Evaluation of surface water–groundwater interaction using environmental isotopes (D, ^{18}O and ^{222}Rn) in Chongli Area, China

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Abstract

In order to understand the interaction between surface water and groundwater in Qingshuihe Basin of Chongli Area, the environmental isotopic D, ^{18}O and ^{222}Rn in surface water and groundwater have been analysis, the study results show that: the calculation results based on the D and ^{18}O, the surface water in middle stream of Donggou River has been recharged by groundwater and river water upstream, the percentage of groundwater recharge is 56%; the calculation results based on the ^{222}Rn, the average seepage rate of surface water is 27.8 m^3/d/m in the upstream section, and the average recharge rate of groundwater is 17.6 m^3/d/m. It is concluded that, the groundwater and surface water interaction is the main characteristics and processes of water cycle in Qingshuihe Basin, and groundwater recharge is the main sources of surface water in draught seasons.

Keywords Qingshuihe Basin · D and ^{18}O isotope · Surface water and groundwater interaction · ^{222}Rn

Introduction

The transformation of surface water and groundwater is the most important water cycle process in the evaluation and management of regional water resources [1–5]. Deeply understanding the transformation relationship between surface water and groundwater is of great significance to the establishment of regional water cycle model and the evaluation and management of regional water resources. Water shortage is the most important factor restricting the sustainable development of social economy and the construction of ecological environment in North China [6–9], research on the relationship between surface water and groundwater transformation is of great significance to the accurate evaluation of regional water resources and water quality [10–12].

Environmental isotope technology has gradually developed into an important means of water resources research, especially the D, ^{18}O and ^{222}Rn [13], which are the components of water, have carried out a lot of research and obtained abundant research results on surface water and groundwater transformation, groundwater recharge sources, water evaporation and mixing and so on [14–28], making the hydrogen and oxygen isotope technology an important and mature means in the research process of the relationship between surface water and groundwater transformation.

Study area

The study area located in Chongli, the northwest of Hebei Province. The traffic location is shown in Fig. 1. The landform of study area belongs to middle and high mountain landforms; the general topographic trend is high in the northeast and low in the southwest, with natural inclination. Its altitude ranges from 820 to 2129 m, and the boundary is surrounded by mountains with rolling hills. The east ditch, middle ditch and west ditch run through the whole area from northeast to southwest.

Chongli Area belongs to the mid-temperate semi-arid continental monsoon climate and it's always dry and rainless. The annual average temperature ranges from 3.2 to 3.7 °C. Influenced by mountainous terrain, the annual precipitation is mostly concentrated in June to September, and sometimes there are hail and rainstorm disasters. According to the data of precipitation and evaporation from 1971 to

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Fig. 1 Study area
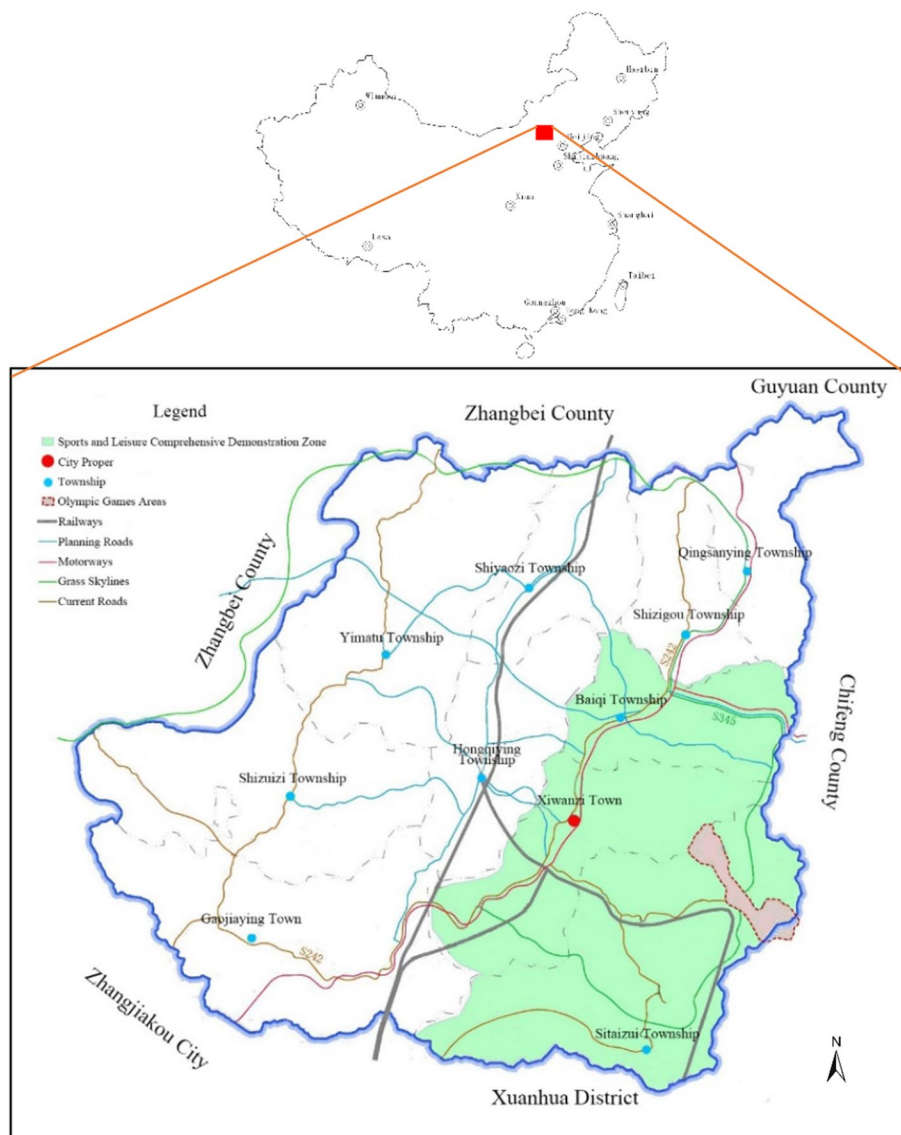
2017, the average annual precipitation and evaporation are 472.83 mm and 1416.45 mm respectively.

The rivers in Chongli belong to two river systems. The eastern part of Qingsanying Township belongs to Chaobai River system, and its watershed area accounts for 4.3% of the total area. The rest belongs to Yongding River system, including Qingshuihe and XiaoQingshuihe (Panchang River), whose basin area accounts for 95.7% of the total area of the region.

Samples and methodology

Water sample collection

According to the hydrogeological conditions and field investigation results of Chongli, in this study, isotope samples were collected from typical surface water and groundwater monitoring sites in east ditch, middle ditch and west ditch respectively. A total of 40 water samples were collected, including 18 surface water samples, 19 groundwater samples and 3 atmospheric precipitation samples. During the sampling process, the well depth, longitude, latitude and surrounding environment of the sampling points are recorded respectively. The spatial distribution of the sampling points is shown in Fig. 2.

From the distribution map of sampling points, we can see that: (1) 12 water samples were collected in east ditch, including 6 surface water samples and 6 groundwater samples; (2) 8 water samples were collected in middle ditch, including 4 surface water samples and 4 groundwater samples; (3) 8 water samples were collected in west ditch, including 5 surface water samples and 3 groundwater

Fig. 2 Distribution of sampling points
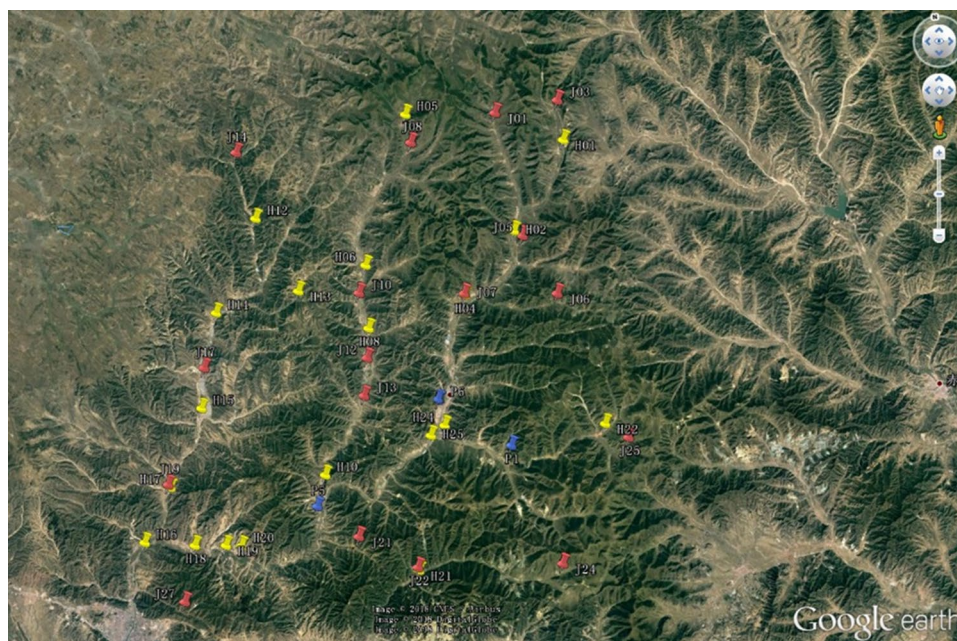
samples; (4) 9 other monitoring points; (5) 3 Meteorological water samples.

Sampling method and testing indicators

Sampling methods of isotope samples refer to the application guideline of isotope hydrology technology in the Ministry of Water Resources Standards of China. Extract at least three times the volume of stable water in wellbore and track and measure field data at any time, such as temperature, pH and conductivity. When these data are stable, water samples are collected through non-polluting instruments and in accordance with relevant sampling requirements.

In order to ensure the reliability of the test results, the following operations must be guaranteed: cleaning the sampler, taking blank samples in the same process as sampling, and collecting parallel samples to determine the errors caused by sampling or experimental analysis.

Stable isotope ^{2}H and ^{18}O samples need no special treatment, they are sealed by screw cap and sampled in a 50 mL linear polyethylene (PE) bottle. Radioisotope ^{222}Rn samples need no special treatment, they are sealed directly with screw caps, glass bottles with a volume of 500 mL can be sampled, sampling time should be recorded accurately to minutes.

Testing units and methods

In this field survey, the main indicators for routine field measurement of hydrochemical components are pH and DO. Among them, pH was measured by PHS-3E pH meter and glass electrode method, DO was measured by JPB-607A

dissolved oxygen meter and electrochemical probe method. Deuterium and oxygen isotopes were tested by Beijing Original Ecology Testing Co., Ltd. in this study, the instrument was L2130-l produced by Picarro Co., USA, using WS-CRDS technology (wavelength scanning optical cavity ring-down spectroscopy). The ^{222}Rn isotope content in water was determined by RAD7 α energy spectrum radon detector of Durridge Co., USA.

Calculation method of groundwater-surface water conversion based on δD and δ^{18}O

The main sources of groundwater recharge in Chongli area are meteoric water infiltration, river water infiltration and lateral groundwater inflow. According to the law of mass conservation of δD and δ^{18}O isotopes, a three-unit mixing model of stable isotopes can be established [7, 24]. The calculation formulas are as follows:

$$\delta D_M = f_1 \delta D_1 + f_2 \delta D_2 + f_3 \delta D_3 \tag{1}$$

$$\delta^{18}O_M = f_1 \delta^{18}O_1 + f_2 \delta^{18}O_2 + f_3 \delta^{18}O_3 \tag{2}$$

$$f_1 + f_2 + f_3 = 1 \tag{3}$$

In the formula, δD_M represents the deuterium isotope values after mixing of different endmembers, δD_1, δD_2 and δD_3 represent the deuterium isotope values of different mixing endmembers, respectively, $\delta^{18}O_M$ represents the oxygen isotope values after mixing of different endmembers, $\delta^{18}O_1$, $\delta^{18}O_2$ and $\delta^{18}O_3$ represent the oxygen isotope values of different mixing endmembers respectively, f_1, f_2 and f_3 represent the mixing ratios of different mixing endmembers.

Calculation method of surface water–groundwater conversion based on ^{222}Rn

In groundwater research, ^{222}Rn as an environmental tracer can determine the age of groundwater in a relatively short time scale, estimate surface water infiltration rate, infer the flow rate of fractured rock aquifer and the relationship between surface water and groundwater, etc. Among them, ^{222}Rn as an environmental tracer is very effective in studying groundwater recharge to rivers, which has incomparable advantages compared with other environmental tracers [14, 17, 27]. This is because the concentration of ^{222}Rn in groundwater is much higher than that in surface water. When groundwater with high concentration of ^{222}Rn enters surface water, it will increase the concentration of ^{222}Rn in surface water at the discharge site, and it has a very short half-life. That is to say, when groundwater leaves the aquifer, ^{222}Rn will decay rapidly and have weak inheritance. Therefore, the location of groundwater discharge and the rate of recharge can be determined by analyzing the variation of ^{222}Rn concentration in surface water along the river [13].

According to the hydrogeological conditions and the results of surface water flow measurement in the study area, the typical sections for studying the transformation of surface water and groundwater in the mainland can be determined. The transformation relationship between surface water and groundwater is quantitatively calculated by using ^{222}Rn tracer principle. According to the law of conservation of mass, the difference between the total ^{222}Rn in a section of upstream surface water and the total ^{222}Rn in a section of downstream surface water comes from the recharge of groundwater to surface water, the decay of ^{222}Rn in surface water and the diffusion loss of ^{222}Rn in surface water to air. According to this principle, different mass conservation equations can be constructed in different recharge relationship between groundwater and surface water to calculate the conversion of surface water and groundwater [18, 26].

For the section of groundwater recharge surface water [23]:

$$C_d Q_d = \int_0^L q_g C_g e^{(-\alpha x)} dx + C_u e^{(-\alpha L)} Q_u \tag{4}$$

$$q_g = \frac{C_d Q_d - C_u e^{(-\alpha L)} Q_u}{C_g} \cdot \frac{\alpha}{1 - e^{(-\alpha L)}} \tag{5}$$

For the section of surface water recharge groundwater:

$$C_d Q_d = C_u e^{(-\alpha L)} Q_u - \int_0^L q_r C_u e^{-\alpha(L-x)} dx \tag{6}$$

$$q_r = \frac{C_d Q_d - C_u e^{(-\alpha L)} Q_u}{C_u} \cdot \frac{\alpha}{e^{(-\alpha L)} - 1} \tag{7}$$

For the section of groundwater recharge to surface water and surface water recharge to groundwater at the same time:

$$\begin{cases} C_d Q_d = C_u e^{(-\alpha L)} Q_u + \int_0^L q_g C_g e^{(-\alpha x)} dx - \int_0^L q_r \frac{(C_u + C_d)}{2} e^{-\alpha(L-x)} dx \\ Q_d = Q_u + q_g L - q_r L \end{cases} \tag{8}$$

$$q_r = \frac{2\alpha (C_d Q_d - Q_u C_u e^{-\alpha L})}{(1 - e^{-\alpha L})(2C_g - C_u - C_d)} - \frac{2C_g(Q_d - Q_u)}{L(2C_g - C_u - C_d)} \tag{9}$$

$$q_g = \frac{2\alpha (C_d Q_d - Q_u C_u e^{-\alpha L})}{(1 - e^{-\alpha L})(2C_g - C_u - C_d)} - \frac{(C_u + C_d)(Q_d - Q_u)}{L(2C_g - C_u - C_d)} \tag{10}$$

The decay of ^{222}Rn in surface water along rivers can be expressed as follows:

$$C_u = C_d \exp(\alpha L) \tag{11}$$

$$\alpha = \lambda / v + \frac{D^{\frac{1}{2}}}{\bar{v}^{\frac{1}{2}} \cdot \bar{h}^{\frac{3}{2}}} \tag{12}$$

where D is molecular diffusion coefficient of ^{222}Rn (m^2/s); C_d and C_u are ^{222}Rn concentration (Bq/L) at downstream and upstream monitoring sites respectively; h and $\bar{h}$ represent the average depth (m) of surface water at the section and the average depth (m) of surface water at the calculated section, respectively; v and $\bar{v}$ are the surface water velocity at the cross section and the average surface water velocity (m/s) at the calculated section, respectively; λ is the radiation decay coefficient of ^{222}Rn; α is the attenuation coefficient along the way; L is the distance between two monitoring sections (m); q_g is the recharge of groundwater to surface water per unit width (m^3/s m); q_r is the recharge amount of surface water to groundwater per unit width (m^3/s m).

Results and discussion

Isotope test results in water

In this study, water samples collected from Chongli were tested for hydrochemistry and isotopes, the test results are shown in Table 1. As can be seen from the table, the overall distribution of deuterium and oxygen isotopes in Chongli is relatively wide. The value of δD varies in the range of −89.16 to −62.93‰, with an average value of −76.11‰; the value of δ^{18}O varies in the range of −12.27 to −8.10‰, with an average of −10.39‰.

Table 1 Deuterium and oxygen isotope test results in surface water and groundwater

ID	$\delta^{18}O$ (‰)	δD (‰)	ID	$\delta^{18}O$ (‰)	δD (‰)
J01	−12.27	−89.16	H04	−11.13	−80.39
J03	−12.02	−85.46	H05	−11.88	−85.84
J05	−10.92	−78.84	H06	−10.65	−78.17
J06	−11.03	−79.97	H08	−10.79	−79.75
J07	−11.21	−81.59	H10	−9.61	−72.18
J08	−12.11	−87.57	H12	−9.67	−72.65
J10	−10.93	−79.53	H13	−9.05	−67.06
J12	−10.79	−79.28	H14	−9.29	−70.21
J13	−10.29	−76.01	H15	−8.44	−65.80
J14	−10.04	−75.24	H16	−9.03	−68.85
J17	−9.30	−70.64	H17	−8.12	−64.04
J19	−8.10	−62.93	H18	−9.92	−73.76
J20	−10.21	−73.99	H19	−10.07	−74.37
J21	−10.11	−71.03	H21	−10.13	−72.82
J22	−10.04	−71.62	H22	−11.22	−81.25
J24	−10.54	−74.62	H24	−11.17	−79.52
J25	−10.95	−78.10	H25	−10.71	−77.78
J27	−9.29	−67.53	P1	−7.42	−55.77
H01	−11.92	−85.72	P5	−9.86	−75.16
H02	−11.21	−82.07	P6	−4.57	−46.05

Table 2 ^{222}Rn isotope test results in surface water and groundwater

Number	Bq/L	Number	Bq/L
J01	29.14	H02	5.29
J03	31.13	H04	6.47
J05	30.97	H05	13.82
J06	21.53	H06	15.55
J07	31.83	H08	12.49
J08	44.17	H10	7.06
J10	37.04	H12	6.53
J12	27.02	H13	4.57
J13	19.66	H14	12.94
J14	24.62	H15	3.60
J17	15.31	H16	7.50
J19	10.76	H17	3.85
J20	11.97	H18	5.35
J21	16.63	H19	5.78
J22	14.03	H21	9.91
J24	17.40	H22	3.45
J25	37.36	H24	6.85
J27	40.22	H25	4.81
H01	12.61		

In this study, ^{222}Rn isotope of water samples collected from Chongli were tested, the results are shown in Table 2. It can be seen from the table that the ^{222}Rn isotope in the water have a relatively wide distribution range, the activity values vary from 3.45 to 44.17 Bq/L, with an average of 16.46 Bq/L. Among them, the ^{222}Rn isotope activity in groundwater varies in the range of 10.76 Bq/L to 44.17 Bq/L, with an average value of 25.60 Bq/L; the ^{222}Rn isotope activity in surface water varies in the range of 3.45 Bq/L to 13.82 Bq/L, with an average value of 7.81 Bq/L. Therefore, the activity of ^{222}Rn isotope in surface water is significantly higher than that in groundwater.

Analysis of the transformation relationship between surface water and groundwater based on D and ^{18}O isotopes

Distribution characteristics of δD and δ^{18}O isotopes in atmospheric precipitation

Influenced by water vapor source area, geographical factors and meteorological factors, the isotope composition of precipitation varies greatly. The isotope composition of precipitation in the same area may vary greatly at different times. However, due to the parallel fractionation of stable hydrogen and oxygen isotopes during precipitation, there is often a linear variation between the values of δ^{18}O and δD in precipitation. Craig [28] found that the hydrogen and oxygen isotope compositions of precipitation in North America changed linearly, and the values of δ^{18}O and δD in precipitation fell on a straight line. Based on these data, the equation of atmospheric precipitation line was fitted, that is, Global Meteoric Water Line of Craig (GMWL):

$$\delta D = 8\,\delta^{18}O + 10$$

The linear relationship between δ^{18}O and δD in precipitation provides a theoretical basis for comparing isotope compositions of groundwater and surface water, deducing groundwater recharge conditions, revealing evaporation losses of various water and their mixing effects. Moreover, the linear relationship between δ^{18}O and δD in precipitation is also important for studying the variation of stable isotopes in the process of water cycle. Influenced by local climate, water vapor sources and other factors, the equation of rainwater line in each region is different, mainly reflected in the difference of slope and intercept of rainwater line.

In order to obtain the characteristics of δD and δ^{18}O isotopes, three samples of precipitation water were collected in this study. The results show that the variation range of δD in precipitation ranges from −75.16 to −46.05‰, with a mean value of −58.99‰, and that of δ^{18}O from −9.86 to −4.56‰, with a mean value of −7.28‰.

According to the characteristics of δD and δ^{18}O isotope contents of atmospheric precipitation, the correlation diagram of δD and δ^{18}O contents in precipitation can be drawn as shown in Fig. 3.

The atmospheric precipitation lines obtained by least square method are as follows:

Fig. 3 The correlation between D and ^{18}O in surface water and groundwater
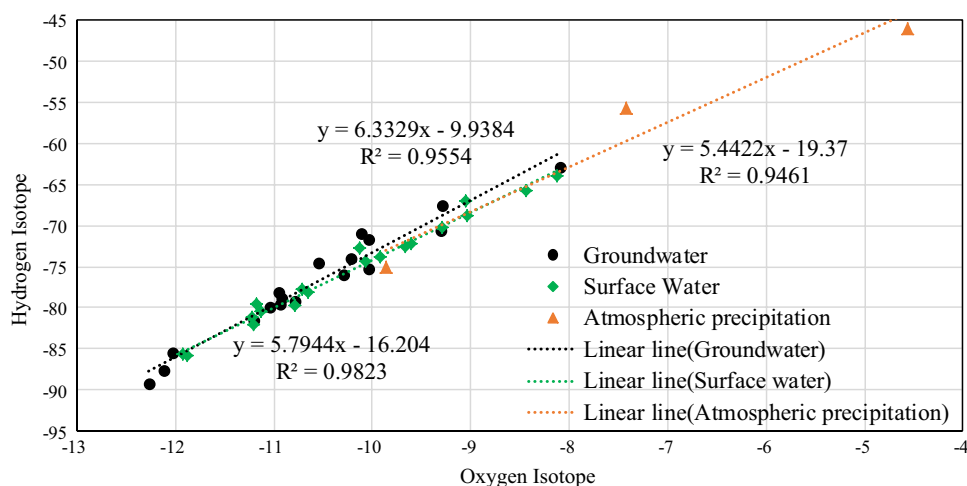
$Y = 5.4422X - 19.37$

It can be seen from Chongli's precipitation line that the slope and intercept are obviously smaller than those of global precipitation line ($Y = 8X + 10$), China's precipitation line ($Y = 7.9X + 8.2$) and Beijing's precipitation line ($Y = 6.467X - 7.553$), which shows that the main source of precipitation is water vapor brought by the ocean monsoon, but the remarkable fractionation process of ocean water vapor occurred during its migration to Chongli. The deuterium surplus from -9.52 to $3.70‰$ with an average of $-0.75‰$, which indicates that Chongli is in the transition zone between semi-arid and semi-humid areas.

Distribution characteristics of δD and δ^{18}O isotopes in surface water

In this study, surface water isotope samples were collected in the upper, middle and lower reaches of east ditch, middle ditch and west ditch, respectively. The results show that the range of variation of δ^{18}O in surface water is -11.92 to $-8.12‰$, the mean value is $-10.21‰$, and the range of variation of δD is -85.84 to $-64.04‰$, the mean value is $-75.38‰$. According to the results of δD and δ^{18}O test in surface water, the correlation diagram between them is drawn, and the linear regression equation can also be obtained by the least square method:

$Y = 5.7944X - 16.204$

From the regression formulas of δD and δ^{18}O in surface water, it can be seen that the slope and intercept of surface water line are larger than that of the atmospheric precipitation line, indicating that surface water has been significantly affected by evaporation.

Distribution characteristics of δD and δ^{18}O isotopes in groundwater

In order to compare and analyze the transformation relationship between surface water and groundwater, in this

study, groundwater isotope samples were collected in east ditch, middle ditch and west ditch, respectively, corresponding to surface water isotope samples. The results show that the range of the value of δ^{18}O in groundwater is -12.27 to $-8.09‰$, with an average value of $-10.56‰$, and the range of the value of δD is -89.16 to $-62.93‰$, with an average value of $-76.84‰$. According to the results of δD and δ^{18}O test in groundwater, the correlation diagram between them is drawn, and the linear regression equation can also be obtained by the least square method:

$Y = 6.3329X - 9.9384$

From the regression formulas of δD and δ^{18}O in groundwater, it can be seen that the slope and intercept of groundwater line are obviously larger than that of surface water line, which indicates that the local groundwater is affected observably by evaporation while receiving the recharge of surface water infiltration.

Quantitative analysis of surface water and groundwater transformation based on D and ^{18}O isotopes

According to the results of δD and δ^{18}O measurements of precipitation, surface water and groundwater, the isotope content characteristics of each typical water body can be obtained. Based on isotope conservation, the transformation relationship and mixing ratio of surface water and groundwater in each typical section can be calculated.

According to the hydrogeological conditions and isotope distribution characteristics, the groundwater is mainly recharged by the infiltration of precipitation, surface water and lateral inflow of groundwater, and surface water is mainly recharged by upstream river water and groundwater discharge. Considering that the isotope content in atmospheric precipitation is affected by significant elevation effect, it is necessary to select a typical control point which is close to the sampling elevation in this study. Because evaporation

affects river water infiltration to recharge groundwater, it is necessary to select surface water and groundwater monitoring points which are close to each other to minimize the impact of evaporation. Based on the above principles and the distribution of sampling points in this field work, the east ditch was selected as the key area of this study.

According to the results of flow measurement in east ditch, it can be seen that in the upper reaches of east ditch, groundwater spillover is the main form of surface water recharge. The characteristics of δD and δ¹⁸O isotopes in groundwater are represented by J05, in surface water by H02, in precipitation by P1, and in lateral recharge sources of groundwater are represented by the average values of J01 and J03. It can be calculated that the contribution ratio of precipitation to groundwater supply is 26%, the contribution ratio of lateral inflow of upstream groundwater to groundwater supply is 70%, and the contribution ratio of surface water infiltration to groundwater supply is only 4% in the upper reaches of east ditch. Thus, it can be seen that the groundwater in the upper reaches of east ditch mainly receives the lateral inflow recharge and the infiltration recharge of local atmospheric precipitation, while the infiltration recharge of surface water is almost non-existent.

The typical section in the middle reaches of east ditch is groundwater spillover to recharge surface water. Therefore, the δD and δ¹⁸O contents in groundwater in the middle reaches of east ditch are represented by J07, the δD and δ¹⁸O contents in local surface water are represented by H04, and the δD and δ¹⁸O contents in surface water in the upper reaches are represented by H04. The results show that the contribution rate of groundwater discharge to sampling point H04 recharge at surface water is 56%, and that of upstream river water to sampling point H04 recharge at surface water is 44%.

Analysis of transformation relationship between surface water and groundwater based on ^{222}Rn

According to the test results of ^{222}Rn isotope in surface water and groundwater, the average activity of ^{222}Rn isotope in groundwater is 25.60 Bq/L, and the average activity of ^{222}Rn isotope in surface water is 7.81 Bq/L. By comparing and analyzing the variation trend of isotope in surface water and groundwater monitoring points, the transformation relationship between surface water and groundwater can be analyzed.

Distribution characteristics of ^{222}Rn along the route in surface water of east ditch

Based on the monitoring results of ^{222}Rn isotope activity in surface water of east ditch, the variation law along the course

is drawn as shown in Fig. 4. It can be seen from the figure that the ^{222}Rn isotope activity in east ditch surface water varied from 4.81 Bq/L at H25 to 12.61 Bq/L at H01, with an average of 7.20 Bq/L. Since H01, the activity of ^{222}Rn isotope in surface water has been decreasing gradually due to decay. The activity of ^{222}Rn isotope in surface water of H02 has been reduced to 5.29 Bq/L, which is much lower than that of ^{222}Rn isotope in surface water of J05 (30.97 Bq/L), it shows that surface water recharges groundwater in this area, and the ^{222}Rn isotope in surface water has natural attenuation; but the ^{222}Rn isotope activity increased slightly from H02 to H24, indicating that surface water began to receive groundwater recharge after entering H02; the Qingshuihe is influenced by the influx of the Taizicheng River in the East and the natural decay of ^{222}Rn isotope, and the activity of ^{222}Rn isotope in surface water decreases again.

Distribution characteristics of ^{222}Rn along the route in surface water of middle ditch

According to the monitoring results of ^{222}Rn isotope activity in surface water of east ditch, the variation law along the course is drawn as shown in Fig. 5. It can be seen from the figure that the ^{222}Rn isotope activity in surface water of Middle Ditch varies from 7.06 Bq/L at H10 to 15.55 Bq/L at H06, with an average of 12.23 Bq/L. From H05 to H06, the activity of ^{222}Rn isotope in surface water increased from 13.82 to 15.55 Bq/L indicating that the river water in this section received the recharge of groundwater and the recharge intensity gradually decreased, and the increase of ^{222}Rn isotope activity from groundwater recharge to surface water was less than the decay rate of ^{222}Rn isotope activity in surface water.

Distribution characteristics of ^{222}Rn along the route in surface water of west ditch

According to the monitoring results of ^{222}Rn isotope activity in surface water of west ditch, the variation law along the
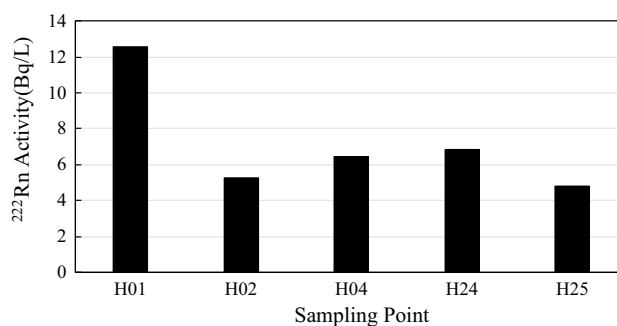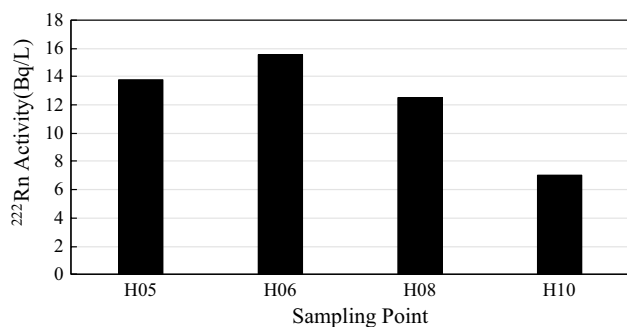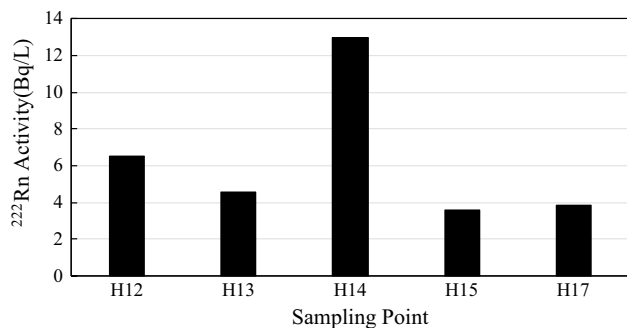

Fig. 4 Change regulation of ^{222}Rn activity in surface water of east ditch

Fig. 5 Change regulation of ^{222}Rn activity in surface water of middle ditch

Fig. 6 Change regulation of ^{222}Rn activity in surface water of west ditch

Table 3 Calculating parameters for each sampling point

Samples	Q (m³/s)	V (m/s)	h (m)	d (m)	Concentration of ^{222}Rn (Bq/L)
H01	28.78	2	2.1	55	1.797
H02	19.63	1.62	1.5	66	3.446
H04	36.82	0.89	0.4	300	2.952

Table 4 Calculation results of groundwater and surface water conversion in each section

Section ID Samples	Section 1 H01–H02	Section 2 H02–H04
C_u (Bq/L)	1.797	3.446
Q_u (m³/s)	228.78	159.63
C_d (Bq/L)	3.45	2.95
Q_d (m³/s)	159.63	107
V (m/s)	1.8	1.26
L (m)	24,000	15,200
q_g (m³/d/m)	63.2	97.6
q_r (m³/d/m)	27.8	17.6

course is drawn as shown in Fig. 6. It can be seen from the figure that the activity of ^{222}Rn isotope in west ditch varied between 3.60 Bq/L at H15 and 12.94 Bq/L at H14, with an average value of 6.29 Bq/L. The ^{222}Rn isotope activity in surface water increased significantly from H12 and H13 to H14, from 6.53 Bq/L in H25 and 4.57 Bq/L in H13 to 12.94 Bq/L in H14, indicating that the surface water in this section received significant groundwater recharge. After H14, the ^{222}Rn isotope activity of H15 and H17 decreased significantly, indicating that the intensity of surface water receiving groundwater recharge gradually decreased, and the natural decay of ^{222}Rn isotope became the main controlling role.

Quantitative analysis of surface water and groundwater transformation based on ^{222}Rn isotopes

Based on the above analysis, several sections with river flow monitoring data were selected to quantitatively calculate the transformation relationship between groundwater and surface water by using ^{222}Rn tracer principle. According to the law of conservation of mass, the difference between the total ^{222}Rn in a section of upstream surface water and the total ^{222}Rn in a section of downstream surface water comes from the recharge

of groundwater to surface water, the decay of ^{222}Rn in surface water and the diffusion loss of ^{222}Rn in surface water to air. According to this principle, different mass conservation equations can be constructed to calculate the conversion between surface water and groundwater in the sections with different recharge relations between groundwater and surface water.

According to the ^{222}Rn isotope characteristics along the river described above, combined with the river discharge relationship at each sampling point, the transformation relationship between groundwater and surface water in each calculation section was verified: surface water is transformed into groundwater in H01–H02 section and groundwater into surface water in H02–H04 section. The relevant parameters of each point (Table 3) are substituted into the corresponding formula and the results are obtained (Table 4). In section H01–H02, the average rate of surface water discharge to groundwater is 27.8 m³/d/m, and in section H02–H04, the average rate of groundwater recharge to surface water is 17.6 m³/d/m, which is consistent with the relationship between surface water and groundwater recharge and drainage as preliminarily determined in the previous paper.

Conclusions

Through collecting surface water and groundwater samples respectively, deuterium and oxygen isotopes and ^{222}Rn distribution characteristics in water are comprehensively

analyzed, and the relationship between surface water and groundwater transformation in Qingshuihe Basin is deeply understood, so as to provide scientific basis for water resources evaluation and sustainable development and utilization in Chongli area. The study results show that:

(1) The calculation results based on the D and ^{18}O, the surface water in middle stream of Donggou River has been recharged by groundwater and river water upstream, the percentage of groundwater recharge is 56%;

(2) The calculation results based on the ^{222}Rn, the average seepage rate of surface water is 27.8 m^3/d/m in the upstream section, and the average recharge rate of groundwater is 17.6 m^3/d/m.

References

1. Banks EW, Simmons CT, Love P et al (2011) Assessing spatial and temporal connectivity between surface water and groundwater in a regional catchment: implications for regional scale water quantity and quality. J Hydrol 404:30–49
2. Du SH, Su XS, Zhang WJ (2013) Effective storage rates analysis of groundwater reservoir with surplus local and transferred water used in Shijiazhuang City, China. Water Environ J 27:157–169
3. Freitas JG, Furquim SAC, Aravena R et al (2019) Interaction between lakes' surface water and groundwater in the pantanal wetland, Brazil. Environ Earth Sci 78:5
4. Song TJ, Chen YX, Du SH et al (2017) Hydrogeochemical evolution and risk assessment of human health in a riverbank filtration field, Northeastern China. Hum Ecol Risk Assess Int J 23(4):705–726
5. Su XS, Lu SH, Yuan WZ et al (2018) Redox zonation for different groundwater flow paths during bank filtration: a case study at Liao River, Shenyang, Northeastern China. Hydrogeol J 26(5):1573–1589
6. Luo X, Jiao JJ, Wang XS et al (2016) Temporal Rn-222 distributions to reveal groundwater discharge into desert lakes: implication of water balances in the Badain Jaran Desert, China. J Hydrol 534:87–103
7. Guo QL, Yang YS, Han YY et al (2019) Assessment of surface-groundwater interactions using hydrochemical and isotopic techniques in a coalmine watershed, NW China. Environ Earth Sci 78(3):91
8. Su XS, Xu W, Du SH (2014) Responses of groundwater vulnerability to artificial recharge under extreme weather conditions in Shijiazhuang City, China. J Water Supply Res Technol Aqua 63(3):224–238
9. Su XS, Cui G, Du SH (2016) Using multiple environmental methods to estimate groundwater discharge into an arid lake (Dakebo Lake, Inner Mongolia, China). Hydrogeol J 24:1707–1722
10. Dhakate R, Modi D, Rao VVSG (2019) Impact assessment of coal mining on river water and groundwater and its interaction through hydrological, isotopic characterstcs, and simulation flow modeling. Arab J Geosci 12(1):8
11. Liao F, Wang GC, Shi ZM et al (2018) Estimation of groundwater discharge and associated chemical fluxes into Poyang Lake, China: approaches using stable isotopes (delta D and delta O-18) and radon. Hydrogeol J 26(5):1625–1638
12. Wang W, Dai Z, Zhao Y et al (2016) A quantitative analysis of hydraulic interaction processes in stream–aquifer systems. Sci Rep 6:19876
13. Nikolov J, Stojkovic I, Todorovic N et al (2018) Evaluation of different LSC method for Rn-222 determination in waters. Appl Radiat Isot 142:56–63
14. Bertin C, Bourg ACM (1994) Radon-222 and chloride as natural tracers of the infiltration of river water into an alluvial aquifer in which there is significant river/groundwater mixing. Environ Sci Technol 28(5):794–798
15. Chanyotha S, Kranrod C, Burnett WC et al (2014) Prospecting for groundwater discharge in the cannals of Bankok via natural radon and thoron. J Hydrol 519:1485–1492
16. Cook PG, Favreau G, Dighton JC et al (2003) Determining natural groundwater influx to a tropical river using radon, chlorofluorocarbons and ionic environmental tracers. J Hydrol 277(1–2):74–88
17. Dimova NT, Burnett WC, Chanton JP et al (2013) Application of radon-222 to investigation groundwater discharge into small shallow lakes. J Hydrol 486:112–122
18. Frei S, Gilfedder BS (2015) FINIFLUX: an implicit finite element model for quantification of groundwater fluxes and hyporheic exchange in streams and rivers using radon. Water Resour Res 51(8):6776–6786
19. Gilfedder BS, Frei S, Hofmann H et al (2015) Groundwater discharge to wetlands driven by storm and flood events: quantification using continuous Radon-222 and electrical conductivity measurements and dynamic mass-balance modelling. Geochim Cosmochim Acta 165:161–177
20. Kalbus E, Reinstorf F, Schirmer M (2006) Measuring methods for groundwater-surface water interaction: a review. Hydrol Earth Syst Sci 10(6):873–887
21. Martinez JL, Raiber M, Cox ME et al (2015) Assessment of groundwater-surface water interaction using long-term hydrochemical data and isotope hydrology: headwaters of the Condamine River, Southeast Queensland, Australia. Sci Total Environ 536:499–516
22. Negrel P, Petelet-Giraud E, Barbier J et al (2003) Surface water–groundwater interactions in an alluvial plain: chemical and isotopic systematics. J Hydrol 277(3–4):248–267
23. Su X, Xu W, Yang F et al (2015) Using new mass balance methods to estimate gross surface water and groundwater exchange with naturally occurring tracer 222Rn in data poor regions: a case study in northwest China. Hydrol Process 29(6):979–990
24. Xu W, Su XS, Dai ZX et al (2017) Multi-tracer investigation of river and groundwater interactions: a case study in Nalenggele River Basin, Northwest China. Hydrogeol J 25(7):2015–2029
25. Xu W, Zhu PC, Yang FT (2019) Evaluation of groundwater recharge sources based on environmental tracers in an arid alluvial fan, NW China. J Radioanal Nucl Chem 319:123–133
26. Yi P, Luo H, Chen L et al (2019) Evaluation of groundwater discharge into surface water by using Radon-222 in the source Area of Yellow River, Qinghai-Tibet Plateau. J Environ Radioact 192:257–266
27. Zhao D, Wang GC, Liao F et al (2018) Groundwater-surface water interactions derived by hydrochemical and isotopic (Rn-222 deuterium, oxygen-18) tracers in the Nomhon area, Qaidam Basin, NW China. J Hydrol 565:650–661
28. Craig H (1961) Isotopic variations in meteoric waters. Science 133:1702–1703

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