Using major ions and stable isotopes to characterize recharge regime of a fault-influenced aquifer in Beiyishui River Watershed, North China Plain

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\textbf{S U M M A R Y}

A thorough understanding of recharge is usually a prerequisite for effective groundwater management. The recharge regime remains unrevealed in the piedmont plain of the North China Plain, where is considered as the main recharge zone of the Quaternary aquifer. To characterize the recharge regime, a case study is presented in the piedmont plain of the Beiyishui River Watershed. The piedmont plain consists of proluvial fan and alluvial fan/plain, and groundwater quality in the two parts is distinct. Total dissolved solids and isotopic compositions are higher in the groundwater of proluvial fan than the groundwater of the alluvial fan/plain. Local precipitation only recharges the groundwater in the proluvial fan. Fracture water ascending along a buried normal fault and lateral inflow from the proluvial fan feed the unconfined aquifer in the alluvial fan/plain. The runoff of the Beiyishui River seeps in the streambed of upper reaches and then overflows seasonally in middle reach. The recharge from middle reach to the aquifer is negligible. In addition, the fracture water originates from precipitation in the mountainous area with an average elevation about 500 m and discharges to the overlaying aquifer. The contribution of fracture water to the aquifer was estimated to be 77.9% in the alluvial fan/plain area. Due to the mixture in the aquifer, major ions leached from soil of the proluvial fan are diluted and the hydrochemical pattern is changed from Ca–Mg–HCO\textsubscript{3} to Ca–Mg–HCO\textsubscript{3}. It is considered that fracture water is the major recharge source of the unconfined aquifer and the variation of precipitation in mountainous area would primarily affect the recharge. This paper also shows the hydrological efficiency of buried normal fault as preferential flow.

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\textbf{1. Introduction}

Groundwater recharge is a critical hydrological parameter. Aquifer-scale recharge estimates are essential to water resource assessment (Scanlon and Cook, 2002). In recent years, the overgrowing population and climate change are putting water resources under pressure all over the world. Sustainable management of aquifers to meet human and ecosystem needs will require accurate estimates of groundwater recharge (Ma et al., 2009).

Although the North China Plain (NCP) is a water scarce region (Jiang, 2009), it is still one of the most developed industrial areas and one of the largest agricultural production areas in China (Sun et al., 2009). Much of this heavily depends on development of groundwater (Foster et al., 2004). For a sustainable development of groundwater, the recharge of groundwater in the piedmont plain, the recharge zone of the Quaternary aquifer (Chen et al., 2004), has been estimated (Chen et al., 2003; Kendy et al., 2003, 2004; Jiang et al., 2008; Wang et al., 2008; Rohden et al., 2010). However, no agreement has been reached. For a better understanding of recharge rate, the recharge regime of the aquifer, which is usually a prerequisite for an accurate estimate of recharge, should be ascertained firstly.

Regional groundwater flow paths have a strong influence on the recharge of aquifers located in tectonic areas (Folch and Mas-Pla, 2008). Tectonic structure, particularly fault, can be important control on groundwater flow; this, in turn, makes the aquifer recharge complex. Fault zone permeability structures and related architecture form primary controls on fluid flow (Caine et al., 1996). On the other hand, where rocks are under tension, a fault will tend to be open and allow water movement; where rocks are under compression, a fault will tend to be tight and not allow water movement (Apaydin, 2010).

Significant studies were performed recently on the relation between tectonic structure and groundwater. Bense and Person (2006) demonstrated that faults can form a preferential path way between aquifers at different depths over vertical distances of...
several hundreds of meters. Morgan et al. (2006), Sultan et al. (2007) and Folch and Mas-Pla (2008) reported that ascending groundwater drain or recharge overlaying aquifer. Sultan et al. (2008) illuminated that major transient fault systems generate ample opportunities for hosting and transmitting groundwater. Ayenew et al. (2008) revealed the hydraulic connection between high rainfall region in the plateau and the rift floor aquifers by transverse fault zones in Awash River basin of Ethiopia. At the same time, it is reported that the Elmabeli fault, a strike-slip fault, has no effect on groundwater flow (Apaydin, 2010). And basin-bounding faults that locally act as a flow barrier may further reduce subsurface inflow into the aquifer along the mountain front (Chowdhury et al., 2008). In the North China Plain, a regional normal fault is buried by alluvial deposit in the piedmont plain area. It is necessary to make clear whether the normal fault acts as a conduit for vertical flow, when the recharge of overlaying aquifer is focused on.

Groundwater isotopes combined with chemistry can produce a more reliable conceptual model of a groundwater system and a useful initial tracer for groundwater recharge (Ma et al., 2009). The authors attempt to acquire insight into the recharge regime of alluvial aquifer in the piedmont plain of the Beiyishui River Watershed using major ions and stable isotopes. The additional objective of this study is to identify the role of the normal fault in the recharge of overlaying alluvial aquifer. It is expected that this study will enhance the understanding of the groundwater recharge and support the sustainable management of groundwater resource in the NCP.

2. Study area

2.1. General settings

The Beiyishui River Watershed (115.20°E–115.76°E and 39.23°N–39.56°N) is located in the west of the NCP (Fig. 1). The area of the watershed is around 828.24 km$^2$. The Beiyishui River, with a length of 59.2 km, is the main tributary of Juma River that is the second order branch of Hai River. More than 1649 reservoirs were established in the upper reaches of Hai River, and 83.5% of total runoff was stored (Zhang et al., 2009). An abrupt decline in run-off occurred in 1978–1985 (Yang and Tian, 2009). Therefore, the Beiyishui River is seasonal in the upper reaches and usually dries up in the lower reaches (Xu, 2004).

The study area belongs to the warm temperature zone with a semi-humid monsoon climate which is characterized by cold, dry winters (December–March) and hot, humid summers (June–August). The mean annual temperature is about 13°C. The mean annual precipitation ranges from 500 to 600 mm (Chen, 1999). The precipitation is dominated by the Asia summer monsoon (Yamanaka et al., 2004). More than 70% of annual precipitation concentrates in rainy season during June to September.

There are two main geomorphic units in the watershed: the mountainous and hilly areas and the piedmont plain area. The piedmont plain with a gradient about 2% could be subdivided into the proluvial fan area and alluvial fan/plain area. The elevation of the proluvial fan varies from 40 m to 80 m, and the alluvial fan/plain locates below 40 m (Fig. 1).

In the mountain and hilly area, the land cover is mainly forest and grassland. The vegetation is typical in the NCP. Farmland is the dominated land use type in the plain area (Fig. 2). Winter wheat and summer maize are the major crops. The wheat–maize double cropping system is largely supported through pumping shallow groundwater (Liu et al., 2002). Agriculture consumes about 85% of the total groundwater withdrawals (Xu et al., 2005). Over-pumping causes the reduction of water level (Nakayama et al., 2006).

2.2. Geological and hydrogeological settings

In the Beiyishui River Watershed, the mountainous and hilly areas belong to the Taihang Mountain uplifting area, and the plain area situates in the Jizhong depression. The ranges consist of Archaean granitic gneiss, Mesozoic dolomite and a little shale. The plain has a Quaternary alluvial (diluvial) deposit.

The shallow groundwater refers to the loose-rock pore water occurring in the Quaternary alluvial aquifer (Zhang et al., 2000, 2009). The aquifer lithology is primarily gravel and coarse sand in the proluvial fan area, and fine sand and sandy clay in the alluvial fan/plain area (Fig. 3). The aquifer with a thickness more than about 60 m overlies partial outcrop granitic gneiss and dolomite that acts as the boundary of the shallow groundwater flow system (Zhang et al., 2009). The SE-dipping high-angle normal fault is a buried fault penetrating the basement and extending along the Taihang orogenic belt under the alluvial aquifer (Fig. 4).

3. Methodology

Field surveys were carried out three times from 2008 to 2009 in the Beiyishui River Watershed. The former two surveys were executed in March and September 2008 respectively, and the last survey was performed in June 2009. The Beiyishui River, a spring and two wells with depths ranging from 6 m to 43 m were surveyed. Four river water samples, three spring water samples and 59 groundwater samples were collected in HDPE bottles, filled to overflowing and capped for isotope and major ions analyses. Eighty-three precipitation samples were taken for isotope analysis after storm events in two sites of the hilly area during the years of 2008 and 2009. Additionally, a well (B24) was surveyed and sampled nearly 48 km away from the site B20 along the normal fault (Fig. 4).

Temperature, electrical conductance (EC) and pH value of water samples were measured in situ (DKK, TOA Corporation, model: WM-22EP). Chemical and isotopic compositions of water samples were analyzed in the laboratory of Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences. The chemical composition was characterized by ICP-OES for cations and Ion Chromatography (Shimadzu LC-10A) for anions with analytical precision of ±1 mg/L. Bicarbonate ion was measured by titration in field. Hydrogen and oxygen isotopes compositions of the water samples were analyzed by the Isotope Ratio Mass Spectrometer (Finnigan MAT-253) with TC/EA method. The δ$^{18}$O and δD values are reported as per mill (‰) deviations from the international standard V-SMOW (Vienna Standard Mean Ocean Water). The δ$^{18}$O and δD measurements were reproducible to ±0.2‰ and ±1.0‰ respectively.

4. Results

4.1. The variation of water table depth

Generally speaking, elevation gradients control phreatic water flows. It was validated in the Beiyishui River watershed. Water level decreases when elevation declines. Shallow groundwater flows towards down gradient direction of elevation.

The water table depth and its variation were markedly different between the proluvial fan area and the alluvial fan/plain area (Fig. 5). The average depth to the water table was 4.1 m in the proluvial fan area, while the average depth was 12.7 m in the alluvial fan/plain area. Furthermore, the depth of water table was smallest after the rain season in September 2008 in the proluvial fan area. But it did not happen in the alluvial fan/plain area.
4.2. Characteristics of temperature pH EC and ORP

The temperature of river water rose from 12.3 °C in March (early spring) to 24.4 °C in September (early autumn). Meanwhile, the average temperature of groundwater changed from 10.2 °C to 16.2 °C in the hilly and proluvial fan areas and from 14.0 °C to 15.6 °C in the alluvial fan/plain area. Specially, the temperature change of groundwater in site of B09 was 12.0 °C, which was almost the same with the variance of river water. It is a strong indicator that the rapid recharge from river water happened (Fig. 6).

Besides the site of B11, the mean pH value of groundwater samples was 7.8 and the pH values changed from 7.3 to 8.4 with no obviously variation among the surveys. The pH values of groundwater varied from 7.0 to 7.1 in the site B11.

The mean EC value of groundwater was always lower in the alluvial fan/plain area than the value in the hilly and proluvial fan areas. The EC value of groundwater was highest in site B11 with a mean value of 2043 µS/cm, which is nearly three times higher than the average of the other sites. Meanwhile, the EC values changed slightly among the surveys (Table 1).

The ORP values of the groundwater in sites of B21 and B23 were 137 mV and 100 mV respectively. Meanwhile, the average is 247 mV with a standard deviation of 32 mV in the other sites.

4.3. Stable isotopic compositions in waters

The isotopic composition of precipitation is primarily controlled by large-scale monsoon activities and shows various $\delta^{18}O$ and $\deltaD$
values (Yamanaka et al., 2004). During the years of 2008 and 2009, the δ¹⁸O values varied from −12.59‰ to −0.15‰, and the δD values ranged from −100.2‰ to 2.4‰ (Fig. 7). The rainfall weighted means of δ¹⁸O and δD were more negative in 2009 than the values in 2008. Combining with the isotopic compositions of local rain water in 2004 and 2005 (Song et al., 2010), the local meteoric water line (LMWL) could be defined as δD = 6.77 δ¹⁸O − 4.50 (n = 192, R² = 0.86).

The δ¹⁸O values varied from −6.86‰ to −5.17‰, and the δD values changed from −53.8‰ to −40.0‰ in the Beiyishui River water. Moreover, river water enriched in heavier isotopes in the lower reaches that was the result of evaporation (Fig. 7).

Water samples of the site B06 were taken from a depression spring. Mean values of δ¹⁸O and δD in the spring water were −7.43‰ and −55.3‰, which are very close to the rainfall weighted means of rain. The δ¹⁸O and δD compositions of the groundwater lie on the LMWL with a narrow scope compared with the compositions of rain (Fig. 7). It is suggested that the groundwater originates from modern precipitation.

Isotopic composition of groundwater was most negative in the third sampling campaign (Table 2). It could be induced by precipitation with less positive isotopic values in 2009. Groundwater in the proluvial fan had a similar isotopic composition with groundwater in the hilly area besides a few sites where isotopic compositions were more positive. Although surveys were conducted in different seasons, the isotopic compositions were always more negative in groundwater of the alluvial fan/plain area than those in the groundwater of hilly and proluvial fan areas (Fig. 8).

4.4. Hydrochemical characteristics of shallow groundwater

All water samples were fresh with content of total dissolved solid (TDS) lower than 1 g/L. Furthermore, the values of TDS were higher in the hilly and proluvial fan areas (average 0.55 g/L) than those in the alluvial fan/plain area (average 0.45 g/L).

Calcium and magnesium varying from 45.1 to 139.8 mg/L and from 10.2 to 50.5 mg/L were the dominant cations of the shallow groundwater. As for the anions, bicarbonate (ranging from 153.7 to 314.8 mg/L) and sulfate (changing from 4.9 to 154.9 mg/L) predominated. Along the flow direction of groundwater, the major water type changed from Ca-Mg-HCO₃-SO₄ in the hilly and proluvial fan areas to Ca-Mg-HCO₃ in the alluvial fan/plain area. It is not consistent with general order of hydrochemical evolution in a groundwater system.

In the groundwater of site B11, the concentration of K⁺ and NO₃ were as high as 176.4 mg/L and 278.9 mg/L respectively, which are 77 times and five times higher than the averages of the other groundwater samples in the hilly and proluvial fan areas. This result suggests the existence of contamination. Considering mining in the upstream mountain area, it is inferred that the excessive K⁺ and NO₃ could be introduced by mine drainage which results in decrease of pH and increase of EC in the contaminated groundwater.

5. Discussion

5.1. The recharge mechanism of the alluvial aquifer

Due to the over-pumping of groundwater, water table declines greatly in the alluvial fan/plain area, which would change the recharge conditions of the alluvial aquifer. The mean depth to the water table increased from about 6 m in 1990 to nearly 10 m in 2002. In this study, the average depth to the water table is nearly 13 m. Most of wells were drilled again to a deeper depth because of the drawdown of water level. According to the previous studies
piedmont plain area is identified as the recharge zone receiving infiltrating precipitation. However, it may be hard to receive direct recharge in the alluvial fan/plain area under the impact of intensive human activities.

The situation can be clarified by the spatial and temporal variance of depths to the water table. After the rainy season of 2008, the water table rose in the hilly and the proluvial fan areas (Fig. 5). It is considered that infiltrating precipitation recharges the unconfined aquifer in those areas. Moreover, the water table increased dramatically in the front of the proluvial fan after the rainy season. It is suggested that rapid lateral flow occurs and is blocked owing to the decrease of sediment permeability. On the contrary, the water table declined from March to September in the alluvial fan/plain area. On one hand, agricultural irrigation is considered the primary reason of the drawdown. The winter wheat is irrigated three times from March to May when the rainfall cannot meet the need of the crop. It is reported that total water consumption averages 453 mm for winter wheat without water deficit (Liu et al., 2002). And 100 mm of water requirement by cultivated land results in about 0.64 m of groundwater decline in the NCP (Yang et al., 2006). On the other hand, the direct infiltration of precipitation could not form the rapid recharge owing to the large depth to the water table. It is supposed that the local precipitation is not the dominant recharge source and most of the infiltration is discharged by evapotranspiration before it reaches the water table in the alluvial fan/plain area.

In Fig. 9, the average isotopic compositions of groundwater in different sites of the alluvial fan/plain area arrange in a line, which shows a two end-members mixing trend. One end-member should be lateral inflow from proluvial fan area, and the other end-member is characterized by low δ-values of stable isotopes in site B20. Considering the normal fault buried under the alluvial aquifer (Fig. 4), it is supposed that the aquifer is recharged by fracture water flowing upward through the fault.

To demonstrate the assumption, site B24 located in the normal fault zone was surveyed and sampled (Fig. 4). The well depth of B24 is 120 m exposing the bedrock. The groundwater samples of B24 were taken from the fracture water. After three surveys, it is found that the isotopic compositions in groundwater samples of B20 are nearly the same with those of B24 (Table 2). Consequently, the groundwater in site B20 is from the fracture water and can be taken as a mixing end-member.

The isotopic composition of the fracture water is similar to those of groundwater fed by precipitation in the Taihang Mountain (Li et al., 2008) and plots on the LMWL. It seems that the fracture water is recharged by precipitation in the Mountain area and flows downwards through the fractures until arriving at the normal fault zone. Altitude is the main geographic factor controlling the isotopic composition of precipitation in the NCP and the δ18O depletes 0.2‰ with the elevation increasing 100 m (Liu et al., 2010). Therefore, the recharge elevation of the fracture water could be estimated to be 500 m by comparing the mean δ18O value of groundwater in site B20 with the value of local precipitation.

The mixture ratio of the fracture water could be assessed using a two end-members mixing model. The average isotopic compositions of the two end-members are employed to calculate the mixture ratios. The result shows that the mixture ratio declines with...
the increasing distance away from the fault on both sides of the fault (Table 3). It is revealed that the flow direction of fracture water is not only downstream but also upstream in the unconfined aquifer. Additionally, the mixing is stronger in the downstream direction that is consistent with the direction of regional groundwater flow.

5.2. The hydrochemical evolution in the shallow groundwater system

Along the downstream direction, the variance of EC values of groundwater reveals the regional flow and the mixture behavior of shallow groundwater in the Beiyishui River Watershed. Aji et al. (2008) showed that EC value of groundwater increased when elevation decreased in Chaobai and Yongding River basin of NCP. The trend is also observed in the Beiyishui River Watershed, which announces the presence of a regional groundwater flow system (Fig. 10). However, high EC values appear in the hilly area and low EC values occur in the alluvial fan/plain area. The shallow groundwater has various flow directions and paths mainly controlled by complicated micro-topography in the hilly area. The amount of dissolved ions in groundwater is variable spatially. Thereby, high EC values exist. In the alluvial fan/plain area, the occurrence of groundwater with low EC values suggests the influence of fresher groundwater from another flow system. It supports the conclusion that the fracture water (average EC value as low as 469 μS/cm) mixes with the shallow groundwater in the alluvial fan/plain area.

Mixture controls the hydrochemical features of groundwater in the alluvial fan/plain area and disturbs the order of hydrochemical evolution. Comparing with groundwater in the hilly and proluvial...
duced by high fractional contribution of the fracture water. The

ture water (Fig. 11).

fan/plain area, the mean contents of SO$_2^-$ respectively). After mixture in the unconfined aquifer of alluvial

fan areas, the fracture water has low concentrations in major ions, especially for SO$_2^-$ in ground-

water are diluted to less than half of those in the hilly and proluvial

areas (average 96.6 mg/L, 51.2 mg/L and 2.3 mg/L respectively).

For the same reason, the water chemical pattern is changed from

Ca$^{2+}$ in the alluvial fan/plain area that is the same with the frac-

tion. Instead, the SO$_2^-$ mass balance is used for the calculation in this case. Firstly, the TDS of groundwater is lower than 1 g/L, and the contents of Ca$^{2+}$ (median 79 mg/L) and SO$_2^-$ (median 91 mg/L) are low in groundwater. Consequently, precipitation of SO$_2^-$ is negligible. Secondly, high ORP values and moderate pH values of groundwater in an open system suggest almost no reduction of SO$_2^-$ (Drever, 1997). Therefore, SO$_2^-$ is stable to a certain extent in this case (Fig. 12). The mean SO$_2^-$ concentrations of groundwater in the sampling site B20 and in the hilly/proluvial fan area are taken as two mixing end-members. The average SO$_2^-$ concentration of groundwater in the alluvial fan/plain stands for the content of mixed water. The mean mixture ratio of the fracture water was then estimated to be 77.9%. Thus, the direct recharge from precipitation accounts for around 22.1% that is similar to the result of Chen et al. (2003).

5.3. The interaction of groundwater and river water

River water seeps through the streambed and recharges the shallow groundwater in the proluvial fan area. Groundwater samples were taken close to the Wanglong River in site B09 (Fig. 4). At that location, the mean depth to the water table is 1.97 m (the smallest depth is 1.68 m). Moreover the change of groundwater temperature is 12 $^\circ$C between the two surveys in 2008. It is almost the same with the temperature change of the surface water. By comparison, the temperature change of the groundwater is 5.0 $^\circ$C in site B08 where the mean depth to the water table is 1.94 m. It is concluded that the groundwater near the river is rapidly recharged by the river water. At the same time, the water of the Beiyishui River was sampled in site B12 and the groundwater samples were taken in site B11. Although the site B11 is very close to the river, the temperature change is just 4.1 $^\circ$C and the mean depth

### Table 1

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$^*$ G = groundwater, S = spring water, R = river water.

Fig. 7. Isotopic compositions of water samples. The rain water samples were collected in the years of 2004, 2005, 2008 and 2009. The others were sampled during field surveys. The line represents the LMWL.
to the water table is 3.61 m (the smallest depth is 3.45 m). In addition, the groundwater of B11 is quite different with the river water in physicochemical features (Table 1). Consequently, the hydraulic connection between the river water and the groundwater may be very weak at that reach.

The groundwater occurring in the sediments of river bed overflows in the front of the proluvial fan. The Beiyishui River disappeared near site B13, and then overflowed seasonally in the reach from site B16 to site B17. Groundwater was sampled near the reach in sites B14, B16 and B17. Meanwhile, river water was sampled in site B18 in the alluvial fan/plain area (Fig. 4). The chemical compositions of the river water of B12, B18 and the groundwater of B14, B16 are very similar (Fig. 13). It demonstrates the close hydraulic connection between the river water and the groundwater in the proluvial fan. In addition, the isotopic composition in groundwater of B16 enriched in heavier isotopes (average \( \delta^{18}O \) = -6.26‰) is similar to that of river water in B12 (average \( \delta^{18}O \) = -6.40‰) which indicates the same source of the waters. Thus, it is inferred that river water seeps through the river bed and dries up eventually near site B13, and then overflowed in the front of

![Fig. 8. Isotopic composition of groundwater in different geomorphic units.](image)

![Fig. 9. Average isotopic compositions of water samples in different geomorphic units.](image)
proluvial fan (around site B16) considering the digging of channel sand and the decreasing permeability of sediment in that area.

The overflowing river water does not recharge the shallow groundwater of the alluvial fan/plain area and is discharged by evaporation. The groundwater of B17 is characterized by low SO$_4^{2-}$ and high NO$_3^-$, about 0.4 and 3.3 times of those values in the river water of B18. Moreover, the K$^+$ concentration in river water of B18 is 8.7 mg/L, while the corresponding value in the groundwater of B17 is just 1.3 mg/L which is consistent with the mean value in groundwater of the alluvial fan/plain area. Consequently, the hydraulic connection may be poor between the river water and the groundwater in the alluvial fan/plain area. The point is supported by a large depth to water table in site B17 (average 9.9 m) and the distinct isotopic compositions (Table 2) between the groundwater of B17 (average $\delta^{18}O = -7.59\%$) and the river water of B18 (average $\delta^{18}O = -5.33\%$). The river water of site B18 has higher isotopic values than the river water of site B12 that shows the effect of strong evaporation.

The alluvial aquifer of the piedmont plain in the Beiyishui River Watershed gains direct and indirect recharge. The proluvial fan area of the piedmont plain receives significantly direct recharge. The normal fault acts as a conduit for fracture water that mixes in the overlaying aquifer in the alluvial fan/plain area. The average contribution of the fracture water is estimated to be 77.9% in the alluvial fan/plain area. The mixture ratio of the fracture water declines with increasing distance from the fault. Additionally, it is implied that the variation of precipitation in mountainous area would influence the recharge of alluvial aquifer primarily.

The fracture water, originating from precipitation in the mountain area with a mean elevation about 500 m, is featured by depletion in heavy isotopes of hydrogen and oxygen and low concentration of major ions especially sulfate. In the alluvial fan/plain area, mixture of groundwater dilutes the concentrations of major ions greatly and alters the water type from Ca$^{2+}$-Mg$^{2+}$-HCO$_3^-$ to Ca$^{2+}$-Mg$^{2+}$-HCO$_3^-$.

The results of this study would enhance the understanding of recharge processes and benefit an accurate estimate of the recharge rate. It also highlights the need for caution in the hydrological interpretation of hydrochemical and isotopic data of groundwater samples, which may result from mixing of waters in tectonic area.

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