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Application of environmental isotopes to identify recharge source, age, and renewability of phreatic water in Yinchuan Basin

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Abstract

The accurate understanding of groundwater circulation pattern and its renewable capacity is vital for groundwater resource assessment and the rational exploitation and utilization of groundwater. Estimation of groundwater recharge is difficult in arid or semiarid area due to the low amount and variability of recharge. A combination of isotope investigation with hybrid model allows a direct calculation of renewability of the aquifer. In this paper, the phreatic water circulation pattern and its renewable capacity of phreatic water in Yinchuan Basin, a semiarid area located at the northwest China, are investigated by the application of environmental isotope method, which mainly focusses on the isotope characteristics of different water bodies, phreatic water isotope age, phreatic water circulation pattern, and phreatic water renewal rate. The results demonstrate that the two dominant recharge sources of groundwater in Yinchuan Basin, local atmospheric precipitation and Yellow River, account for 13% and 87%, respectively. The average residence time of phreatic water in Yinchuan Basin is about 48 years, and the average renewal rate is 3.38%/a. The results indicate that the phreatic water has a strong renewable capacity and the regeneration rate distribution is consistent with that indicated by isotope age.

1 | INTRODUCTION

Sustainable utilization of groundwater resources requires a quantitative estimation of groundwater fluxes and storage (Döll & Fiedler, 2008) and also circulation pattern and renewability of groundwater (Edmunds, 2012). Although estimations of groundwater renewability are very difficult with the conventional hydrogeological methods such as water budget, groundwater balance, or Darcy's law in arid area (Huang, Pang, Li, Xiang, & Zhao, 2017a, 2017b), environmental tracers and groundwater age have been proved to be the robust tools in evaluating the renewability of groundwater reservoirs (Edmunds, 2003; Huang et al., 2017a, 2017b; Kazemi, Lehr, & Perrochet, 2006a, 2006b).

Since the early 1960s, isotope techniques have been increasingly applied to hydrological studies, mostly addressed to comprehend the origin of waters (Minissale & Vaselli, 2011). There is an increasing interest in using groundwater age dating to estimate recharge sources and renewability of groundwater. Hydrogen and oxygen isotopes have been considered as the ideal geochemical tracers of water because their concentrations generally do not vary as the water interacts with the aquifer material. Therefore, they are currently deemed as the "DNA" of water bodies because they are sensitive to changes in the environment and trace effectively these changes (Qian, Li, Wu, & Zhou, 2013; Qian, Wu, Zhou, & Li, 2014; Yang et al., 2018). They can be interpreted to gain some valuable information on hydrological events, identify the origin of water, renewal potential of aquifer, and residence, and transit time of water in the system, which often may not be readily obtained by other techniques (Ette et al., 2017). The application of environmental isotope method can help us understand the circulation and evolution of groundwater. There are a variety of studies on different topics, such as origin or recharge source of groundwater recharge by using D and ^{18}O (Chen, Wei, Liu, Wang, & Chen, 2011; Edmunds, 2008, 2009; Lian, 2007; Zhao et al., 2012); the recharge sources and hydrochemical evolution of phreatic water in complex groundwater system (Li, Pan, Tang, Zhang, & Yu, 2008); investigation of the circulation pattern of groundwater by the difference of stable isotope composition of oxygen and hydrogen in different water bodies (Fang, 2012; Jin et al., 2016; Yin et al., 2011; Zhao, 2015); study of lake water supply and evaporation extent with the stable isotope of oxygen and hydrogen (Qian et al., 2014); and determination of groundwater age by radioisotopes (Kamtchueng et al., 2015). The most important application of groundwater age is that it can be used to assess the renewability or replenishment of the groundwater resources and it can provide the sound evidence to indicate that groundwater resources are recharged by modern or old precipitation (Kazemi et al., 2006a, 2006b), especially for aquifers located in arid zones and in less developed countries where no scientific data exist to study the aquifer recharge processes (Huang et al., 2017a, 2017b).

Determination of circulation mechanism is of great importance for calculating infiltration flux, which affects the water balance computation in the aquifer (Blasch & Bryson, 2007; Fang, 2012; Li et al., 2008; Lian, 2007). However, we can estimate the age of groundwater and the renewable rate of groundwater with isotope technology, so as to help evaluate the renewable capacity of groundwater (Huang et al., 2017a, 2017b; Kazemi et al., 2006a, 2006b; Shi, Dong, Li, & Zhang, 2012; Wood & Sanford, 1995).

It is known that the concentration of the radioactive isotope T changes continuously in the atmosphere after the nuclear explosion test. The age of "young" groundwater can be estimated by the concentration of T in groundwater (Gao, 2008; Zhai, Wang, Huan, Zhou, & Wei, 2013). Due to the influence of dispersion and mixing in groundwater system, we usually use the total mixed isotope model to estimate the groundwater renewability rate (Leduc, Favreau, Marlin, & Drag, 2000).

The arid area is generally confronted with various environmental concerns such as water shortages and fragile ecological environment. Yinchuan Basin is located in the north of Ningxia Hui Autonomous Region of China and belongs to the middle temperate inland arid climate zone. Yinchuan Basin is rich in mineral resources, oil resources, and gas resources. It is not only a relatively developed social and economic area in Ningxia Province but also an important agricultural and industrial base in northwest China (Su & Lin, 2004). With the continuous development of economy, Yinchuan Basin has an increasing demand for water resources. However, local water resources are very scarce, especially deep groundwater (Su, 2002). Water shortage will threaten the sustainable development and ecology of Yinchuan Basin. Therefore, it is of strategic significance to fully understand the groundwater circulation and renewable capacity of the research area (Lian, 2007).

The present study aims at evaluating the circulation pattern and renewable capacity of the phreatic water in Yinchuan Basin, which focusses on the following aspects: (a) the analysis of isotopic characteristics of different water bodies in Yinchuan Basin; (b) determination of recharge ratio of phreatic water via a simple hybrid model; (c) estimation of the average residence time of phreatic water using the exponential model; and (d) estimation of phreatic water renewal rate by fully mixed isotope model.

2 | MATERIALS AND METHODS

2.1 | Study area

Yinchuan Plain is located in the northwest of China. It is situated between 105°45′–106°56′ and 37°46′–39°23′N. It extends 165 km in the N-S direction and 42–60 km in the E-W, covering 7,790 km^2. The elevation of the Yinchuan Plain is 1,100–1,200 m above mean sea level, the lowest in Ningxia Hui Autonomous Region. The plain covers Yinchuan City, Shizuishan City, and Wuzhong City (Figure 1).

The climate of study area has a typical continental climate characterized by less rain, strong evaporation, and dry climate. The average monthly temperature varied from −7.73°C in January to 23.63°C in July, and the average annual temperature is 8.92°C. In addition, the annual mean precipitation amount is 186.7 mm and is mainly concentrated in June to September, which accounts for more than 68.1% in the total annual precipitation amount; the annual potential evaporation amount is 1,838.44 mm, which is about 10 times as much as the rainfall for the area. Besides, the annual mean humidity is 55%. Groundwater in study area can be divided into four types: porous water in loose deposits (phreatic water), clastic fissure water, carbonate fissure water, and bedrock fissure water, and the target aquifer in this study is the phreatic water in loose deposits (Qian et al., 2014; Yang et al., 2018). Phreatic water in study area can be recharged by leakage and irrigation infiltration from the Yellow River, precipitation, and lateral runoff. Phreatic runoff is influenced by natural and artificial factors such as topography, lithology, drainage, and ditches. Phreatic water flows from southwest to northeast in study area, but there are some differences in runoff direction and conditions in different regions. In the surrounding area of the Yinchuan Plain, groundwater flows from the sides to the middle of the area with large hydraulic gradient. In the southern area, phreatic water flows to the Yellow River (Yang et al., 2018).

2.2 | Data collection and measurement

A total of 30 groups of precipitation data, which come from the global atmospheric precipitation monitoring data and materials of International Atomic Energy Agency, are collected in this thesis. Fifty-three isotopic water samples of other water bodies are collected, including 11 Yellow River water samples and 47 phreatic water samples. We

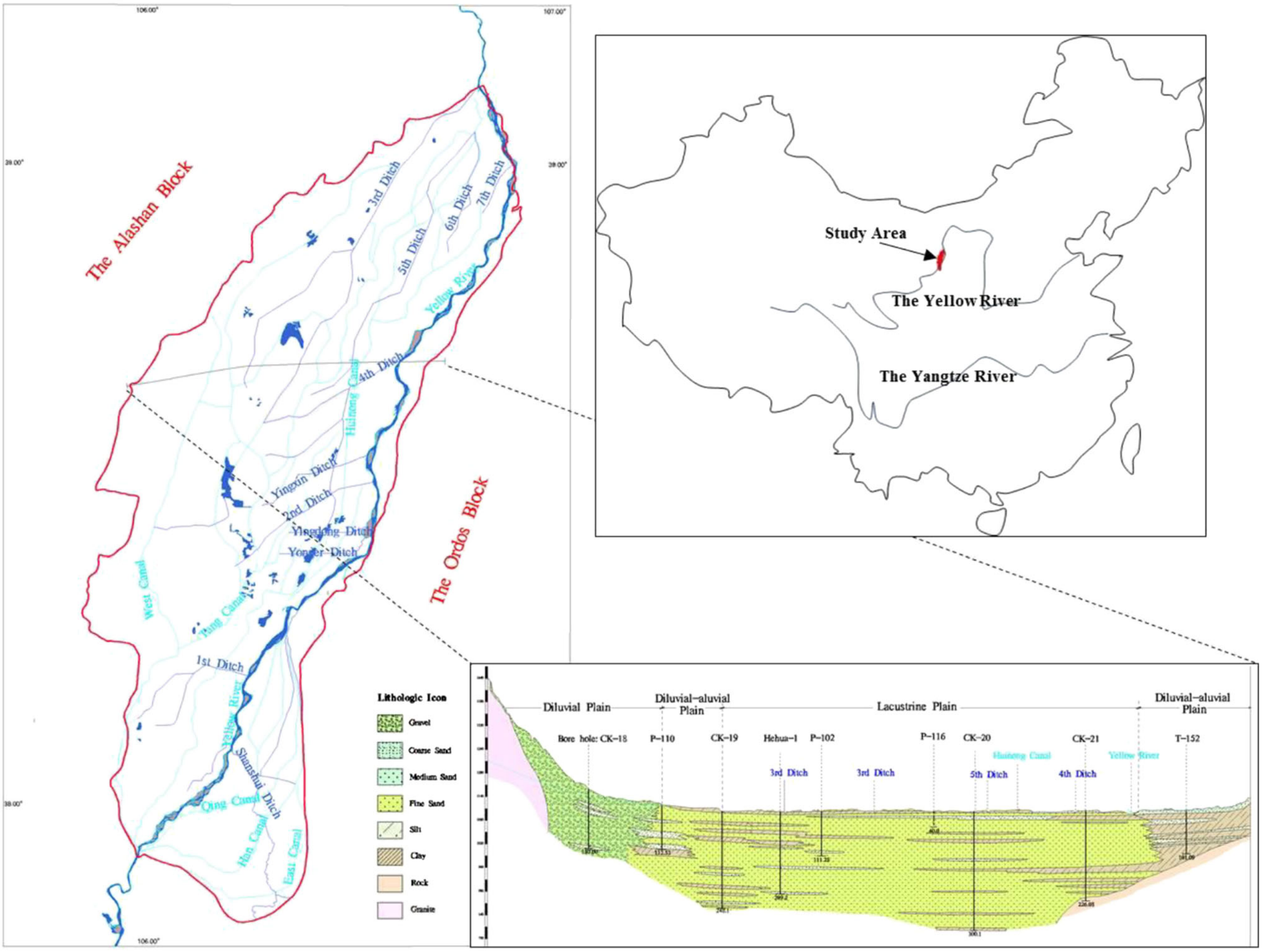

FIGURE 1 Location map of Yinchuan Basin

use 30-ml LPET brown plastic bottle to collect water samples. Before the samples are collected, the samples were filtered through a 0.02-μm filter, and the collection bottles were washed three times with the samples. The samples were sent to Xian China Geological Survey Center, and the LGR liquid water isotope analyser was used to determine the isotopic composition of $\delta^{18}O$, δD, and δT in the samples. It is effective to use them to analyse isotope characteristics.

2.3 | Data availability statement

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

3 | THEORETICAL METHOD

3.1 | Age calculation of phreatic water

Tritium (^3H) physically mathematical model is used to estimate the age of the phreatic water in the research area. It is assumed that under the condition of steady flow, the variation of groundwater flow velocity can be ignored and ^3H transfer in groundwater system obeys the linear rule; thus, groundwater system can be conceptualized into a linear lumped-parameter system. ^3H transfers between the input and output are subject to the following model (Malaszewski & Zuber, 1996; Wang, 1991):

$$C_{out}(t) = \int_0^{\infty} C_{in}\left(t - t'\right) g\left(t'\right) e^{-\lambda t'} dt', \tag{1}$$

where t is sampling time, t' is ^3H migration time, λ is the decay coefficient of ^3H (0.055764), $C_{out}(t)$ and $C_{out}(t - t')$ ^3H are the output and input concentration in groundwater system, respectively, and $g(t')$ is the distribution function of groundwater age.

Hydrogeological conditions of the research area indicate that the exponential model can be used to represent the distribution function of groundwater age. The model assumes that the groundwater with different ages is mixed uniformly at any time in the groundwater system and the output content is equal to the average content of the groundwater (Malaszewski & Zuber, 1996), which is expressed as (where t_t is average residence time of tracer)

$$g(t') = t_t^{-1} \exp(-t'/t_t). \quad (2)$$

Groundwater samples were collected in September 2004, so t = 2004 and t' = 1953, $t - t'$ = 51 years. Thus, Equation (1) can be written as follows:

$$C_{out}(t) = \frac{1}{t_t} \sum_{t'=0}^{51} C_{in}(t - t') e^{-t'\left(\frac{1}{t_t}+0.055764\right)}. \quad (3)$$

3.2 | Renewal rate calculation of phreatic water

The fully mixed isotope model with annual time steps is used to estimate the renewal rate of groundwater. The model of a fully mixed aquifer assumes that a complete mixture of groundwater issued from successive recharge events occurs within the aquifer, which is proposed to tritium data. On the basis of the mixture in the aquifer and radioactive decay, this model can be directly used to ^3H. Therefore, ^3H output concentration can be calculated from the radioactive decay in solution and the annual input, which is formulated as Equation (4) (Le Gal La Salle et al., 2001):

$$A_{gi} = (1 - R_i)A_{gi-1}e^{-\lambda} + R_i A_{0i}, \quad (4)$$

where A_{gi} is the concentration of radioactive isotopes in groundwater, R_i is annual renewal rate, A_{0i} is radioactive isotope concentration of input water, λ is the decay coefficient of ^3H, and i is calculation time by year, ranging from 0 to 53 (corresponding to the calendar year 1952–2004). Equation (4) takes into account the annual input change of ^3H since 1952. Before 1952, the groundwater system is assumed to be at a steady state, and the ^3H concentration of groundwater is set as a constant input (A_0 = 10 TU). The expression is as follows:

$$A_{g1952} = \frac{A_0}{(\lambda/R + 1)}. \quad (5)$$

Assuming that annual supply is proportional to annual precipitation, on this basis, annual renewal rate (R_i) can be weighted by average renewal rate (R) and annual precipitation (P_i; Miao, 2011). Therefore, the calculation formula of annual update rate is as follows:

$$R_i = \frac{(P_i - P_t)}{(P_m - P_t)} R, \quad (6)$$

where P is annual precipitation; P_m is average precipitation over many years; and P_t is minimum rainfall to produce recharge.

3.3 | Calculation of recharge proportion of phreatic water

The recharge source of the phreatic water in the research area can directly use the hydrogen–oxygen stable isotope of water to determine the mixing ratio of two different types of water by virtue of the $\delta^{18}O$ or δD. The expression is as follows:

$$\lambda_A = \frac{\delta_M - \delta_B}{\delta_A - \delta_B}, \lambda_B = 1 - \lambda_A, \quad (7)$$

where λ_A and λ_B are the ratio of the two ends of mixed water; δ_A and δ_B are isotope content of water in two units; and δ_M is isotope content of mixed water.

4 | RESULTS AND DISCUSSION

4.1 | Identification of groundwater recharge source

D and ^{18}O stable isotopes of groundwater can provide insightful information on recharge sources. According to the precipitation observation from 1988 to 2000, the local meteoric water line (LMWL) is $\delta D = 7.22\delta^{18}O + 5.50$ (Figure 2). The weighted mean of δD and $\delta^{18}O$ in precipitation is −45.59‰ and −6.93‰, respectively. The stable isotopic composition has large variations of $\delta^{18}O$ ranging from −19.97‰ to 3.86‰ and δD ranging from −147.7‰ to 5.1‰. The slope of the LMWL is 7.22, which is slightly less than the global average of 8 (Craig 1961; $\delta D = 8\delta^{18}O + 10$, global meteoric water line [GMWL]). Yinchuan Basin belongs to the semiarid climate zone, there is less rainfall with high intensity in the basin, and the precipitation falls to the earth's surface after a certain degree of evaporation.

The Yellow River, as the second longest river following Yangtze River in China, flows through the Yinchuan Basin from southwest to northeast. The tributaries and mainstreams of the Yellow River are widely distributed in the study area and servers as the primary water supply. According to the sampling points collected in Yellow River, the linear correlation equation of the Yellow River is $\delta D = 3.73\delta^{18}O - 36.70$. It can be seen in Figure 3 that the Yellow River evaporation line (dashed red line) deviates significantly from GMWL and LMWL, its slope (3.73) is much smaller than that of GMWL (8) and LMWL (7.22), and the isotopic compositions of the Yellow River waters are smaller and more depleted than those of precipitation, which indicates that Yellow River water has undergone an intensive evaporation.

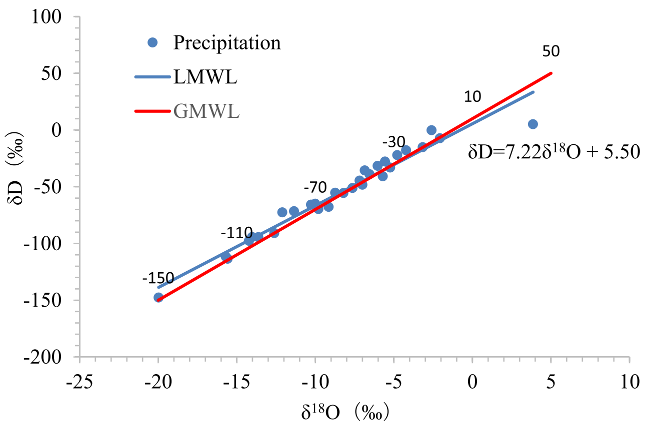

FIGURE 2 The local meteoric water line of Yinchuan Basin

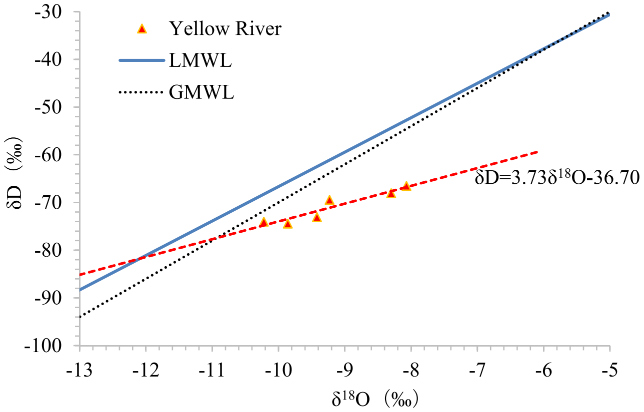

FIGURE 3 Scattered plot of δD versus $\delta^{18}O$ for Yellow River samples

Figure 4 shows that the composition of phreatic water isotopes has a significant aggregation phenomenon ($\delta^{18}O$ ranging from −11.43‰ to −8.19‰ and δD ranging from −88.89‰ to −61.51‰) and the sampling points are located below LMWL. The linear correlation equation of phreatic water is $\delta D = 3.88\delta^{18}O - 38.76$, and its slope lies between that of LMWL and Yellow River, which indicates that the phreatic water is recharged primarily by Yellow River water and local precipitation. The evaporation line of phreatic water is nearly parallel to that of Yellow River; therefore, it can be inferred that the primary recharge source of phreatic water in Yinchuan Basin is the Yellow River. It is also found that the average value of shallow groundwater and Yellow River is very similar (with a value of −70.48‰ and −72.45‰ for D and −9.42‰ and −9.56‰ for ^{18}O), suggesting that the Yellow River contributes more to the recharge of shallow groundwater.

Through the analysis of isotope characteristics of different water bodies, the phreatic water in Yinchuan Basin is mainly supplied by the Yellow River and precipitation.

The results calculated by the two-terminal mixed model are shown in Table 1. It can be seen that the two major recharge sources to phreatic water, the Yellow River and precipitation, account for 87% and

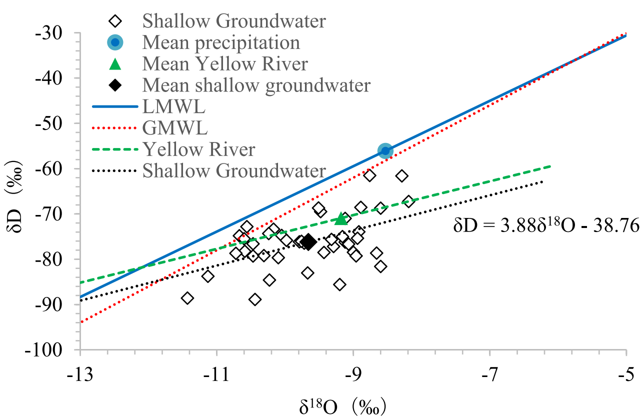

FIGURE 4 δD versus $\delta^{18}O$ scatter plot for shallow groundwater samples

TABLE 1 The recharge proportion of phreatic water from the Yellow River and precipitation (%)

Parameter	Yellow River	Precipitation
$\delta^{18}O$	86	14
δD	88	12
Average value	87	13

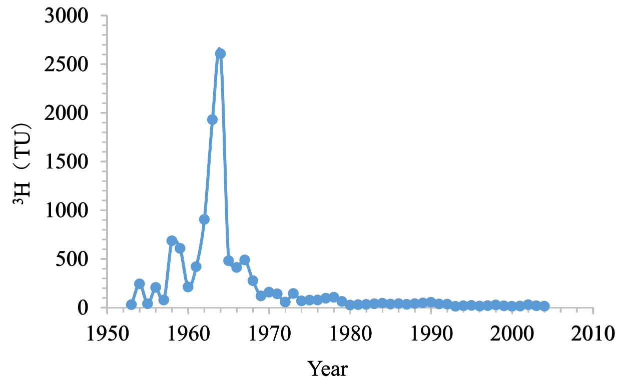

FIGURE 5 ^{3}H recovery curve of atmospheric precipitation in Yinchuan Basin

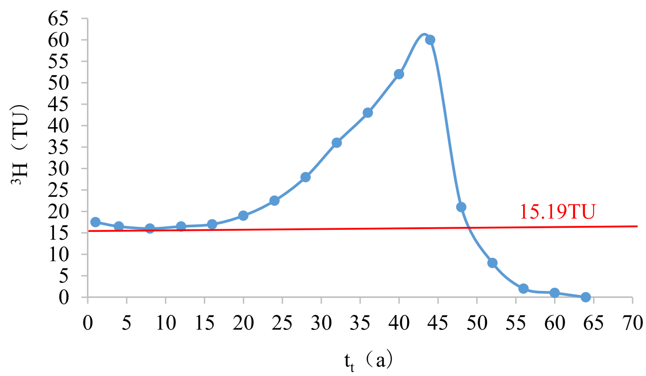

FIGURE 6 ^{3}H output concentration curve of Yinchuan Basin

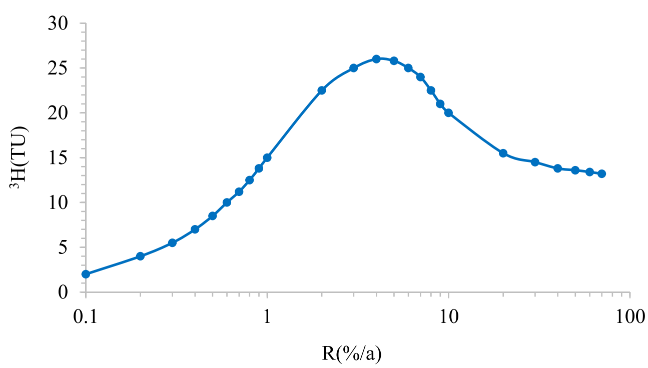

FIGURE 7 Relation curve between renewal rate and ^{3}H concentration

TABLE 2 Calculation results of phreatic water renewal rate in Yinchuan Basin

Sample	^3H (TU)	R (%/a)	$R_{confirm}$ (%/a)
YT23	31.99	3.2	3.2
YT24	19.01	1.3, 12	1.3
S-70	3.85	0.2	0.2
S-200	14.85	1, 30	1
S-60	0.55	0.1	0.1
S-42	<0.50	0.1	0.1
S-47	<0.50	0.1	0.1
S-24	1.97	0.1	0.1
S-78	16.25	1.1, 15	1.1
S-12	17.95	1.3, 12	1.3
S-27	11.9	0.7	0.7
S-4	7.42	0.4	0.4
S-3	19.81	1.6	9.5
S-2	7.38	0.4	0.4
S-6	36.05	3.2	3.2
S-51	<0.50	0.1	0.1
S-56	32.74	3.2	3.2
S-72	17.99	1.3, 12	1.3
S-77	39.82	3.2	3.2
S-71	<0.50	0.1	0.1
S-67	<0.50	0.1	0.1
S-61	<0.50	0.1	0.1
S-62	10.28	0.6	0.6
S-50	16.08	1.1, 15	15
S-44	23.05	2.1, 7	7
S-45	0.72	0.1	0.1
S-46	10.64	0.6	0.6
S-73	22.89	2, 8	2
S-16	<0.50	0.10	0.10
S-36	l1.34	0.7	0.7
S-33	3.29	0.2	0.2
S-11	26.31	2.6, 6	6
S-13	10.17	0.6	0.6
S-18	16.46	1.1, 15	15
S-20	5.76	0.3	0.3
S-40	18.67	1.3, 12	1.3
S-79	20.07	2, 9	9
S-8	13.7	0.9, 50	50
S-23	10.43	0.6	0.6
S-14	4.12	0.2	0.2
S-25	17.41	1.3, 12	1.3
S-29	6.82	0.4	0.4

13% of the total recharge, respectively. It is quantitatively proved that the main supply source in Yinchuan Basin is the Yellow River.

4.2 | Residence time of groundwater

The ^3H recovery results of Yinchuan Basin were obtained by using the ^3H data of atmospheric precipitation from the International Atomic Energy Agency, as well as the precipitation data of Irkutsk and Hong Kong from 1969 to 1976, which is shown in Figure 5.

According to the input concentration of atmospheric precipitation $C_{in}(t - t')$ and a set of average residence time (t_t), the ^3H output concentration $C_{out}(t)$ under different t_t conditions can be obtained, which is plotted in Figure 6. Then, the fitting point (average duration of stay in phreatic water) corresponding to the measured ^3H value of the sample is found. In this paper, the average residence time of phreatic water in Yinchuan Basin was fitted using the average value of ^3H (Liu, Liu, & Xu, 1997). The mean value of ^3H phreatic water in Yinchuan Basin is 15.19 TU (red line), so the optimal fitting point obtained from Figure 6 is t_t = 48a.

Interpolation method is employed to recover ^3H concentrations of precipitation since 1952, which is thereby used as the input values of the fully mixed model. ^3H output concentration (A_g) in sampling year (2004) of groundwater and the corresponding annual renewal rate (R) can be obtained, which is demonstrated in Figure 7. The measured ^3H concentrations of the sampling points are projected in Figure 7, and the renewal rate (R) of the phreatic water is obtained accordingly, which is listed in Table 2.

4.3 | Renewability rate of groundwater

The renewal rate of the phreatic water in Yinchuan Basin ranges 0.1–50%/a, with an average value of 3.38%/a. The phreatic water in different regions of Yinchuan Basin is affected by different external geological environment, so their renewable capacity is also different. The results of the model show that phreatic water has a strong renewable capacity and the regeneration rate distribution is basically consistent with that indicated by isotope age.

5 | CONCLUSIONS

The present paper examines the isotope environmental signatures of three water bodies to estimate quantitatively its circulation pattern and to ascertain the renewability. On the basis of the above discussions, the findings are reached: (a) The phreatic water in Yinchuan Basin is supplied by precipitation and Yellow River. The proportion of precipitation and Yellow River, respectively, is 13% and 87%.The Yellow River is the main source of groundwater recharge in Yinchuan Basin; (b) Yinchuan Basin phreatic water actively participates in the modern hydrological cycle. The isotope age of the phreatic water sample is more than 50a, accounting for 42% of the total samples. The average retention time (t_t) of phreatic water in Yinchuan Basin is 48 years, which means that it will take 48 years for all the phreatic water in Yinchuan Basin to be fully renewed; and (c) the mean renewal rate of phreatic water in Yinchuan Basin is 3.38%/a, and the variation range of the renewal rate of the phreatic water is 0.1–50%/a, indicating that the phreatic water in Yinchuan Basin has a strong renewal ability. The regeneration rate distribution is basically consistent with that indicated by isotope age. However, there is no involvement of deep groundwater in the present study due to lack of data, because there is close hydraulic connection between shallow groundwater and deep groundwater. It is therefore encouraged to make further study on the deep groundwater renewability in the future.

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