karst water system has the characteristics of a concentrated drainage area (e.g., spring water). Therefore, some easy-to-obtain indicators (e.g., spring water flow, water temperature, EC, and pH) analysis can reveal the hydrogeological issues (such as the supply source of karst water system). For example, conducted the short-term scale (i.e., hourly and daily scale) of trace experiments and introduced transfer function approach to describe the transport of fluorescent dye solutes [22], through long-term monitoring of the chemical characteristics of spring water, revealed the origin of spring water and showed inversely how the law of karst water system changes [23], the conductivity frequency distribution (CFD) method is used to determine the composition of the source of spring water supply [24], stage of karst development [25,26], and etc. [27,28]. The frequency of spring water temperature analysis method is used to analyze the depth of groundwater circulation and others.

Karst areas are widely distributed in the north of China. In Shandong and Shanxi provinces, most of the karst areas contain concentrated discharge zones of spring water. Specifically, the Baotu Spring in Jinan is a typical representative of big karst springs in the north of China. Briefly, Jinan is a well-known "spring city". Since the 1970s, a large number of groundwater in the spring area have been exploited due to human activities, resulting in the interruption of spring water flow. To restore the continuous gusher of famous springs, artificial replenishment has been performed successively in the recharge area of the spring group since 2003 [29]. Nevertheless, the spring water in the withered water period is still threatened by the flow. For example, the largest daily replenishment source was up to $4.0 \times 10^5$ m$^3$/day in 2018. On June 18, 2019, the Heihu Spring broke off, and the water level of the Baotu Spring and Heihu Spring was 27.46 m and 27.39 m, respectively. This indicates that the existing
Artificial replenishment activities failed to stop the falling spring water level. In this sense, studying the source and proportion of spring replenishment is important for precisely identify the source location.

Based on previous studies, combined the spring water level and spring discharge data, we explore the contribution rates of different aquifers to spring water in accordance to the tracer tests, EC, and water temperature frequency distribution methods. We also determine the recharge sources and proportions of different aquifers. This study should provide a scientific basis for the implementation of artificial replenishment measures in Jinan and protection of other springs.

2. Study Area

The Jinan spring area is located in the inland mid-latitude zone which is characterized by the temperate monsoon climate. The average annual rainfall is 645 mm. The atmospheric precipitation is the main source of spring water supply [30]. The terrain is high in the south and low in the north, with a relative height difference of 30–650 m and a total area of 1114 km². The Jinan spring area is based on the Archean Eonothem Taishan Group (Art), overlying the Cambrian and Ordovician strata, and the strata inclines to the north, forming a monoclinic structure (Figure 1). The exposed and semi-exposed Ordovician limestone and the limestone of the Fengshan Formation of the Cambrian are the direct recharge zones of the karst water system, with an area of 318.7 km²; while the southern exposed Cambrian Zhangxia Formation limestone is an indirect supply area, with an area of 201.61 km². In the Cambrian, the relative confining bed of the Changshan Formation and Gushan Formation blocked the hydraulic connection between the karst water in the upper fissure and the karst water in the lower fissure. The groundwater tends to migrate northward along the stratum. It meets the Yanshanian intrusive rocks in the north to form four major spring groups. There are 118 dew springs in the range of 2.6 km², of which there are 32 springs in the Baotu Spring Group and 43 in the Zhenzhu Spring Group. There are 29 springs in the Wulongtan Spring Group, and 14 springs in the Heihu Spring Group. Under natural conditions, spring water is the main drainage form of the karst water system. In 1972–2003, spring water was intermittently cut off due to excessive exploitation of groundwater. Since 2003, measures such as the artificial replenishment and closure of groundwater sources have been implemented [31]. Whilst these measures achieved a continuous gush of spring water, the spring water level has not been restored to its natural state in the 1960s.
3. Materials and Methods

3.1. Dynamic Monitoring of Spring Water Quality, Water Temperature, and Water Level

The water levels of the Heihu Spring and Baotu Spring are measured using wireless telemetering water level gauges with an accuracy of 1 mm and an observation frequency of once per day. These water levels have been continuously observed since 2003. Due to the large number of spring points, four single springs with relatively large flow rates, namely the Baotu Spring, Heihu Spring, Tanxi Spring and Zhenzhu Spring, were selected to monitor their real-time temperature, pH and EC. They represent the water quality dynamics of the four spring groups, namely the Baotu Spring Group, Heihu Spring Group, Wulongtan Spring Group and Zhenzhu Spring Group. Since 2013, field measurement has been conducted at a frequency of once per week. The measurement device is the Aqua TROLL 600 multi-parameter detector, with the electrical conductivity (EC) accuracy of ±0.1 µS·cm⁻¹ and temperature observation accuracy of ±0.01 °C.
3.2. Tracer Test

The tracer selected for the tracer test was ammonium molybdate \((\text{NH}_4)_6\text{Mo}_7\text{O}_{24}\cdot4\text{H}_2\text{O}\). The peak amount of molybdenum ion concentration at the spring water receiving point was 15 ppb. This amount was estimated based on the characteristics of the flow field in the study area, and the formula for the amount of tracer \([32]\). The first tracer test was performed at Cuima Village (Figure 2). In that test, 250 kg of ammonium molybdate was dropped into the source hole with a depth of 201.8 m, and the water level was buried at a depth of 49.65 m. The release strata were the Cambrian Zhangxia Formation aquifer, with a total of eight spring water sampling sites and 29 karst water sampling sites of the Cambrian and Ordovician limestone. In the second tracer test, a reagent was placed in the Quanlu River Channel, and ammonium molybdate was injected into the channel sinkhole so that it entered the Cambrian Zhangxia Formation limestone aquifer. In that test, 44 Cambrian Zhangxia aquifer sampling wells were arranged. There are 18 Ordovician aquifer sampling wells and seven spring sampling points for a total of 5216 tests. The third tracer placement point was the Xingji River. The exposed stratum in the channel was the Cambrian Fengshan Formation limestone, with 17 karst water monitoring points and 10 spring water monitoring points.

![Figure 2](image-url)

**Figure 2.** Map of tracer monitoring points. 1: fault; 2: magmatic rock; 3: Cambrian Fengshan Formation bottom limit; 4: spring group; 5: Cambrian Zhangxia aquifer monitoring point; 6: Ordovician aquifer monitoring point; 7: tracer drop well in Cuima village; 8: tracer drop river course in leakage section of Xingji and Quanlu river.

For each tracer test, we dissolved all ammonium molybdate in water before putting it in, and started monitoring after the reagent was put in for eight hours. The monitoring frequency varied from one to five days depending on the groundwater flow direction. The Shimadzu atomic absorption spectrophotometer AA7000-graphite furnace method and ICPMS were used for the molybdenum ion test. Among these tests, the Xingji River tracer test determined the runoff characteristics of the recharge area; the Cuima tracer test and Quanlu tracer test revealed the hydraulic relationship between the Cambrian Zhangxia Formation karst water and the Ordovician karst water.

3.3. Frequency Decomposition Method

Regarding the research of spring water recharge, there are two methods which are capable of being adopted into frequency analysis. One is to establish the conceptual reservoir model and use Fourier spectra analysis to study the relationship between the spectral changes of natural tracers and different discharges within the model \([33]\). This method requires high requirements for hydrogeological
conditions and data in the study area, therefore, compared with the above methods, we choose the simple method-the CFD.

For groundwater from a single recharge source, its conductivity and water temperature frequency should show a normal distribution, and the value should fluctuate within a certain range. In the north of China, there are the Ordovician carbonate strata with a thickness of thousands of meters. The lithological composition and karst fissures in different layers are unevenly developed. The degree of connectivity between the different areas and the atmosphere is very different. Due to various groundwater runoff pathways and different sizes of runoff channels, a variety of recharge sources have mixed the karst spring water. In a sense, the values of spring EC and water temperature of the karst spring water reflect the combined outcome due to the superposition of multiple supply sources. A Gaussian fitting function can be used to fit the frequency data, given by:

\[ y = a_0 \exp \left[ -\frac{1}{2} \left( \frac{x - a_1}{a_2} \right)^2 \right] \]  

where \( x \) is the test data, \( y \) is the frequency data, \( a_0 \) is the curve peak, \( a_1 \) is the peak center value, and \( a_2 \) is the peak width.

Through multiple iterative fitting, the peaks of the frequency curve (including the peaks hidden in the original curve) are obtained [24]. The EC of spring water and water temperature are affected by different factors. The EC of spring water is affected by the precipitation, surface water, formation lithology, length of migration pathways, leakage, hydrogeochemical process, artificial recharge and other factors. The temperature of spring water is influenced by the cycle depth, air temperature, artificial replenishment and groundwater mixing in different aquifers. Different influencing factors and degrees of influence would cause differences in the conductivity and water temperature of the four major springs. To this end, the wave crest analysis of frequency curve can distinguish the influence degree or contribution degree of different influencing factors to the spring water.

4. Results and discussion

4.1. Dynamic Characteristics of Spring Water

4.1.1. Characteristics of the Conductivity Duration Curves of the four spring groups

According to the statistics of the measured conductivity data of the four springs from January 2015 to December 2018 (Figure 3 and Table 1), the EC curve of the springs of the same spring group is stable, and the range is less than 100 µS·cm\(^{-1}\). There is a large difference in the conductivity of springs between different spring groups. In general, the relative EC of the four major spring groups in descending order is: Heihu Spring > Baotu Spring > Tanxi Spring > Zhenzhu Spring.

![Dynamic chart of the electrical conductivity (EC) of spring water.](image)

**Figure 3.** Dynamic chart of the electrical conductivity (EC) of spring water.
Table 1. Characteristic values of the EC of spring water.

| Spring name      | Average Value/(µS·cm⁻¹) | Minimum Value/(µS·cm⁻¹) | Max/(µS·cm⁻¹) |
|------------------|-------------------------|-------------------------|---------------|
| Heihu Spring     | 896                     | 851                     | 931           |
| Baotu Spring     | 778                     | 743                     | 810           |
| Tanxi Spring     | 709                     | 677                     | 773           |
| Zhenzhu Spring   | 682                     | 641                     | 742           |

4.1.2. Characteristics of the Temperature Duration Curves of the Four Spring Groups

According to the monitoring data of the spring water temperature of the four major springs from September 2016 to September 2018 (Figure 4), the spring water temperature narrowly fluctuates between 16 and 19 °C. The relative temperature of the spring water follows this ascending order: Heihu Spring ≤ Baotu spring < Tanxi Spring < Zhenzhu Spring.

![Figure 4. Curves of the water temperature duration of the four major springs.](image)

Theoretically, the temperature of groundwater in deep circulation is high and stable, while the temperature of the Zhenzhu Spring and Tanxi Spring is high, but the temperature range and the dispersion coefficient are lower than those of the Heihu Spring and Baotu Spring (Table 2). The highwater temperature range and dispersion coefficient of the Zhenzhu Spring and Tanxi Spring indicate that its supply source is different from the Baotu Spring and Heihu Spring.

Table 2. List of characteristic values of spring water temperature data.

| Spring Name | Observation Date       | Average Value/(°C) | Range/(°C) | Standard Deviation | Dispersion Coefficient |
|-------------|------------------------|--------------------|------------|--------------------|------------------------|
| Heihu Spring| 2016/9–2017/9          | 17.24              | 2.50       | 0.6358             | 0.0369                 |
|             | 2017/9–2018/9          | 17.28              | 3.30       | 0.7974             | 0.0462                 |
| Baotu Spring| 2016/9–2017/9          | 17.18              | 2.70       | 0.6758             | 0.0393                 |
|             | 2017/9–2018/9          | 17.50              | 3.95       | 0.9403             | 0.0537                 |
| Tanxi Spring| 2016/9–2017/9          | 17.59              | 3.00       | 0.8925             | 0.0508                 |
|             | 2017/9–2018/9          | 17.65              | 4.18       | 1.3250             | 0.0751                 |
| Zhenzhu Spring| 2016/9–2017/9        | 17.74              | 4.00       | 1.1319             | 0.0638                 |
|             | 2017/9–2018/9          | 17.62              | 4.62       | 1.3622             | 0.0773                 |
4.2. Frequency Fitting Results

4.2.1. EC Frequency Fitting Results

EC fitting results of Baotu Spring and Heihu Spring

Based on the long-term monitoring data calculations, the CFDs of the Baotu Spring and Heihu Spring show two included peaks (Figures 5 and 6, P is the peak area), and the two peak areas account for a certain proportion of the total area. Table 3 presents the CFD ratio of the Baotu Spring and Heihu Spring. The CFDs of the Baotu Spring reveals that $P_1$ accounts for 31–54%, and $P_2$ accounts for 45–69%. The CFDs of the Heihu Spring demonstrates that $P_1$ accounts for 25–31%, and $P_2$ accounts for 69–75%.

![Figure 5. The conductivity frequency distributions (CFDs) of the Baotu Spring.](image)

![Figure 6. The CFDs of the Heihu Spring.](image)

| Spring. | Date | $P_1$/% | $P_2$/% | Q/(m³·s⁻¹) |
|---------|------|---------|---------|------------|
| Baotu spring | 2015 | 53.85 | 46.15 | 0.37 |
| | 2016 | 43.42 | 56.58 | 0.64 |
| | 2017 | 31.33 | 68.67 | 0.69 |
| | 2018 | 54.55 | 45.45 | 0.58 |
| Heihu spring | 2015 | 27.63 | 72.37 | 0.39 |
| | 2016 | 24.67 | 75.33 | 0.63 |
| | 2017 | 31.27 | 68.73 | 0.47 |
| | 2018 | 31.21 | 68.79 | 0.46 |
Fitting Results of the Zhenzhu Spring and Tanxi Spring

The CFDs of the Zhenzhu Spring and Tanxi Spring are both multimodal (Figures 7 and 8). The ratios of the CFDs of the Tanxi Spring and Zhenzhu Spring reflect that in the CFDs of the Tanxi Spring (Table 4), \( P_1, P_2, P_3, P_4 \) account for 58–68%, 15–17%, 9–21%, and 6%, respectively. In the Zhenzhu spring CFDs, \( P_1, P_2, P_3, P_4 \) account for 57–59%, 22–25%, 13–14%, and 5–6%, respectively.

![Figure 7. The CFDs of the Tanxi Spring.](image)

![Figure 8. The CFDs of the Zhenzhu Spring.](image)

| Spring Name    | Date   | \( P_1/\% \) | \( P_2/\% \) | \( P_3/\% \) | \( P_4/\% \) |
|----------------|--------|--------------|--------------|--------------|--------------|
| Tanxi Spring   | 2017   | 58.09        | 14.97        | 21.04        | 5.89         |
|                | 2018   | 68.09        | 17.36        | 8.71         | 5.84         |
| Zhenzhu Spring | 2017   | 57.29        | 24.66        | 12.93        | 5.12         |
|                | 2018   | 58.62        | 21.89        | 13.74        | 5.76         |

4.2.2. Characteristics of the Temperature Duration Curves of the Four Spring Groups

Based on the spring water temperature data of the four major spring groups in 2016–2018, the water temperature frequency distribution curve is plotted (Figure 9). The Baotu Spring and Heihu Spring both show three peaks, while the Tanxi Spring and Zhenzhu Spring show 4–5 peaks.
4.2.2. Characteristics of the Temperature Duration Curves of the Four Spring Groups

Based on the spring water temperature data of the four major spring groups in 2016–2018, the water temperature frequency distribution curve is plotted (Figure 9). The Baotu Spring and Heihu Spring both show three peaks, while the Tanxi Spring and Zhenzhu Spring show 4–5 peaks.

4.3. Mixing Ratio of the Sources of the Four Major Spring Groups

4.3.1. Tracer Test Reveals that Spring Water Is Recharged by the Ordovician Fractured Karst Water and Cambrian Karst Fractured Water

The Xingji River tracer test in the Ordovician limestone and the Cambrian limestone’s Cuima and Quanlu tracer tests show the following (Figure 10):

(1) The fault structure is an important channel for the hydraulic connection between the limestone aquifer in the Zhangxia Formation and the Ordovician karst water. The tracer dropped at Cuima village migrated northward in the Zhangxia limestone aquifer. The tracer was detected in a large area in the northern Ordovician limestone-igneous rock contact zone, and the fault zone has good water conductivity. For example, A6 at the monitoring point is farther from the tracer drop point than A5. However, it is close to the fault zone, and its initial peak arrival time is earlier than A6.

(2) The velocity of karst-fractured water in the Zhangxia Formation is smaller than that in the Ordovician. The apparent velocity in the detection area of the Cuima tracer test is 88–489 m/day, and the maximum velocity is along the fault zone. The groundwater flow velocity along the fault structure zone in Quanlu test area is 100–148 m/day, and the groundwater velocity away from the
influence zone of the fault structure is 50–75.8 m/day. The Xingji River test is closely related to spring water, and the karst fissures developed in the Baotu Spring Group, Wulongtan Spring Group, and Zhenzhu Spring Group are well developed.

![Figure 10. Schematic diagram of tracer test movement. 1: fault; 2: magmatic rock; 3: Cambrian Fengshan Formation bottom limit; 4: tracer diffusion concentration isochrons; 5: tracer transport direction; 6: tracer undetected area; 7: tracer detection range; 8: tracer drop river; 9: spring groups; 10: Cambrian Zhangxia aquifer monitoring point; 11: Ordovician aquifer monitoring point; 12: tracer drop point.](image)

Tracer tests show that there is a hydraulic connection between the Ordovician Sanshanzi Formation karst water and Cambrian karst water. They supply water to the spring groups, and there is a large difference in connectivity and groundwater movement.

4.3.2. Spring Water Dynamics Reflect Differences in Supply Sources

In nature, the typical thickness of carbonate strata is more than hundreds of meters. For example, the thickness of the Ordovician limestone and Cambrian limestone in the study area is up to several kilometers. The permeability of carbonate rocks with fissure or karst fissure is generally anisotropic, and the permeability of the strata generally decreases with the buried depth, with the characteristics of upper strength and lower weakness [29]. The carbonate rocks deposited by stratification are different in vertical lithology, so the permeability of the strata is also different, which leads to the existence of a water-impermeable layer or a weakly permeable layer between the two rock layers. For example, the Gushan Formation and Changshan Formation in the study area do not have developed karst, but own certain water-repellent properties. These properties separate the upper Fengshan Formation from the lower Zhangxia Formation aquifer, and hinder the hydraulic connection between the deep Zhangxia water-bearing system and the shallow Ordovician-Fengshan Formation water-bearing system (Figure 11).

![Figure 11.](image)

The karst observation of the cores near the four spring groups revealed that void types (e.g., pores, solution crack, fissures, and karst caves coexist in the karst aquifer) form the storage space and runoff channel of the karst water system in Jinan. The depth above 100 m is primarily the limestone of the Ordovician Sanshanzi Formation, with karst developed. The development rates of karst caves at the depths of 10–20 m, 30–40 m, 60–70 m, and 70–80 m reach 10.92%, 16.15%, 17.46%, and 17.31%, respectively. The buried depth of 100-200 m contains the limestone of Changshan Formation and Gushan Formation, and the fissure is not developed. The depth below 300 m is primarily the limestone of the Zhangxia Formation, with fissures developed. Recent drilling statistics suggested that the karst development rate of the Ordovician Sanshanzi Formation limestone aquifer was higher than 50%, and the deep Cambrian karst rate was lower than 20% [29]. Apparently, in the vertical direction,
the karst development degree near the spring group gradually weakens with increasing depth. The shallow-buried Ordovician limestones have developed cracks and karsts, but the deep-buried Cambrian Zhangxia Formation has low karst development, mainly karst cracks. Therefore, during the wet season, shallow karst pipeline flows and karst cave flows can receive concentrated atmospheric precipitation replenishment quite quickly, and the spring water levels rise. According to the long-term records of the Baotu Spring and Heihu Spring (Figure 11), the spring water level shows the characteristics of rapid rise in the wet season and long-term decay in the dry season. When the water level of the Baotu Spring is lower than 28.67 m, it is lower than that of the Baotu Spring. When the water level of the Heihu Spring is around 28.67–28.81 m, the water level of the Heihu Spring and Baotu Spring differs by −0.01–0.01 m, and the elevations of the two are basically the same. When the water level of the Heihu Spring exceeds 28.81 m, it is higher than that of the Baotu Spring. Relative to the Baotu Spring, the shallow karst in the spring water recharge area of the Heihu Spring is more developed, and the rainfall infiltration is rapid.

The monthly spring flow curve (Figure 12) demonstrates that the spring flow of the Heihu Spring in the wet season rises and falls rapidly, indicating the development of shallow karst which can quickly receive atmospheric precipitation infiltration and discharge through the spring water. The instability coefficient of spring discharge of the Heihu Spring is the smallest, which belongs to the instability spring. Compared to the Heihu Spring and Baotu Spring, the change of the flow rate of the Zhenzhu Spring in the dry season is significantly lower, which belongs to the stable spring. This reflects the high proportion of karst water replenishment of the Zhangxia Formation from the deep circulation of the Zhenzhu Spring water. The slow release of water from the karst fissure flow and the solution crack matrix flow maintain the stability of the Zhenzhu Spring water. It can be seen that the flow dynamics of the four major spring groups reflect the differences in the sources of spring water supply.

![Figure 11. Water level duration curve of the Heihu Spring and Baotu Spring.](image1)

![Figure 12. Monthly flow curves of the four major springs.](image2)
4.3.3. Magmatic rock barrier changes groundwater runoff pathway near the spring group

The Yanshanian magmatic rock barrier is the main driver of the Formation of Jinan spring water. After the invasion of magmatic rock, it experienced a long period of erosion and gradually formed the ascending springs, such as the Baotu spring (Figure 13a) and Heihu spring (Figure 13b). The magmatic rock intrusion has developed secondary tectonic fissures in the contact zone of limestone and magmatic rocks and a certain area above it. Furthermore, the permeability of the local contact zone was enhanced which developed contact springs, such as the Zhenzhu and Tanxi spring (Figure 14).

![Figure 13. Schematic diagram of geological section. (a) I-I'; (b) II-II'.](image)

1: Quaternary clay; 2: Ordovician carbonate; 3: Cambrian Fengshan Formation limestone; 4: Cambrian Gushan Formation and Changshan Formation limestone; 5: Cambrian Zhangxia Formation limestone; 6: magmatic rock; 7: groundwater flow line; 8: spring group; 9: water level; 10: karst cave.

![Figure 14. Geological three-dimensional structure of the spring.](image)

1: boring number; 2: spring; 3: cohesive soil; 4: gravel layer; 5: limestone; 6: magmatic rock.

From the regional hydrogeological conditions, the Cambrian Fengshan Formation-Ordovician limestone is a unified aquifer, while the Changshan Formation-Gushan Formation has no karst development and has certain water permeability. The tracer tests confirm that the Cambrian Zhangxia Formation aquifers have a hydraulic connection with the spring water [26]. This indicates that the connection between the fault zone and the igneous rock contact zone enabled the spring group to be recharged by both the Ordovician Formation-Fengshan Formation aquifer and Zhangxia Formation aquifer.

In addition, the geological structure can affect the recharge conditions of the spring group. There is a tension fault cutting limestone aquifer in the southwest of the Baotu Spring (Figure 13a). The karst water of the Zhangxia Formation is mixed into the Ordovician aquifer along the fault zone. Since the igneous rocks (with a thickness of more than 150 m) cover the Ordovician limestone, the
Baotu Spring has good compressive pressure. Nevertheless, the southeast of the Heihu Spring lacks magmatic rock block (Figure 13b), and there are more karst caves distributed in the borehole along the section line direction. The shallow karst in this direction is more developed and able to receive precipitation quickly.

From the stratigraphic structure near the spring group (Figure 14), the Heihu Spring and Baotu Spring are overlying conglomerates with thicknesses of 15 m and 8.5 m, respectively, and the Ordovician limestone below, without the Quaternary clay cover. However, diorite is absent from the Baotu Spring, the spring water is exposed through the skylight, and there is no recharge of pore water and fissure water. Most of the Ordovician karst water intercepted by the Baotu Spring and Heihu Spring flows from south to north.

The distribution of the Zhenzhu Spring and Tanxi Spring area is characterized by a relatively stable clay layer, with thickness of 6–9 m and local inclusion of consolidated conglomerate. The thickness of diorite is stable at 35–40 m. The Zhenzhu Spring and northern Tanxi Spring are blocked by huge diorite. The Ordovician and Cambrian karst water passes through the diorite structure fissures and emerges as a spring through the gravel layer and clay layer. Therefore, the Zhenzhu Spring and Tanxi Springs have the Ordovician Sanshanzi Formation karst water from the southern runoff and deep Zhangxia Formation karst water that surges along the contact zone between the diorite and limestone. Due to the pressure of the Ordovician and Cambrian karst water, the Ordovician and Cambrian karst water penetrates the diorite and quaternary loose layers, carries pore water and intrusive rock fissure water and drains through spring water. Since the quaternary loose layer and diorite weathering fissures are extremely poor in water yield property, there is less pore water and magmatic rock fissure water mixed with spring water. Hence, there are differences in the spring formation and supply sources of the four spring groups.

### 4.3.4. Mixing Ratio of Spring Water Supply Source

Large karst spring is the concentrated discharge outlet of karst water system. The change of conductivity in spring reflects the contribution rate of different recharge water sources in the system. The frequency distribution of conductivity depends on the source of the water, and different peaks reflect the contribution of different quality currents to karst water. Therefore, the CFD can distinguish the contribution of water from different sources to spring water. Since the method has been proposed, the research on karst water systems in Spain and France has applied it [4]. As mentioned earlier, the frequency decomposition method (Formula 1) can decompose the peaks contained in the diachronic curve in detail, and after the verification of the four annual data from 2015 to 2018, the number of peaks in the CFD curve is fixed, indicating that the types of spring replenishment sources are relative fixed. It should be noted that the source of recharge determined by frequency analysis of conductivity must be consistent with the characteristics of the stratum structure, aquifer type, water temperature and other characteristics.

### Spring Water Temperature Fitting Results Reveal Spring Water Replenishment Source

According to the spring water temperature monitoring data (Figure 4), extreme values of spring water temperature occurred in winter and summer, indicating that the karst water system is an open system. The temperature of the shallow circulation groundwater has increased due to the influence of atmospheric temperature, therefore, the water temperature frequency curve shows two peaks, i.e., high and low. The frequency of spring water temperature suggests that three peaks appeared in the frequency curve of spring water temperature of the Heihu Spring and Baotu Spring (Figure 9a,b). The peaks P1 and P3 of the Heihu Spring and Baotu Spring are explained as the recharge of spring water by shallow cyclic Ordovician karst water influenced by atmospheric temperature. The deep cycle is less affected by atmospheric temperature, the temperature of groundwater changes is small, and the frequency curve becomes a single peak. Therefore, P2 is the recharge of karst fissure water of the Zhangxia Formation in deep cycle.
Similar to the Heihu Spring and Baotu Spring, the peaks P1, P2, and P3 of the temperature frequency curve of the Zhenzhu Spring and Tanxi Spring represent the recharge of the Ordovician karst water to the spring water. Relative to the Heihu Spring and Baotu Spring, deep karst-fractured water provides higher supply to the Zhenzhu Spring and Tanxi Spring. To ensure the stable spring water flows in the dry season, artificial replenishment is carried in the dry season (from February to July) when the temperature is high. Artificial recharge water is significantly affected by temperature. The impact caused the temperature difference of spring water to rise during the source period and the degree of dispersion increased (Table 2). Therefore, the P4 and P5 peaks in the higher temperature zone represent the recharge of spring water by artificial recharge water, pore water and fissure water (Figure 9c,d). In view of the low contribution of pore water and fissure water to spring water in the dry season, the lowest temperature peaks cease to appear in the Zhenzhu Spring and Tanxi Spring.

The Recharge Source of the Baotu Spring and Heihu Spring

The frequency analysis of the EC of the Heihu Spring and Baotu Spring indicates that the positions of P1 and P2 in CFDs are relatively unchanged in the past years. This means that the spring water has been replenished by two water source components for many years and is unaffected by the external environment. Based on the conclusion that the Baotu Spring and Heihu Spring mainly accept the recharge of Ordovician fracture-karst water and Cambrian Zhangxia Formation karst-fractured water, it is inferred that peak P1 and P2 are interpreted as the Ordovician fracture-karst water and Cambrian Zhangxia Formation karst-fractured water.

The shallow karst in the recharge area of the Heihu Spring is developed, and the precipitation replenishment can be obtained quickly. From the peak curve of the frequency curve of the spring discharge and the EC, it can be seen that P2 would occupy when the high-water level is high (Table 3). The proportion is significantly increased, and it is inferred that P2 represents the Ordovician karst water recharge source, while P1 represents the karst-fractured flow of the Zhangxia Formation. It can be deduced that the karst-fractured water supply of the Zhangxia Formation of the Baotu spring accounts for 31–54%; the Ordovician fracture-karst water supply of the Baotu spring accounts for 45–69%; the Zhangxia Formation karst-fractured water supply of the Heihu Spring account for 25–31%, and the Ordovician fracture-karst water replenishment accounts for 69–75%.

The recharge source of the Zhenzhu spring and Heihu spring

To evaluate the mixture ratio of recharge sources of the Zhenzhu Spring and Tanxi Spring, the water chemical composition and the EC of pore water, fissure water, karst water and artificial replenishment water near the spring group are determined (Table 5). K+ + Na+, SO4^{2-}, Cl− contents in the pore water and fracture water are significantly different from the karst water. The real-time monitoring records of the electrical conductivity in the field show that the conductivity values of different types of water sources in descending order are as follows: pore water and fissure water > artificial replenishment water > karst water. In CFDs, the value of conductivity is represented as the size of the central peak of the wave peak. In other words, in CFDs, the central peak of the wave peaks of pore water and fissure water in intrusive rocks is the largest, followed by supplementary water and karst water (i.e., the smallest one). Therefore, it is inferred that the P4 peak in the conductivity frequency curve of the Zhenzhu Spring and Tanxi Spring represents the recharge of pore water and fissure water; the P3 peak represents the recharge water replenishment; P1 is the karst fissure water replenishment of the Zhangxia Formation; and P2 represents the Ordovician karst water recharge. Specifically, the karst-fractured water supply of the Zhangxia Formation in the Tanxi Spring recharge source accounts for 58–68%; the Ordovician fracture-karst water supply accounts for 15–17%; the recharge water supply accounts for 9–21%; the pore water and weathering fissures water replenishment accounts for 6%. The Zhangxia Formation karst-fractured water replenishment accounts for 57–59% of the Zhenzhu Spring recharge source; the Ordovician fracture-karst water replenishment accounts for 22–25%; the
artificial replenishment water accounts for 13–14%; and the pore water and weathering fissure water replenishment accounts for 5–6% (Table 6).

Table 5. Summary of water chemical characteristics.

| Groundwater Type | Cation Content/(mg·L\(^{-1}\)) | Anion Content/(mg·L\(^{-1}\)) | EC/(µS·cm\(^{-1}\)) |
|------------------|----------------------------------|---------------------------------|---------------------|
|                  | K\(^+\) + Na\(^+\) | Ca\(^{2+}\) | Mg\(^{2+}\) | Cl\(^-\) | SO\(_4^{2-}\) | HCO\(_3^-\) | NO\(_3^-\) |                     |
| Pore water       | 114.29 | 152.32 | 24.7 | 130.34 | 450.68 | 317.88 | 45.1 | 1023                 |
| Fissure water    | 90.9 | 131.06 | 23.63 | 120.52 | 437.02 | 301.98 | 20.05 | 995                  |
| Artificial recharge water | 99.58 | 62.32 | 22.73 | 140.34 | 208.93 | 61.3 | 3.03 | 955                  |
| Baotu Spring Karst water | 14 | 103.45 | 19.05 | 26.02 | 88.15 | 263.44 | 35.44 | 744                  |
| Heihu Spring Karst water | 20.67 | 118.01 | 21.38 | 29.27 | 106.71 | 280.58 | 45.36 | 858                  |
| Zhenzhu Spring Karst water | 10.78 | 87.36 | 18.12 | 17.89 | 62.64 | 244.17 | 25.99 | 681                  |
| Tanxi Spring Karst water | 20.67 | 118.01 | 21.38 | 29.27 | 106.71 | 280.58 | 28.01 | 738                  |

Table 6. Connections of different types of groundwater to spring.

| Strata | Groundwater Type | Heihu Spring | Baotu Spring | Tanxi Spring | Zhenzhu Spring |
|--------|------------------|--------------|--------------|--------------|----------------|
| Cohesive soil | Pore water | 0 | 0 | 6% | 5–6% |
| Magmatic rock | Fissure water | 0 | 0 | 9–21% | 13–14% |
| Cambrian Fengshan Formation to the Ordovician Formation limestone | Cambrian Fengshan Formation to the Ordovician Formation fracture-karst water | Cambrian Zhangxia Formation limestone karst-fractured water | 69–75% | 45–69% | 15–17% | 22–25% |
| Cambrian Zhangxia Formation limestone | 25–31% | 31–54% | 58–68% | 57–59% |

4.3.5. Uncertainty Analysis

Uncertainty is a significant issue in the study of karst water systems. At present, scholars have implemented sensitivity analysis of model parameters and quantified uncertainty [34]. The key is to determine the hydrological processes in the study area [35], in order to determine the rationality of various parameters in the model. According to our research, the uncertainty of the calculation results of the mixing ratios of the four spring groups is mainly reflected in the large differences in mixing ratios in different years, for instance the proportions of the Baotu Spring recharged by the Ordovician Sanshanzi Formation fracture-karst water in 2017 was 1.49 times as large as that in 2018. However, this uncertainty does not affect the consistency of the calculation results with the hydrogeological conditions in the study area. This is to say that the Baotu spring discharge in 2017 was 1.86 times as large as the 2015 discharge, that is, the Ordovician limestone aquifer recharge ratio increased in the year when the spring discharge was large. Furthermore, it shows that Ordovician limestone aquifer is the main source of karst water system supply. The Baotu Spring and Heihu Spring with large spring flow mainly are recharged by Ordovician karst water. The temperature curve decomposition also shows that Baotu Spring and Heihu Spring are mainly shallow cycles. Therefore, the CFD analysis of the source of spring water recharge is in line with the actual conditions of the karst water system in Jinan.

5. Conclusions

The key findings of this study are:

(1) The CFD analysis of the Baotu Spring and Heihu Spring showed that there are two hidden wave peaks which represented the contribution rates of karst-fractured water from the Zhangxia Formation and Ordovician Sanshanzi Formation. The proportions of the Baotu Spring and Heihu...
Spring supplied by karst-fractured water from the Zhangxia Formation are 31–54% and 25–31%, respectively; while those supplied by the Ordovician Sanshanzi Formation fracture-karst water are 45–69% and 69–75%, respectively.

(2) The CFD curves of the Zhenzhu Spring and Tanxi Spring resembled a multi-peak shape. The recharge sources of the Zhenzhu Spring and Tanxi Spring were confirmed from the geological structure of spring area, temperature data of the spring water, and analysis of the groundwater hydrochemistry. For the Tanxi Spring, the recharge proportions of karst-fractured water of the Zhangxia Formation, Ordovician Sanshanzi Formation, artificial replenishment, and pore water and fracture water are 58–68%, 15–17%, 9–21%, and 6%, respectively. For the Zhenzhu Spring, the recharge proportions of the Zhangxia Formation, Ordovician Sanshanzi Formation, artificial replenishment, and pore water and fracture water are 57–59%, 22–25%, 13–14%, and 5–6%, respectively.

(3) According to the frequency analysis of spring water temperature, the water circulation depth of the Heihu Spring is the shallowest among the major spring groups; while the water circulation depth of the Zhenzhu Spring is the deepest. Artificial replenishment water has certain effect on the water temperature of the Zhenzhu Spring and Tanxi Spring, minimal effect on the Heihu Spring and Baotu Spring. The Ordovician fracture-karst water has the largest ratio of recharge to spring water. To effectively maintain springs, the Ordovician strata distribution area with high karst development should be selected.

(4) The study confirmed that the karst of Jinan aquifer medium is unevenly developed; the hydraulic connection of different karst aquifers is linked by the fracture structure and magmatic rock. The sources of spring water supply are predominantly karst aquifers in the Zhangxia Formation and the Ordovician. The mixing ratio of the source of karst water supply can be determined using the CFD spectrum analysis method.

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