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Interaction between surface water and groundwater in the Alluvial Plain (anqing section) of the lower Yangtze River Basin: environmental isotope evidence

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Abstract

This study aimed to accurately understand the interaction between surface water and groundwater in the alluvial plain (Anqing section) of the lower Yangtze River basin. To this end, the distribution characteristics of hydrogen and oxygen stable isotopes and ^{222}Rn isotopes in different water bodies were analyzed using the multiple environmental isotope tracing method. The results show that the Yangtze River is generally recharged by groundwater in the alluvial plain (Anqing section), whereas it is stimulated by human activities to recharge groundwater in the urban section of Anqing; the first-order stream of the Yangtze River, the Wan River, receives groundwater recharge in the hilly area and recharges groundwater in the flat area. The main sources of groundwater in the alluvial plain are precipitation and lake water, which account for 45.25% and 54.75%, respectively, of the total recharge. This study provides a reliable scientific basis for quality evaluation, pollution prevention and remediation of the water resources in the alluvial plain (Anqing section) of the lower Yangtze River basin.

Keywords Environmental isotopes · Yangtze River · SW-GW interaction · ^{222}Rn · Hydrogen and oxygen stable isotopic

Introduction

Surface water and groundwater are indivisible and important parts of water resources. The frequent interaction between surface water and groundwater is an important factor influencing the formation and structure of regional water resources [1]. Their interaction is also the core and premise of regional water resources evaluation and management. Therefore, determining the mutual transformation relationship between surface water and groundwater has high theoretical significance and practical value for establishing regional water cycle models, revealing the formation mechanism of water resources, reasonably evaluating the total amount of water resources, as well as the rational development, utilization and scientific management of water resources [2].

The interaction between groundwater and surface water has been a hot and difficult topic in the field of hydrology and hydrogeology. Since Boussinesq began to study the interaction between surface water and groundwater in 1877 [3], many scholars have been applying various research methods and approaches to different regions and basins. The main methods include investigation and analysis, water balance, simulation calculation, and environmental tracing [4]. Among them, the method of investigation and analysis is time-consuming and laborious; the water balance method involves complicated identification and quantification processes for each source and sink term. With the refinement and quantification of research on the interaction between surface water and groundwater, the simulation calculation and environmental tracing methods have become more common [5]. However, coupling simulation is difficult, requires a large amount of data, is complicated to operate, and is greatly affected by the accuracy of parameters. It is generally used for large areas with large amounts of long-sequence data. The environmental tracing method is simple in principle, practical and effective, and can be combined with data from multiple sources for analysis. It has been widely used and significant achievements have been made [6].

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As an important part of surface water and groundwater, environmental tracers (such as water environment parameters, dissolved components, and isotopes) record the formation and evolution history of water bodies to a certain extent, and can indicate the mutual transformation relationship between surface water and groundwater [7]. Hydrogen and oxygen stable isotopes (^{18}O and D) are direct components of water molecules, and they are widely used as ideal environmental tracers in tracing the water cycle [8–11]. ^{222}Rn is the most stable radon isotope with a short half-life. ^{222}Rn is widely used as a highly reliable and accurate tracer in the study of the interaction between surface water and groundwater because it exhibits prominent differences between groundwater and surface water and is convenient to measure [12–19].

The Yangtze River is the largest river in China and the third largest river in the world. It plays an important role in the sustainable development of regional economy and ecology [20, 21]. To strengthen the protection and restoration of the ecological environment in the Yangtze River basin, facilitate the effective and rational use of resources, safeguard ecological security, ensure harmony between human and nature, and achieve the sustainable development of the Chinese nation, the 24th Standing Committee session of the 13th National People's Congress passed the first river basin law "Yangtze River Protection Law" on December 26, 2020, and this law came into effect on March 1, 2021. Anqing is located beside the river on the alluvial plain in the lower reaches of the Yangtze River. It is an important city in the Yangtze River Economic Belt and the Yangtze River Delta. Since the 1980s, many large-scale chemical plants have been built in Anqing City, posing a serious risk of water pollution [22–24]. Therefore, the study of the interaction between surface water and groundwater in Anqing is of great practical significance to the prevention and control of water pollution and the restoration of the ecological environment in the Yangtze River.

In this study, the distribution characteristics of hydrogen and oxygen stable isotopes as well as ^{222}Rn isotopes in surface water and groundwater of the alluvial plain (Anqing section) in the lower Yangtze River Basin were analyzed to determine the transformation relationship between surface water and groundwater and determine the source of groundwater recharge. Moreover, the recharge ratio was calculated using the two-terminal mixed model.

Study area

Anqing City is located in southeastern China, on the north bank of the lower reaches of the Yangtze River. It lies between 29°47′–31°16′N and 115°45′–117°44′E. It spans three geomorphic units: the middle and low mountains of the Dabie Mountains, the low hills along the Yangtze River, and the alluvial plain along the Yangtze River. The topography has a general trend of higher in the northwest and lower in the southeast. The altitude of the Dabie Mountains is more than 400 m a.s.l in the northwest and 100–200 m a.s.l in the middle; the alluvial plain of the Yangtze River is flat in the south. The alluvial plain of the Yangtze River was taken as the study area, as shown in Fig. 1.

Anqing city is located in the northern subtropical humid climate zone, with mild climate and moderate rainfall. The annual average temperature ranges from 14.4 to 16.6 ℃, with obvious geomorphic zonation. The annual average temperature in the Dabie Mountain area is 14.4 ℃, and that in the area along the Yangtze River is 16.1–16.6 ℃. The multi-year average rainfall is 1466.2 mm, and the multi-year average evaporation is 917.4 mm.

The study area has a well-developed surface water system, with many rivers and lakes. In the study area, the main stream of the Yangtze River is approximately 243 km in length, and the Wan River, with a total length of 94 km, is its primary tributary. An obvious peak of river water level is observed every year. The lowest and highest water levels are observed during January–February and July–August, respectively. According to the water level of the Yangtze River monitored at the Anqing hydrological station for the period 2009–2018, the highest water level is 16.98 m (July 2016) and the lowest is 5.72 m (February 2014). The main lakes include Longgan Lake, Daguan Lake, Po Lake, and Pogang Lake.

The Quaternary strata in the study area are well developed and distributed from lower Pleistocene to Holocene. The gravel layer of the lower Pleistocene Anqing Formation is partly exposed in the third terrace and partly buried in the lower part of the second terrace. The gravel layer has a thickness of 15–30 m and unconformably overlies the Red Bed basement. The gravel is mainly composed of quartzite and quartz sandstone, with good sorting and roundness, and the particle size can reach 1–6 cm. The lower part of the Middle Pleistocene Qijiaji Formation is a 1–4 m thick mud-bearing gravel layer, and the upper part is 3–8 m thick reticulated laterite. The lower member of the upper Pleistocene Xiashu Formation is 3–6 m thick khaki sub-clay, containing iron and manganese, widely distributed in the second terrace; the upper member is light yellow sub-clay, mainly distributed in the first terrace. The stratum of the Holocene Wuhu Formation is mainly distributed in the alluvial plains of the Yangtze River and the main tributary valleys of the Wan River. The stratum can be divided into 3 sections from bottom to top: the lower part comprises a gravel layer and gravel-bearing medium-coarse sand (approximately 10 m thick); the middle part comprises medium–fine sand (10–20 m thick); the upper part comprises grayish yellow–blue gray silty clay (4–10 m thick). In the area with fluvial–lacustrine sediments,

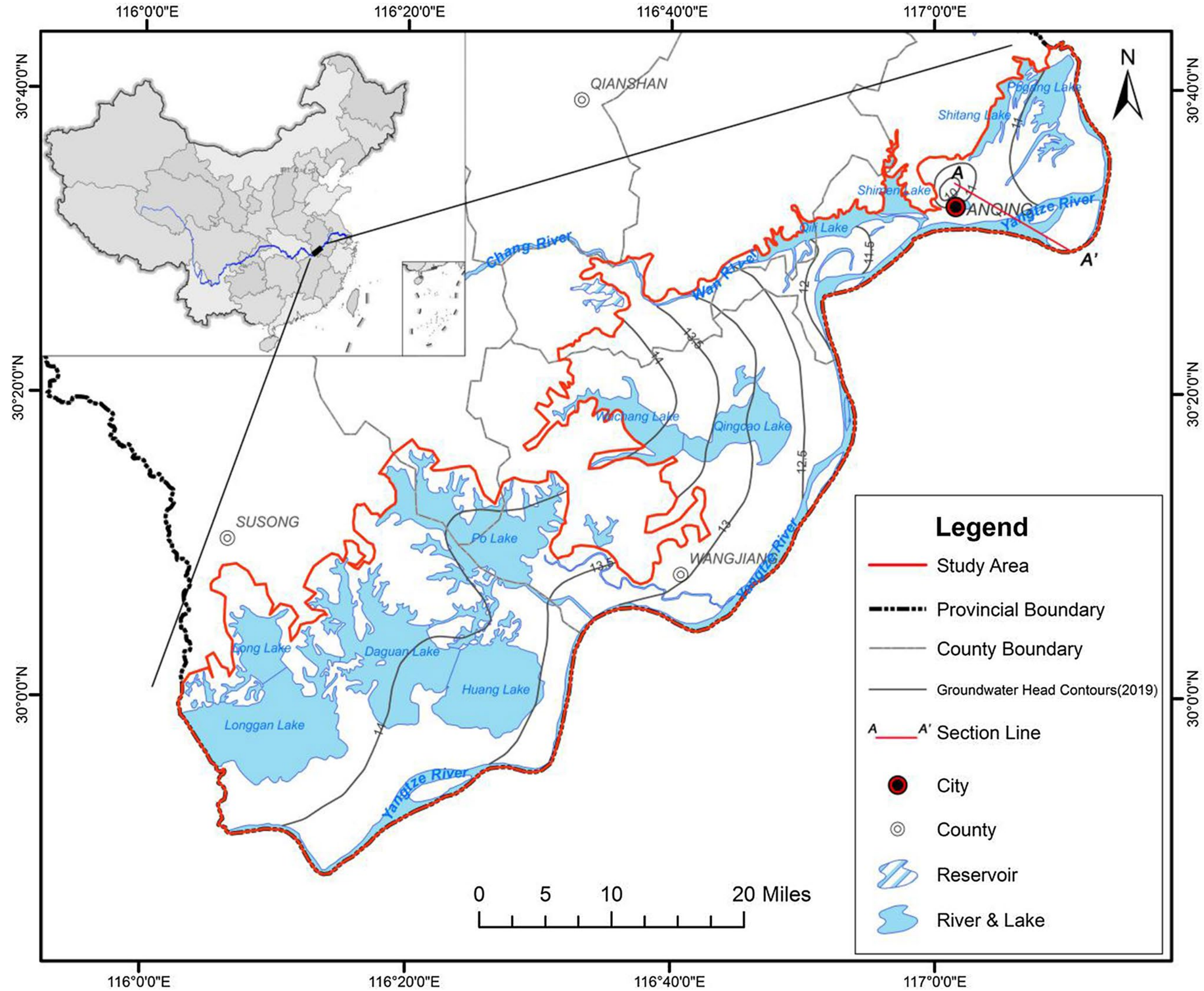

Fig. 1 Alluvial plain (Anqing section) of the lower Yangtze River basin

the Wuhu Formation is deposited only on the shallow surface, with a thickness not more than 3 m.

The Quaternary aquifers in the study area are mainly Holocene sand and gravel phreatic aquifers and lower Pleistocene gravel confined aquifers, with thicknesses of 7–50 m and 0–24 m, respectively. There is no continuous aquifuge between the aquifers, but some areas have relative aquifuges, as shown in Fig. 2.

Materials and methods

In this study, hydrogen and oxygen stable isotope and chemical samples were collected from two phases of precipitation, groundwater, and surface water in August 2018 and May 2019, comprising 3 sets of precipitation samples, 54 sets of diving samples, 39 sets of confined water samples, and 54 sets of surface water samples. ^{222}Rn isotopes samples were collected from Wan River, Yangtze River, and groundwater in 2018. The distribution of sampling points is shown in Fig. 3.

Before sampling, new sampling bottles were soaked in 10% nitric acid solution for 1–2 days and in tap water for 1–2 days. They were then rinsed to neutral pH, and finally rinsed with ultrapure water three times. During sampling, the sample was collected after rinsing the container with the water sample more than 3 times.

For surface water, the sampling bottle was placed below the water surface and water was allowed to slowly enter the container; the sampling bottle was sealed underwater to avoid bubble contamination. For groundwater, the samples were collected after pumping water for more than five minutes to discharge long-term residual groundwater in the well pipe.

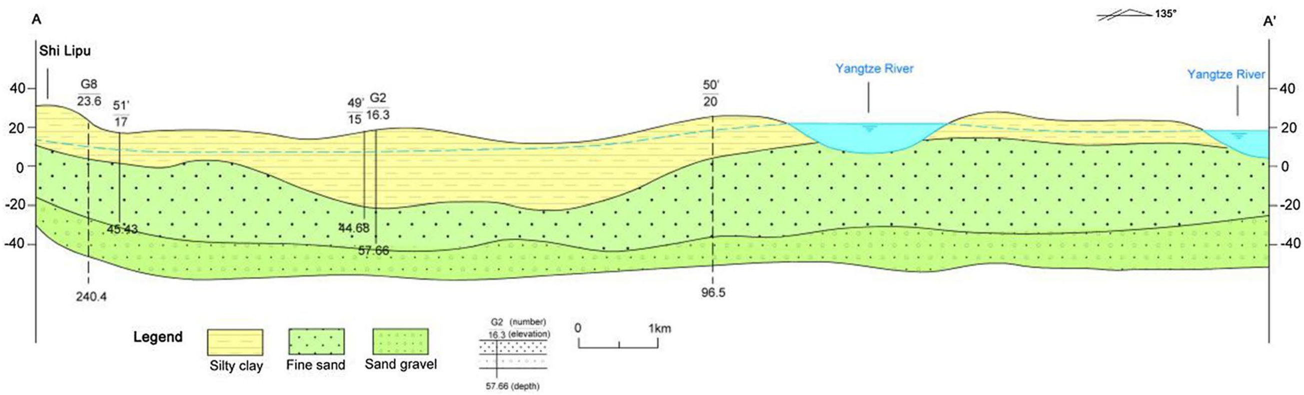

Fig. 2 Hydrogeologic cross sections along the transect A- A' in Fig. 1

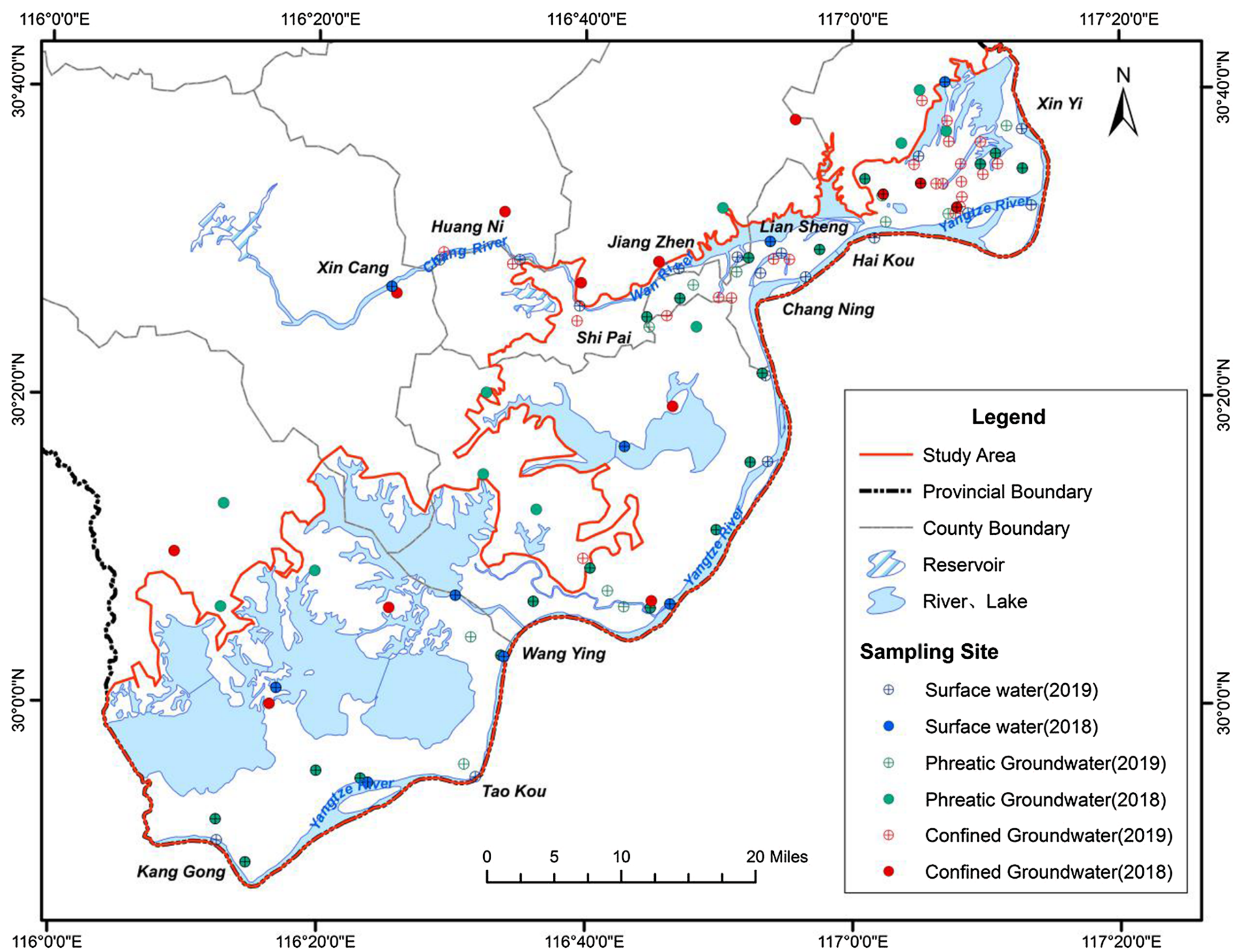

Fig. 3 Map of the sampling locations in 2018 and 2019

Water samples were analyzed for stable isotopes ratios of $\delta^{18}O$ and δD by Beijing Original Ecology Testing Co., Ltd. in this study. The results are reported relative to the Vienna Standard Mean Ocean Water, as delta (δ) values of per mil (‰). Overall, the analytical uncertainty was better than 0.3‰ for $\delta^{18}O$ and 0.8‰ for δD, respectively. ^{222}Rn isotope samples were collected in a 40 ml headspace bottles; sampling time was recorded accurately to minutes. The ^{222}Rn isotope content in water was determined by the RAD7 α energy spectrum radon detector of Durridge Co., USA.

Theoretical method

Hydrogen and oxygen stable isotope tracing method

Different water bodies in the water circulation system have characteristic isotopic compositions owing to their different genesis, that is, stable isotopes of hydrogen (D) and oxygen (^{18}O) exhibit different degrees of enrichment. The recharge source of groundwater can be traced according to the distribution characteristics of hydrogen and oxygen stable isotope composition of groundwater, precipitation, and surface water [11, 25–29].

As one of the elements of water molecules, oxygen isotopic distribution plays an important role in the analysis of water source, evolution, and movement. The oxygen isotopic composition of water varies according to the source, providing indications for investigating interactions between surface water and groundwater. The formation of oxygen isotope zonation is an important evidence of groundwater flow. Regular changes of oxygen isotopes in groundwater and surface water along the flow direction of surface water can be inferred to effectively trace the transformation relationship between groundwater and surface water [30–34].

^{222}Rn isotope tracing method

^{222}Rn is increasingly being used in the study of interactions between surface water and groundwater [35–39]. It is an excellent tracer for water exchange due to its inert chemical properties as a noble gas and a large differences (1–3 orders of magnitude) in activity between groundwater and surface water. The difference in activity is maintained by the short residence time of ^{222}Rn in surface water due to radioactive decay ($t_{1/2}=3.8d$) and loss to the atmosphere. When groundwater is recharged by local surface water in large quantities, the concentration of ^{222}Rn in groundwater collected on the shore of surface water (river, lake, estuary, and shallow sea basin) is always lower than the steady state. On the other hand, a sudden increase in the concentration of radon in surface water collected from the shore reflects groundwater recharge by water with high radon concentration [40].

Calculation of recharge proportion of groundwater

In this study, a two-terminal-member mixing model based on the composition of stable hydrogen and oxygen isotopes was used to calculate the mixing ratio of groundwater recharge sources [41–43]. The following assumptions were made: isotopic values of each end member are relatively uniform in time and space, and the mixing between the two end members follows a linear law, and the mixing mechanism is only the mixing of water quantity, which is not affected by other factors.

The formula is as follows:

$$\begin{cases} \delta_1 n_1 + \delta_2 n_2 = \delta_S \\ n_1 + n_2 = 1 \end{cases} \quad (1)$$

where δ_1, δ_2, and δ_S are the stable isotope δ values (‰) of hydrogen and oxygen in end-member 1, end-member 2, and the mixed water body; n_1 and n_2 are the mixing ratios of end-member 1 and end-member 2, respectively.

Results and discussion

Characteristics of hydrogen and oxygen stable isotopes in natural water

Precipitation

Affected by climatic conditions and different sources of water vapor, the hydrogen and oxygen stable isotopic compositions of precipitation exhibit wide variations, and the isotopic composition of precipitation in the same area may vary over time. However, due to the parallel fractionation of stable isotopes of hydrogen and oxygen in the process of evaporation and condensation, the $\delta^{18}O$ and δD values of precipitation exhibit a linear relationship.

Beibei Zhang collected 155 precipitation samples from June 2015 to June 2017 in Anqing City (δD value ranged from − 168.3 to − 2.8‰, with an average of − 47.6‰; $\delta^{18}O$ value ranged from − 21.66 to − 1.41‰, with an average of −7.23‰) and obtained the equation of Local Meteoric Water Line (LMWL) in Anqing City: $\delta D=(8.08\pm0.06)\delta^{18}O+(10.84\pm0.48)$ (R2 = 0.99) [44]; its slope and intercept were consistent with the Global Meteoric Water Line (GMWL:$\delta D=(8.17\pm0.08)\delta^{18}O+(10.56\pm0.64)$) obtained by Craig [45], as shown in Fig. 4. It shows that Anqing has a relatively humid climate, which is mainly affected by ocean water vapor. In this study, precipitation samples were collected in August 2018 and May 2019. The hydrogen and oxygen stable isotopic compositions were distributed at the lower right of the LMWL, and the slope of the δD-$\delta^{18}O$ line

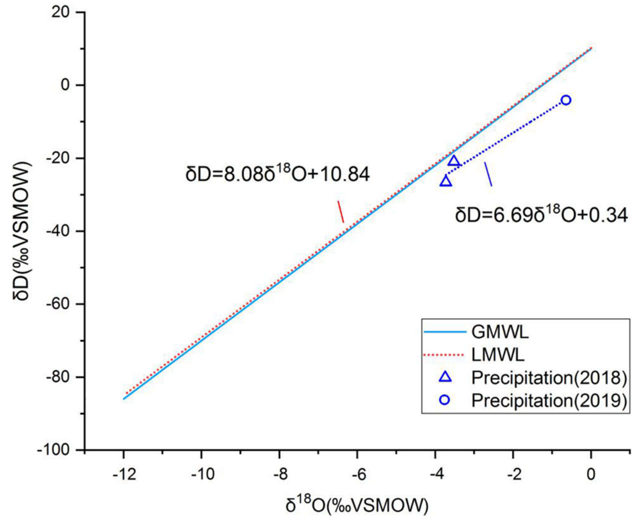

Fig. 4 The local meteoric water line of An Qing

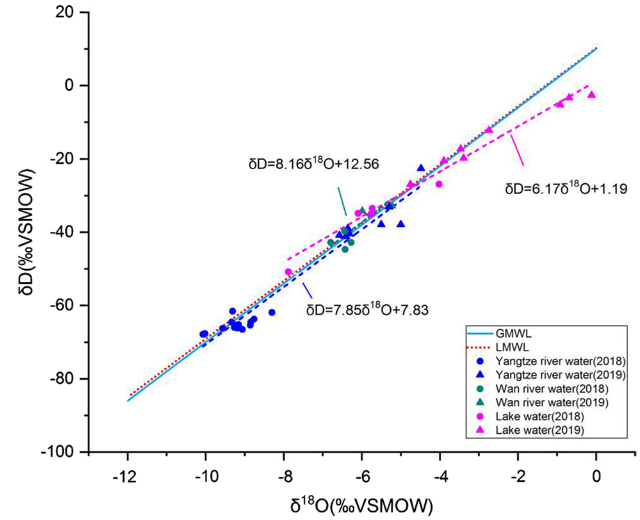

Fig. 5 Distribution of hydrogen and oxygen stable isotope in surface water

(6.69) was lower than the slope of the LMWL (8.08). This is because the air temperature was relatively high during the sampling period, and due to seasonal effects, precipitation reached the surface after secondary evaporation.

Surface water

The hydrogen and oxygen stable isotopic compositions of the surface water in the study area were distributed along the LMWL, indicating that precipitation is the main recharge source of surface water in the study area. The distribution range and mean value of δD and δ^{18}O values are shown in Fig. 5 and Table 1. The sample points of Yangtze River water were concentrated in the lower right of the LMWL, and the slope of δD-δ^{18}O line (7.85) is slightly lower than that of the LMWL (8.08), which can be attributed to the influence of altitude and ice and snow melting [46]. The slope (8.16) of the δD-δ^{18}O line at the water sample point of the Wan River was slightly higher than the slope of the LMWL (8.08). This is attributable to the influence of the water from the upper reaches of the mountainous area where the composition of heavy hydrogen and oxygen isotopes is relatively depleted. The δD and δ^{18}O values of lake water exhibited a wide distribution range, and the slope of the δD-δ^{18}O line (6.17) was lower than the slope of the LMWL (8.08), indicating that the lake water is affected by different degrees of evaporation, which leads to D and ^{18}O enrichment. The stable isotopic composition of hydrogen and oxygen in the lake water was similar to that of precipitation, which further indicates that the lake water is mainly supplied by precipitation. However, the stable isotopic composition of hydrogen and oxygen in groundwater is quite different from that in surface water, which is a possible source of groundwater recharge.

Compared with August 2018, the stable isotopes of hydrogen and oxygen in the Yangtze River, Wan River and lake water were enriched in May 2019. This can be explained by surface water in the study area being supplied by precipitation with relatively rich heavy isotopes of hydrogen and oxygen in May 2019.

Groundwater

The hydrogen and oxygen stable isotopic compositions of groundwater in the study area exhibited an obvious aggregation phenomenon. The sample points were generally distributed near the LMWL, and the slope of the δD-δ^{18}O line (phreatic water 7.74, confined water 6.33) was between the LMWL (8.08) and the surface water (lake water 6.17), which indicates that the groundwater in the study area is mainly supplied by local precipitation and surface water. The distribution range and mean value of δD and δ^{18}O are shown in Fig. 6 and Table 1. The distribution range of phreatic water was wider than that of confined water, and the hydrogen and oxygen stable isotopic compositions of phreatic water and confined water were similar, almost overlapping, indicating that a relatively close hydraulic connection between them. The hydrogen and oxygen stable isotopic composition was more enriched in phreatic water than in confined water due to evaporation.

Compared with August 2018, the δD and δ^{18}O of groundwater were enriched in May 2019, which can be attributed to recharge by precipitation and surface water with relatively enriched δD and δ^{18}O.

Table 1 Hydrogen and oxygen stable isotope data of surface water and groundwater

Sample types	Sampling period	δD		$\delta^{18}O$	
		Scope (‰)	Mean value (‰)	Scope (‰)	Mean value (‰)
Yangtze River	2018	− 67.90 to − 61.54	− 65.38	− 10.07 to − 8.30	− 9.27
	2019	− 41.192 to − 22.611	− 36.408	− 6.572 to − 3.552	− 5.754
Wan river	2018	− 44.74 to − 34.87	− 41.01	− 6.80 to − 6.10	− 6.40
	2019	− 34.910 to − 32.835	− 34.143	− 5.986 to − 5.229	− 5.683
Lake water	2018	− 50.84 to − 26.94	− 36.24	− 7.88 to − 4.02	− 5.90
	2019	− 26.991 to − 2.685	−13.504	− 4.753 to − 0.112	− 2.495
Phreatic water	2018	− 46.551 to − 23.447	− 37.786	− 7.472 to − 3.792	− 6.231
	2019	− 41.129 to − 6.543	− 25.849	− 6.482 to − 1.876	− 4.554
Confined water	2018	− 45.787 to − 34.271	− 38.5130	− 7.247 to − 5.537	− 6.20
	2019	− 42.854 to − 17.163	− 31.655	− 6.654 to − 3.131	5.185

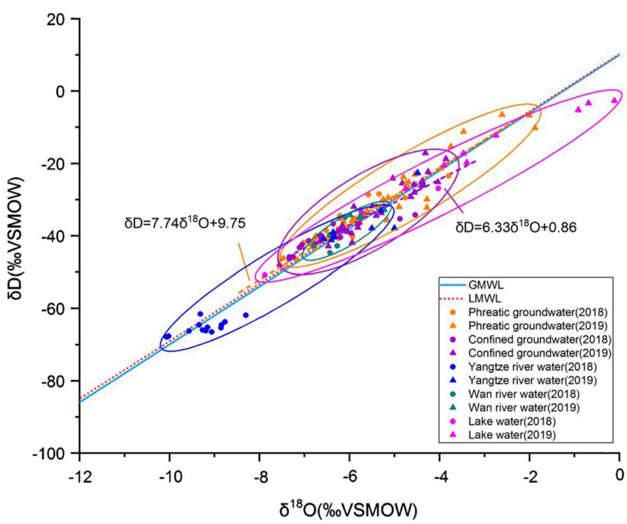

Fig. 6 Distribution of hydrogen and oxygen stable isotopes in natural water

Analysis of the transformation relationship between surface water and groundwater

Isotopic evidence for the transformation relationship between the Yangtze River and groundwater

^{18}O isotope tracing method

The ^{18}O isotopic composition of Yangtze River water was relatively depleted ($\delta^{18}O$ values ranging from − 6.572 to − 4.484‰, with an average of − 5.876‰), while that of groundwater was relatively enriched ($\delta^{18}O$ values ranging from − 5.863 to − 1.998‰, with an average of − 4.581‰). According to differences in the spatial distribution of $\delta^{18}O$ values of river water and groundwater in the north (Fig. 7), the $\delta^{18}O$ value of river water appears to be lower than that of groundwater along the river.

The terrain of the plain along the river in Susong section is gentle, higher in the northwest and lower in the southeast. There are many lakes in this section, and groundwater flows into the Yangtze River after receiving vertical recharge of lake water. Nevertheless, alluvial lacustrine deposit aquifers in the terraces along the Yangtze River weaken the connection between river water and groundwater. The $\delta^{18}O$ values of groundwater samples gradually increased from − 7.168 at Kanggong village to − 3.792 ‰ at Wangying Village in 2018, while it was relatively stable at approximately − 4.2 ‰ (from Kanggong village to Wangying village) in 2019. The $\delta^{18}O$ values of river water samples gradually decreased from − 9.565 at Kanggong village to − 10.045 ‰ at Taokou village in 2018 and from − 4.484 at Kanggong village to − 6.572 ‰ at Wangying village in 2019. The hydraulic connection between the river water and groundwater appears to be weak in this section, and the difference in the $\delta^{18}O$ value between river water and groundwater is not mainly attributable to water exchange. However, from the topography and hydrogeological conditions, the relationship between surface water and groundwater in this section can be ascertained to be groundwater serving as a recharge source of river water [44–46].

The groundwater in the plain along the river is affected by the topography in the Wangjiang section, which leads to a large hydraulic gradient and a large amount of groundwater being discharged as recharge water for the river. According to the distribution of $\delta^{18}O$ values of river water and groundwater, the $\delta^{18}O$ value of river water in the Wangjiang section gradually increased from − 9.310 at Wangying village to − 8.841‰ at Changning village in 2018 and from − 6.572 at Wangying village to − 4.999‰ at Changning village in 2019. The values are significantly higher in the Wangjiang section than in the Susong section, indicating that the river

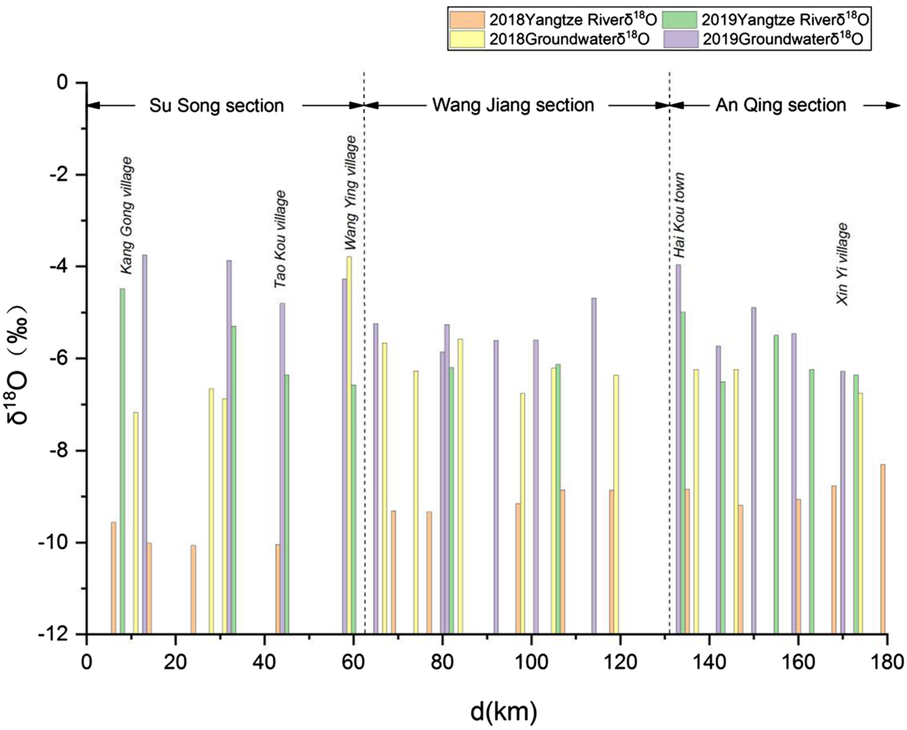

Fig. 7 Variations in $\delta^{18}O$ values of Yangtze River and groundwater on the left bank along the Yangtze River

water in this section is mainly recharged by groundwater with high $\delta^{18}O$ values.

In the Anqing section, aquifers are relatively thick and comprise relatively coarse lithologic particles, supporting a close hydraulic relationship between groundwater and river water. The groundwater in the area is affected by industrial exploitation, leading to a groundwater level falling funnel and river water recharge. The $\delta^{18}O$ value of groundwater gradually decreased from − 6.242 at Changning village to − 7.24‰ at Haikou town in 2018 and from − 3.966 at Changning village to − 5.732‰ at Haikou town in 2019, indicating that near Haikou town, groundwater is recharged by river water with lower $\delta^{18}O$ values. The $\delta^{18}O$ value of groundwater gradually increased from − 9.193 at Haikou town to − 8.302‰ at Xinyi village in 2018 and from − 6.499 at Haikou town to − 5.559‰ at Xinyi village in 2019, indicating that in this section, river water is recharged by groundwater with higher $\delta^{18}O$ values.

^{222}Rn isotope tracing method

The ^{222}Rn concentration of groundwater along the Yangtze River in the study area was generally high (Fig. 8), with a variation range of 16.14–36.49 Bq/L and an average value of 23.51 Bq/L. However, the ^{222}Rn concentration in the Yangtze River water was relatively low and with a relatively large variation range of 1.39–19.67 Bq/L and an average of 9.41 Bq/L. According to differences in the spatial distribution of ^{222}Rn concentration in Yangtze River water and groundwater along the Yangtze River, the concentration of ^{222}Rn in groundwater is significantly higher than that in Yangtze River water and the concentration of ^{222}Rn in river water shows obvious fluctuations along the river flow direction, indicating different transformation relationships between surface water and groundwater in different sections along the Yangtze River. Combined with the analysis of hydrogeological conditions in the study area, the variation of ^{222}Rn concentration in surface water can reflect the mutual transformation between surface water and groundwater.

As shown in Fig. 8, in the Susong section, the ^{222}Rn concentration in the river water ranged from 3.84 to 8.77 Bq/L, with an average of 5.09 Bq/L. The concentration was relatively low and exhibited a decreasing trend. the decrease in ^{222}Rn concentration in river water can be attributed to radioactive decay and gas exchange, which indicates a weak hydraulic connection between river water and groundwater in this section.

In the Wangjiang section, the ^{222}Rn concentration of river water increased significantly from 3.84 at Taokou village to 19.67 Bq/L at Wangying village, indicating that river water began to receive groundwater recharge. On the other hand, in the Wangjiang section, the ^{222}Rn concentration value of the river water ranged from 8.43 at Changning village to 19.67 Bq/L at Wangying village), with an average value of 13.86 Bq/L, which is significantly higher than those in the Susong and Anqing sections. This shows that the transformation relationship between groundwater and the Yangtze River in this section can be characterized by groundwater

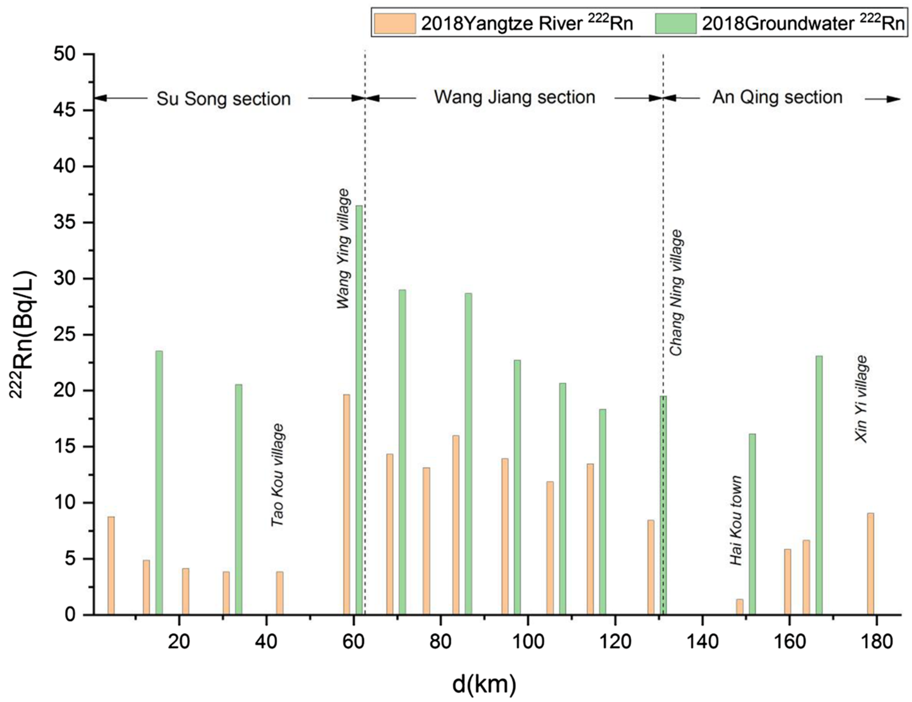

Fig. 8 Variation of ^{222}Rn concentration of Yangtze River water and groundwater along the Yangtze River

recharging Yangtze River water. It is noteworthy that the Wangjiang section of the Yangtze River completely cuts the aquifer, and the groundwater has a close relationship with river water. Controlled by the topography of the plain along the Wangjiang section, the groundwater has a large hydraulic gradient, due to which a large amount of groundwater with high ^{222}Rn content replenishes the Yangtze River, thus increasing the ^{222}Rn content of river water.

In the Anqing section, the ^{222}Rn concentration of river water at Haikou town was 1.39 Bq/L, which is the lowest in the whole area, indicating that the river water near Haikou town is no longer recharged by groundwater. Under the influence of human activities, the river water near Haikou town is artificially stimulated to recharge groundwater. The ^{222}Rn concentration in the river water increased gradually from 1.39 at Haikou town to 9.07 Bq/L at Xinyi village, which indicates that the groundwater supplies the Yangtze River water in this section. The analysis results of ^{222}Rn concentration appear to be consistent with those of ^{18}O concentration.

Isotopic evidence for the transformation relationship between the Wan River and groundwater

^{18}O isotope tracing method

Affected by evaporation, the ^{18}O isotope of the Wan River was relatively enriched, with δ^{18}O values ranging from − 5.986 to − 3.466‰ and an average of − 4.849‰. In contrast, the ^{18}O isotope of groundwater along the bank was relatively depleted, with δ^{18}O values ranging from − 7.550 to − 5.164‰ and an average of − 6.070‰. According to differences in the spatial distribution of δ^{18}O values of the Wan River and groundwater along the bank (Fig. 9), the δ^{18}O value of the Wan River is higher than that of groundwater.

In the hilly area (from Xincang town to Shipai town), the Wan River receives groundwater recharge. As shown in Fig. 9, the δ^{18}O value of the Wan River gradually decreased from − 4.742 at Huangni town to − 5.985‰ at Shipai town in May 2019 and from − 6.270 at Xincang town to − 6.695‰ at Shipai town in August 2018, indicating that the Wan River receives groundwater recharge with low δ^{18}O values in this section.

In the flat area along the Yangtze River (from Shipai town to Liansheng village), the velocity of the Wan River decreases, and the river water is more strongly affected by evaporation, which decreases the ^{18}O isotope concentration of the Wan River in the flat area along the Yangtze River. Along the flow direction of groundwater, the δ^{18}O value of groundwater also increased gradually from − 7.106 at Shipai town to − 6.211‰ at Liansheng village in August 2018 and from − 6.21 at Shipai town to − 5.164‰ at Liansheng village in May 2019, indicating that the groundwater is recharged by the Wan River with high δ^{18}O values.

^{222}Rn isotope tracing method

Using the ^{222}Rn isotope tracing method, the transformation relationship between the Wan River water and groundwater was further determined. According to the distribution

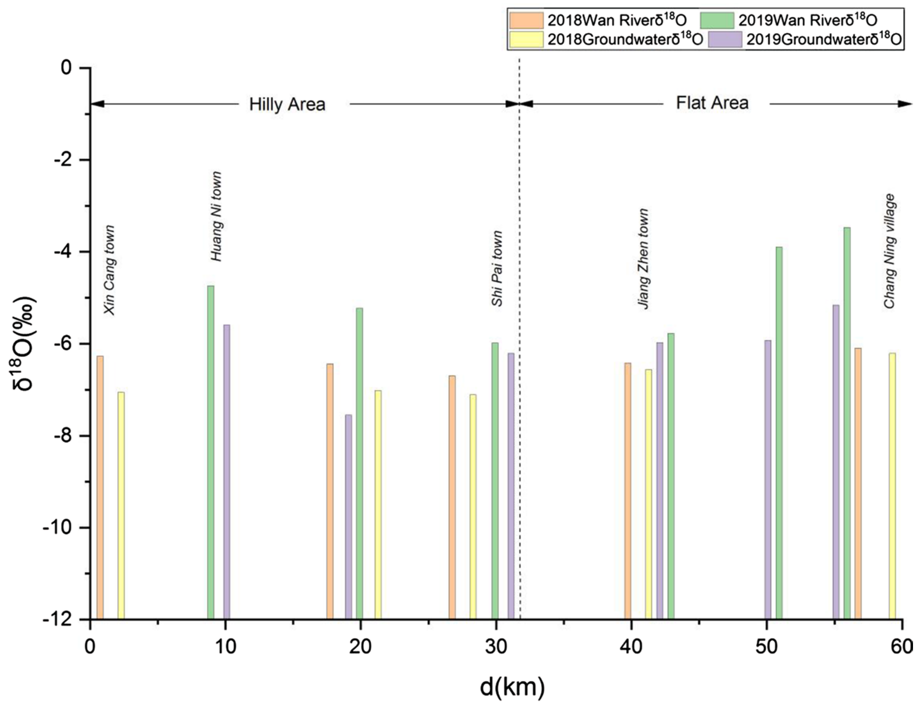

Fig. 9 Variation of $\delta^{18}O$ values of the Wan River and groundwater along the Wan River

of ^{222}Rn concentration in the Wan River and groundwater (Fig. 10), ^{222}Rn concentration in the Wan River ranged from 5.54 to 12.76 Bq/L, with an average of 9.08 Bq/L; in groundwater, it ranged from 10.15 to 17.55 Bq/L, with an average of 13.93 Bq/L. The ^{222}Rn concentration of the Wan river was lower than that of groundwater along the bank.

In the hilly area, the ^{222}Rn concentration of the Wan River increased significantly from 6.58 at Xincang town to 12.11 Bq/L at Shipai town, indicating that the Wan River is

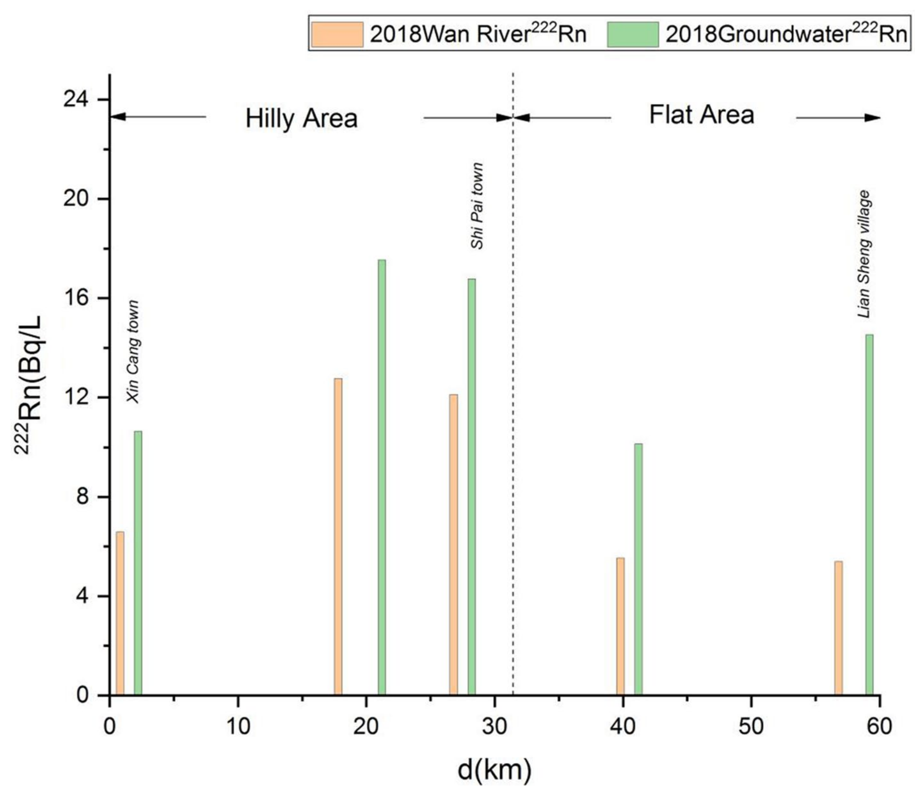

Fig. 10 Variations of the ^{222}Rn concentration of the Wan River water and groundwater along the Wan River

Table 2 Proportion of precipitationSS and lake water recharge for groundwater

Parameter	Precipitation (%)	Lake water (%)
$\delta^{18}O$	49.65	50.35
δD	40.85	59.15
Mean value	45.25	54.75

recharged by groundwater with higher ^{222}Rn concentration in this section.

In the flat area, the ^{222}Rn concentration of the Wan River was relatively low, with narrow fluctuations. However, the ^{222}Rn concentration of groundwater along the Wan River decreased significantly from 16.77 at Shipai town to 14.53 Bq/L at Liansheng village, reflecting that the groundwater in this section is recharged by the Wan River.

The results of the ^{222}Rn isotope tracing method are consistent with the results of the ^{18}O isotope tracing method.

Recharge sources and recharge proportion of groundwater

According to the hydrogen and oxygen stable isotopic composition in different water bodies and the isotopic evidence of the transformation relationships between the Yangtze River, Wan River, and groundwater, the recharge sources of groundwater in the study area can be ascertained to be precipitation, Yangtze River, Wan River, and lake water. The analysis of the relationship between surface water and groundwater shows that the Yangtze River and Wan River only recharge groundwater in local sections, and the recharge quantity is small; these sources are not the main supply sources. Therefore, the groundwater supply sources in the study area are generalized into precipitation and lake water.

The mean values of precipitation $\delta^{18}O$ and δD were − 7.23‰ and − 47.6‰, respectively; the mean values of lake water $\delta^{18}O$ and δD were − 3.802‰ and − 22.249‰, respectively; the mean values of groundwater $\delta^{18}O$ and δD were − 5.504‰ and − 32.606‰, respectively. According to the mixed model (Eq. 1), the results are shown in Table 2. The two major recharge sources of groundwater, precipitation and lake water, accounted for 45.25% and 54.75% of the total recharge, respectively.

Conclusions

Based on multiple environmental isotopic characteristics of three natural water bodies in the alluvial plain of the lower Yangtze River basin (Anqing), this study determined the recharge sources of groundwater, evaluated the transformation relationships between Yangtze River water, Wan River water, and groundwater, and calculated the recharge proportions of the main recharge sources. The following conclusions can be drawn:

(a) The transformation relationship between the Yangtze River and groundwater in the alluvial plain can be characterized as follows: in the Susong section, groundwater recharges the Yangtze River although its contribution is small; controlled by the terrain, groundwater recharges the Yangtze River in the Wangjiang section, and its contribution is large; in the Anqing section, the river water close to the urban area is artificially stimulated to recharge groundwater, but groundwater resumes recharging river water after crossing the urban area.
(b) The transformation relationship of the Wan River, the main river in the alluvial plain, with groundwater is as follows: groundwater recharges the Wan River in the hilly area, but it is recharged by the Wan River in the flat area.
(c) The main recharge sources of groundwater in the alluvial plain are precipitation and lake water, which account for 45.25% and 54.75%, respectively.
(d) The ^{222}Rn tracing method is simple, practical, and effective in determining the transformation relationship between surface water and groundwater, and it can be extended to extend to various regions as an effective method.

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