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A study of surface water and groundwater using isotopes in Huaishahe basin in Beijing, China

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Abstract By identifying the spatial distribution of isotopic signatures and electrical conductivity of water samples at different sites along the river channel in the study basin, the recharge–discharge relationship between the surface water and groundwater can be clearly evaluated. In this study, spring water, surface water and shallow groundwater in the study area of the Huaishahe Basin in Beijing, China were sampled and analysed for δD, $\delta^{18}O$, pH and conductivity in order to evaluate the characteristics of the spatial distribution of surface water and groundwater. Using a combination of the topographic characteristics of the basin, the runoff characteristics of the river network and the isotopic compositions of the water samples, spring water, surface water and shallow groundwater can be spatially delineated into four regions in order to evaluate the recharge–discharge characteristics.

Key words isotopic indicator; spatial distribution; surface water–groundwater relationships

INTRODUCTION

The capital of China, Beijing, is the most densely populated, cultivated and industrialized area in north China. Most of the fresh water resources in this area are supplied by surface water transported by the Jingmi aqueduct from Miyun Lake and recharged by the Chao and Bai River basin. As is typical in many basins in north China, runoff has decreased in this area over recent decades and this phenomenon has been the target of investigation. A perennial question motivating recharge and runoff studies in the study basin has been whether the ongoing decrease of recharge reflects the interaction between the surface water and groundwater. There is a pressing requirement to assess available surface water resources and to achieve sustainable development in the area, as well as to reverse the damage which has already occurred. In order to achieve these goals, a full understanding of the relationship between surface water and groundwater is required.

Environmental isotope techniques have been proved to be extremely valuable in hydrological studies. For example, Harrington *et al*. (2002) used this approach to study the spatial and temporal variability of groundwater recharge in central Australia, from which they determined the processes affecting evolution of the groundwater. Katz *et al*. (1997) also used the distinct differences between the isotopic and chemical compositions of groundwater and surface water as a means of quantifying their

interactions. Furthermore, variations in the stable isotopic compositions of spring water in Greece were used by Payne *et al*. (1978) to define the area of recharge to the Kalamos springs and to identify the recharge elevation. The effect of altitude on the isotopic composition of precipitation, making the assumption of stable climatic conditions, was used by Weyhenmeyer *et al*. (2002) to identify predominant recharge areas and groundwater flow paths as well as to evaluate the mixing ratios of groundwater components recharged at different altitudes.

The present paper describes an investigation of environmental isotopes and field study of the interaction between the surface water and groundwater in the mountainous Huaishahe Basin, a typical catchment adjacent to the Chao and Bai River Basin. Isotopic data for spring water, river water and shallow groundwater were sampled for different parts of the basin and were evaluated to determine the recharge and discharge inter-relationships between the surface water and groundwater.

SITE DESCRIPTION

The Huaishahe basin is located in the Yan Mountains in the northwest of Huairou District of Beijing (Fig. 1) and has an area of approximately 158 km^2. The main river channel originates in the northwest part of the basin at an altitude of 1200 m. It then incises the Jurassic granite terrain located in the upper part of the basin and wanders its way southeast through the granite basement and the alluvial-diluvial plain, formed in the Quaternary, in the middle parts of the basin. Finally it discharges into the artificial lake of Huairou at an altitude of 78 m.

In this semihumid area, the annual average precipitation is 645 mm, average annual discharge is 243 mm, and the average annual potential evaporation rate is about 1005 mm. Precipitation, potential evapotranspiration, and stream discharge are strongly seasonal, and approximately 82% of the annual rainfall occurs mainly in the summer months from June to September.

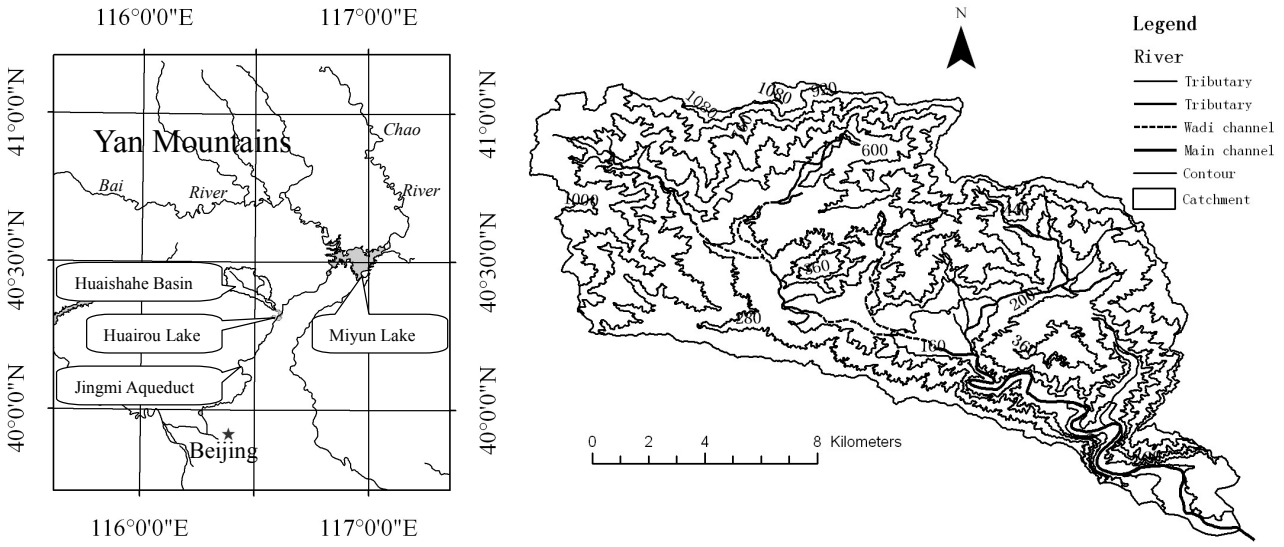

Fig. 1 Location and topography of the study basin.

However, in recent years there has been a decrease in discharge that has prompted the present study. The causes of decreasing discharge are likely to include increased vegetation cover through reforestation, and the construction of numerous artificial barriers along the main channel. Impoundment has meant that some reaches of the main channel, as well as some tributaries, have become dry.

SAMPLING PROCEDURES AND ANALYTICAL METHODS

Spring water, river water and shallow groundwater samples for isotopic analyses were collected at different sites along the river channel in August 2002 (Table 1). Electrical conductivity and pH were measured in the field with a WM-22EP hand-held electrical conductivity and pH meter. δD and $\delta^{18}O$ were measured by the mass spectrometer (Delta S Thermoqest) in the laboratory of Chiba University. Analytical precisions were ±1.0 and ±0.1 per mil for δD and $\delta^{18}O$, respectively. Deuterium and oxygen-18

Table 1 Properties of collected water samples.

Location	Sampling date	Water type	EC (μs cm^{-1})	pH	Altitude (m)	δD	$\delta^{18}O$
HS 1	14-Aug-02	surface water	391	7.07	76	–64.7	–7.84
HS 1-1	14-Aug-02	spring water	438		78	–65.4	–7.67
HS 1-2	14-Aug-02	ground water	773		82	–72.3	–8.40
HS 2	14-Aug-02	surface water	416	7.33	92	–64.3	–7.79
HS 3	14-Aug-02	surface water	394	7.63	172	–69.6	–8.47
HS 3-1	14-Aug-02	ground water	476		178	–70.1	–8.97
HS 4	20-Aug-02	spring water	316		290	–71.2	–8.64
HS 4-1	20-Aug-02	ground water	380	7.43	190	–72.7	–8.62
HS 4-2	20-Aug-02	ground water	418		180	–64.5	–7.90
HS 5	20-Aug-02	surface water	375	7.87	219	–74.1	–9.15
HS 5-1	20-Aug-02	ground water	389		217	–72.1	–8.48
HS 6	20-Aug-02	surface water	326	7.13	360	–71.5	–8.72
HS 7	21-Aug-02	surface water	310	7.26	490	–68.2	–9.10
HS 8	21-Aug-02	surface water	287	7.69	490	–62.1	–8.40
HS 9	14-Aug-02	surface water	408	7.68	105	–62.7	–8.21
HS 9-1	14-Aug-02	ground water	544		110	–61.4	–8.61
HS 10	14-Aug-02	ground water	451		180	–62.0	–8.67
HS 10-1	14-Aug-02	surface water	255		172	–61.9	–7.77
HS 11	14-Aug-02	spring water	355	7.23	220	–67.3	–8.98
HS 12	20-Aug-02	spring water	342		270	–71.1	–8.95
HS 13	20-Aug-02	surface water	422		139	–68.9	–9.02
HS 14	20-Aug-02	surface water	379	7.15	135	–64.6	–8.78
HS 15	20-Aug-02	surface water	424	7.48	140	–68.2	–8.65
HS 16	20-Aug-02	spring water	273	7.08	720	–70.1	–9.80
HS 17	20-Aug-02	spring water	324		305	–69.6	–10.09
HS 18	21-Aug-02	spring water	229	7.18	646	–66.8	–9.22
HS 19	21-Aug-02	surface water	209	7.1	570	–61.9	–8.06
HS 20	21-Aug-02	surface water	204		570	–62.2	–8.30
HS 21	21-Aug-02	surface water	356	7.32	510	–64.5	–8.28
HS 22	21-Aug-02	spring water	242		450	–68.9	–9.34

are reported in the conventional delta notation (δD and $\delta^{18}O$) relative to Vienna Standard Mean Ocean Water (VSMOW).

RESULTS

For the interpretation of stable isotope ratios, the meteoric water line (MWL) was calculated by least squares regression using isotopic values reported from analysis undertaken for 27 GNIP stations in China by IAEA during the 1980s and 1990s. The calculated MWL is:

$$\delta D = 7.82 \times \delta^{18}O + 8.48 \quad (1)$$

A graph of δD and $\delta^{18}O$ values of water samples can be used to distinguish the various origins of spring waters, shallow groundwaters and surface waters in the study area (Fig. 2). Here the three different water types mentioned are clustered together, following three distinct δD–$\delta^{18}O$ relationships. Most waters in this area lie along, or immediately to the lower right of the local meteoric water line (MWL), which has a slope of 7.82.

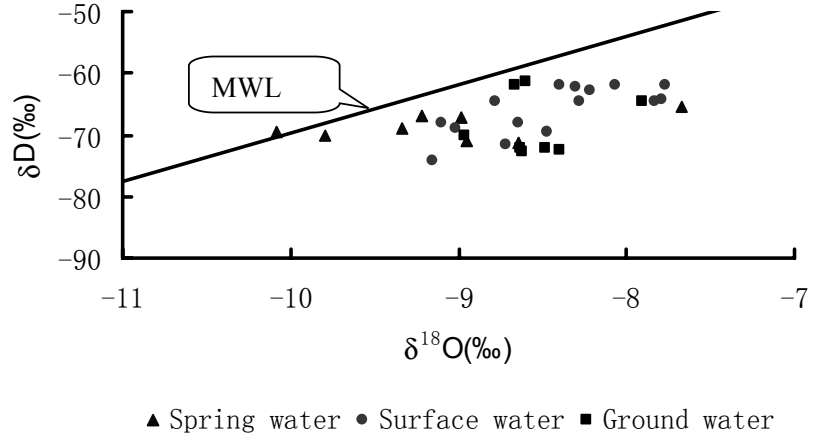

Fig. 2 Stable isotopic compositions of the water samples in the study basin.

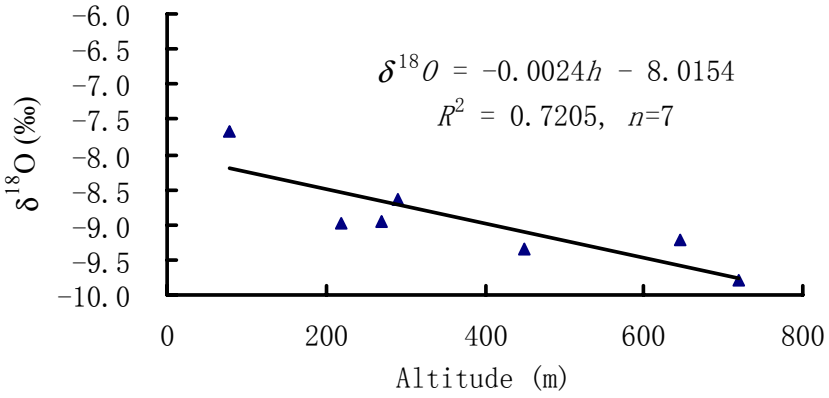

Fig. 3 The relationship of $\delta^{18}O$ in spring water samples and altitude.

The spring water samples are clustered together along a line under the MWL, indicating that the spring water has undergone some degree of isotopic modification due to evaporation before recharge at the surface. Excluding sample HS17, an obvious relationship exists between the $\delta^{18}O$ and altitude of the spring (Fig. 3), which shows that there is an altitudinal effect on the isotopic composition of precipitation and, in turn, spring water as demonstrated by Bartarya *et al*. (1995) for the Kumaun Himalaya in India.

Spring water samples collected from various sites in the range from 78 m to 720 m suggest an altitudinal effect of –0.24‰ per 100 m elevation. On this basis, major recharge areas and groundwater flow paths can be identified following the approach of Weyhenmeyer *et al*. (2002), and it can be suggested that the recharge altitude of spring water sample HS17 should be above 864 m or higher. Two factors therefore appear to modify the isotopic signatures of the springs, namely the altitude effect on springs which were recharged directly by precipitation, and the evaporation effect on rainfall before recharge to the aquifer. The δD and $\delta^{18}O$ compositions of surface water and shallow groundwater exhibit a narrower domain on the δD–$\delta^{18}O$ plot than the rainfall samples, and range from –74.1 to –61.4‰ for δD and from –9.15 to –7.77‰ for $\delta^{18}O$.

Through a comparison of the isotopic signature and electrical conductivity of the water samples collected in different parts of the basin, varying water types with varying isotopic signatures can be delineated as described below:

Spatial distribution of isotopic signatures in spring water Four regions where springs recharge the surface water can be discriminated on the basis of spring location and isotopic signature (Fig. 4):

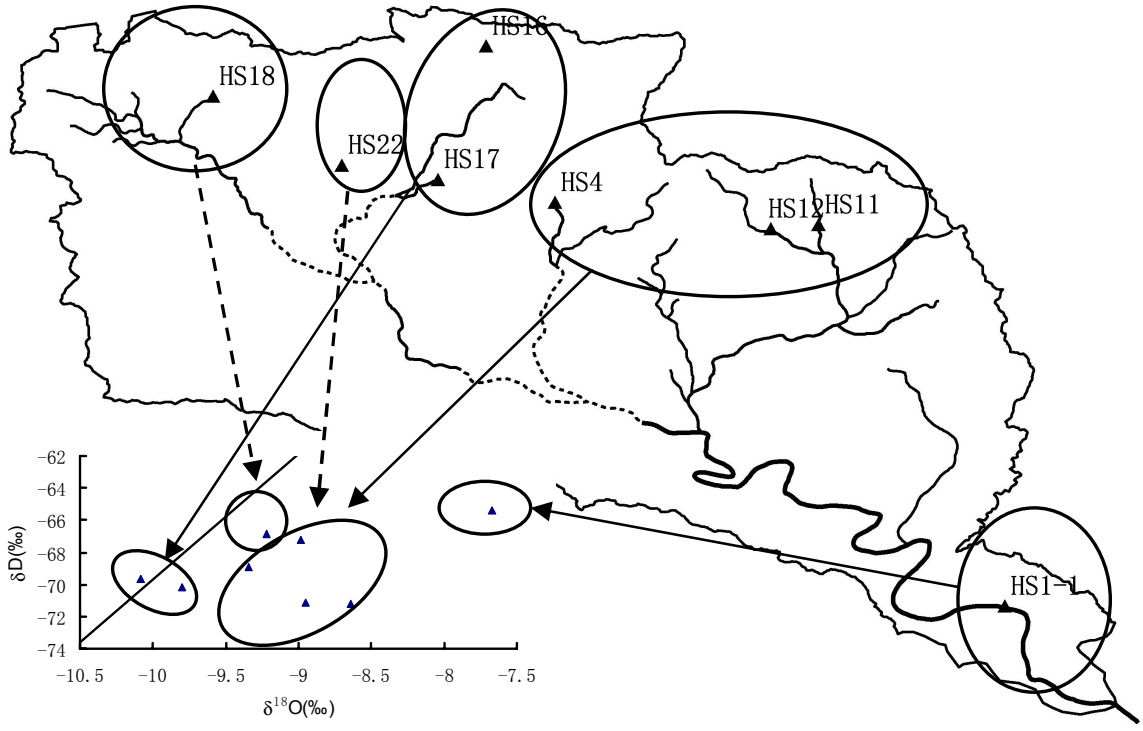

Fig. 4 Spatial distribution of isotopic signatures of spring water.

(a) Middle and upper recharge region in the higher mountains—the springs are recharged directly by precipitation, which after evapotranspiration losses moves through the unsaturated soil zone and then resides in the saturated zone for a shorter residence time before discharging to the river channel. These spring water samples were most isotopically depleted because of the altitude effect. The sample sites included in this region are HS16 and HS17 where the depleted isotopic composition suggests a recharge altitude of 720 m or higher. The isotopic compositions of the samples range from –70.1 to –69.6‰ for δD and from –9.80 to –10.09‰ for $\delta^{18}O$.

(b) Upper recharge region in higher mountains—this region is located in the headwaters of the river network. Lower electrical conductivity and depleted isotopic signatures for δD and $\delta^{18}O$ of –66.8 and –9.22‰, respectively, from one typical spring water sample (HS18) indicate a lower evaporation rate exists in this region.

(c) Middle mountains recharge region in the middle reaches of the river—this region included sample sites HS22, HS4, HS11 and HS12 which had isotopic signatures of δD ranging from –71.1 to –66.8‰ and of $\delta^{18}O$ ranging from –9.3 to –8.7‰.

(d) Lower mountains recharge region in the lower reaches of the river –spring water is discharged directly into the river in this region which included sample site HS1-1 that has a lower altitude of 78 m and a more enriched isotopic signature. Values of δD and $\delta^{18}O$ for this sample were –65.4‰ and –7.67‰, respectively, and reflect a higher evaporation ratio.

Spatial distribution of isotopic signatures in surface water Following prolonged dry periods, the surface water in the study basin was recharged by spring water, shallow groundwater and surface water from upper channels. On the basis of isotopic signature and electrical conductivity of water samples, separate recharge-discharge relationships can be recognized in four regions (Fig. 5):

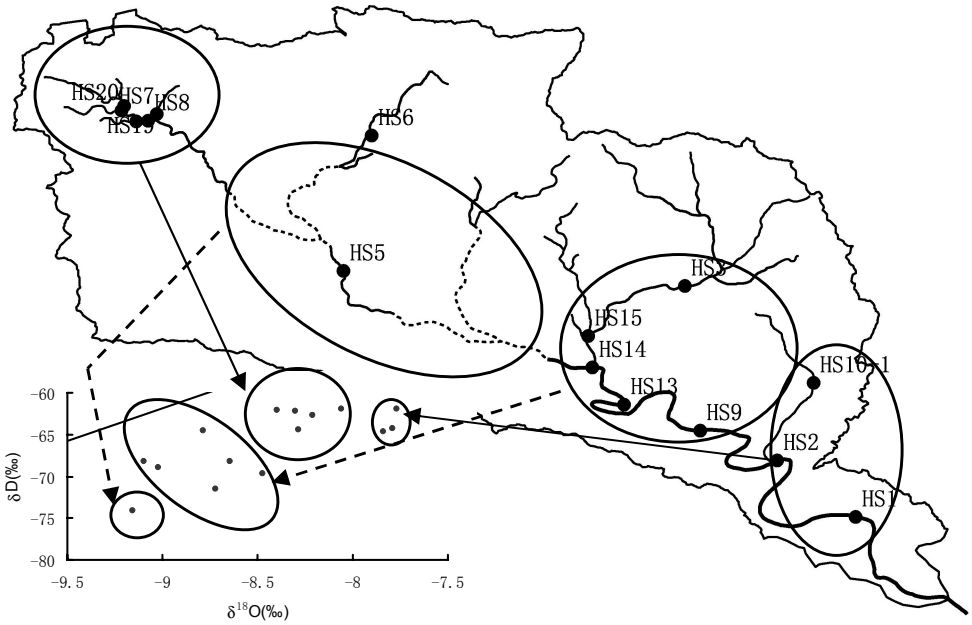

Fig. 5 Spatial distribution of isotopic signatures of surface water.

(a) Dominant recharge by spring water—this region is located in the headwaters of the basin where the isotopic signature and electrical conductivity of the surface water samples show minimal difference with that of the spring water. The samples sites include HS7, HS8, HS19, HS20 and HS21, where isotopic compositions ranged from –64.5 to –61.9‰ for δD and from –8.40 to –8.06‰ for $\delta^{18}O$. When the surface water reaches an artificial concrete dam built about 2 km downstream on the main river, the surface water disappears underground and recharges the groundwater.
(b) Region of strong exchange between surface water and groundwater—the similarity of the isotopic signature and electrical conductivity indicates that a close recharge relationship exits between the surface water and the groundwater. The isotopic signature of δD and $\delta^{18}O$ of sample HS5 are –74.1 and –9.15‰, respectively. Several segments of wadi channel exist in this region because of lower runoff in the river and higher infiltration rates in the river bed. In particular, a segment of wadi channel in the main river channel has been dry for several years because of sand-excavating activity.
(c) The runoff region in the middle reaches of the river—river flow is sustained by recharge from the upper river and by spring water. The sampling sites include HS3, HS13, HS14 and HS15, with the isotopic values ranging from –71.5 to –64.6 for δD and from –9.15 to –8.47‰ for $\delta^{18}O$, The isotopic signature and EC values indicate that the surface water has undergone significant mixing and been affected by an evaporation effect.
(d) The lower reaches of the river—in this region, river runoff was recharged from the upper reaches and from spring water subject to significant evaporation. The sample sites include HS1, HS2 and HS10-1, with isotopic signatures for δD ranging from –64.7 to –62.0‰ and for $\delta^{18}O$ ranging from –7.84 to –7.77‰.

Variations in stable isotopic composition along flow lines suggest a number of recharge mechanisms. The use of environmental isotopes has proved to be an effective way of resolving the relative importance of several recharge processes. An alternative approach is to use the stable isotopic composition of water as a natural tracer to study the interaction between groundwater and surface water.

Spatial distribution of isotopic signatures in shallow groundwater The shallow groundwater was recharged by the direct diffuse recharge of precipitation, as well as the recharge from surface water. At the same time, the groundwater will recharge the surface water in different regions with different form. The groundwater type can be discriminated between four regions according to the form of recharge and the location of the sample sites, as well as the isotopic signature (Fig. 6):

(a) The region of dispersive recharge by rainfall in the middle reaches of the river—this is mainly located in the diluvium plain in the middle part of the basin where groundwater was recharged diffusely and directly by rainfall. The water level in this region is shallow and the isotopic signature becomes enriched during the infiltration process because of evaporation. The included samples are: HS4-2, HS4-1 and HS5-1, with isotopic signatures ranging from –72.7 to –72.3‰ for δD and from –8.62 to –8.40‰ for $\delta^{18}O$.
(b) The region recharged by shallow groundwater from the lower mountains includes samples HS9-1 and HS10 which are located on the isotopic plot near to the MWL

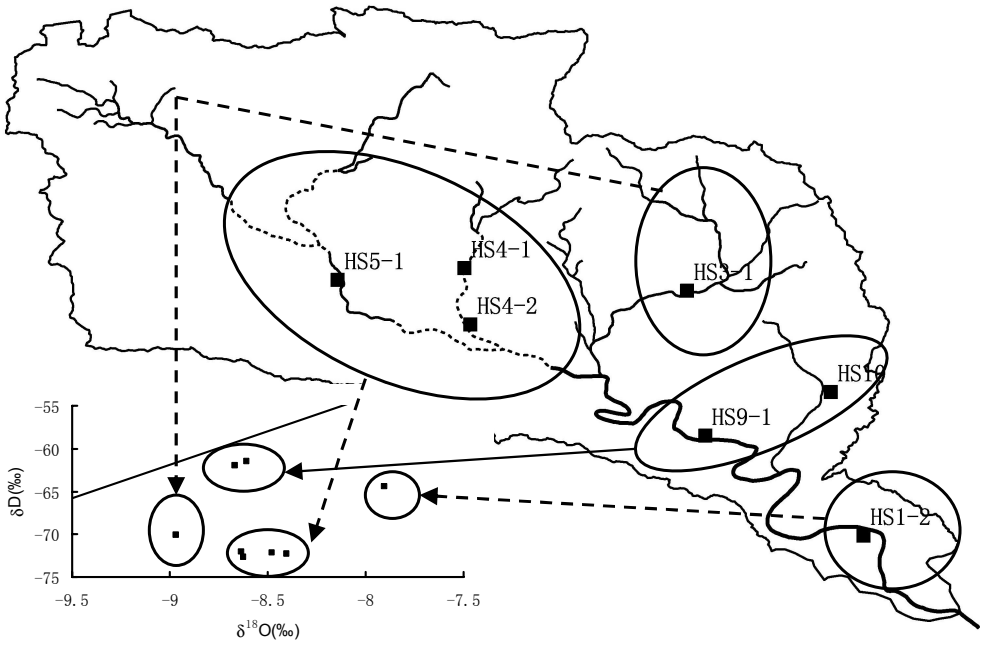

Fig. 6 Spatial distribution of isotopic signatures of groundwater.

and have signatures ranging from –61.4 to –62.0‰ and from –8.61 to –8.67‰ for δD and $\delta^{18}O$, respectively.

(c) The lower reaches of the river—shallow groundwater is recharged from surface and mainly spring water, and has an isotopic signature close to that of the spring water. Sample HS3-1 from this region has a δD value of –70.1‰ and $\delta^{18}O$ value of –8.97‰.

(d) Region recharged mainly by surface water in the lower reaches of the river—this region is mainly located in the diluvium plain and is characterized by the similarity of the isotopic signature between the groundwater and the surface water, as well as by a higher electrical conductivity in groundwater than surface water. The sample site included in this region is HS1-2 which had a δD value of –72.3 and a $\delta^{18}O$ value of –8.40‰.

CONCLUSIONS

The isotopic signatures of the springs directly recharged by rainfall were affected by altitude and by evaporation. The evapotranspiration rate of spring water and groundwater cannot be estimated simply from the comparison of the isotopic signatures of rainwater and spring water, because of the enrichment of isotopic compositions of water as a result of evapotranspiration in the soil zone and also due to the altitude effect of the rainwater during the precipitation process.

Clear spatial distribution of the isotopic signature and electrical conductivity of the water samples indicates the spatial variability of the water type and the recharge–discharge relationship in the basin. Spring water was mainly recharged by precipitation that has undergone evapotranspiration; surface water was mainly recharged by the

spring water at a higher altitude and shallow groundwater in the middle plain; while the recharge–discharge relationship of the shallow groundwater is complex.

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