

# The formation of shallow fresh groundwater in the north of Yanchi county, Ningxia, China: main influencing factors and mechanism

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**Abstract** Shallow fresh groundwater is not common in the middle of basins in arid and semiarid areas with strong evaporation where shallow groundwater is often brackish water or saline water. In this study, the shallow fresh groundwater in the north area of Yanchi county, China was investigated for the main influencing factors and mechanisms of its formation. The results showed that freshwater of HCO<sub>3</sub> and SO<sub>4</sub> types with mean salinity of 0.78 g/L formed in the north of the study area while brackish and saline water of SO<sub>4</sub>·Cl–Na type with mean salinity of 2.28 g/L formed in the west and south of the study area. The fresh groundwater formed owing to the special physico-chemical properties of the aeolian sand which has the good permeation of atmospheric precipitation, the weak evaporation of the groundwater, the low salt contents in the vadose zone and aquifer medium, the weak water–rock interaction and the good hydrodynamic condition. The lateral recharge of low salinity groundwater also played a mixing and diluting role in the formation of the fresh groundwater. The findings should provide a scientific basis for the exploitation and utilization of local groundwater resources and be of significance in the exploration and exploitation of fresh groundwater in arid and semiarid regions.

**Keywords** Fresh groundwater · Influencing factor · Formation mechanism · The north of Yanchi county

## Introduction

Groundwater is an important water source for life, agricultural and industrial production in arid and semiarid regions. Groundwater quality directly influences the exploitation and utilization of groundwater resources and the health of local people. Therefore, the formation and evolution mechanism of groundwater quality is one of the hot topics in hydrogeology. Employing hydrogeochemistry, environmental isotope, geophysical exploration and multivariate statistic methods, many experts have investigated the variation patterns of the major constituents, trace elements and salinity of groundwater and revealed the influencing mechanisms of lithofacies paleogeography, hydrogeochemical processes and human activities on the formation and evolution of groundwater quality (Fisher and Mullican 1997; Laaksoharju 1999; Favara et al. 2000; El Mandour et al. 2008; Monjerezi et al. 2012; Wang et al. 2013).

Constrained by such factors as formation lithology, landform, groundwater flow rate and an arid climate with strong evaporation, groundwater in arid and semiarid regions often has a distribution pattern of saline water overlying fresh water. Based on actual survey data, Ding and Zhang (2005) revealed the formation mechanism of the deep (>200 m below surface) fresh groundwater in the lower basin of the Hexi Corridor Plain. Hydrogeochemical action is also one of the main actions influencing the formation of fresh groundwater. For example, Vandenberghe and Lebbe (2002) found that the main hydrochemical evolution processes for freshwater lenses were the

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oxidation of organic matters, the dissolution of calcites and ion exchanges. In addition, human activity is also the main driving force behind the salinization of fresh groundwater especially in the coastal areas and the freshwater–saltwater coexisting areas. Ibe and Agbamu (1999) demonstrated the spatial distribution of the saline and fresh water aquifers in the alluvial plain of the Warri River Delta in Southwest Nigeria, discussed the influence of human activity on groundwater quality, pointed out the fragile freshwater areas that could be easily salinized, and revealed the evolution process of groundwater quality. Based on 356 shallow groundwater samples, Park et al. (2005) investigated the salinization of the groundwater in the western coastal area of South Korea and found that over 60 % of the groundwater in the coastal aquifer was affected by seawater intrusion and human activities. The above findings drive forward the research on the formation and evolution mechanism of fresh groundwater in arid and semiarid regions.

Yanchi county of the Ningxia Hui Autonomous Region was located in the arid and semiarid Western Ordos Basin, connecting the four provinces (or autonomous regions) of Shaanxi, Gansu, Ningxia and Inner Mongolia. Wind blows frequently throughout the year with little rainfall. Annual evaporation is high and water resource is in great shortage. According to survey in 2005, there was almost no surface water resource in the Yanchi area that can be used in agriculture, husbandry, and as drinking water for human or livestock. Groundwater as the only water resource has been exploited. Most of the groundwater in the area has poor quality, high in fluoride and salinity with TDS of approximately 3 g/L. The shallow fresh water resource was only found near the Luotuojing in the northeast of Yanchi county (Hou and Zhang 2006). Some investigations have been conducted on the occurrence and hydrochemical properties of the groundwater in the Yanchi area, especially the source and accumulation trends of the fluorides in the groundwater, and the suggestions on where to find low fluoride water have been made by experts (Shen 2005; Dou 2007; Han et al. 2009). However, no study has been performed on the formation mechanism of shallow fresh groundwater.

On the basis of previous studies by others, the northern area of the Yanchi county was taken as a typical study area in this study to investigate the distribution and hydrochemical characteristics of saline and fresh groundwater. The main factors influencing the formation of the shallow fresh groundwater were discussed, and a model was developed to elucidate the formation mechanism of shallow fresh groundwater. The findings of this study are expected to provide scientific basis for the exploitation, utilization and protection of fresh groundwater resources in arid and semiarid regions.

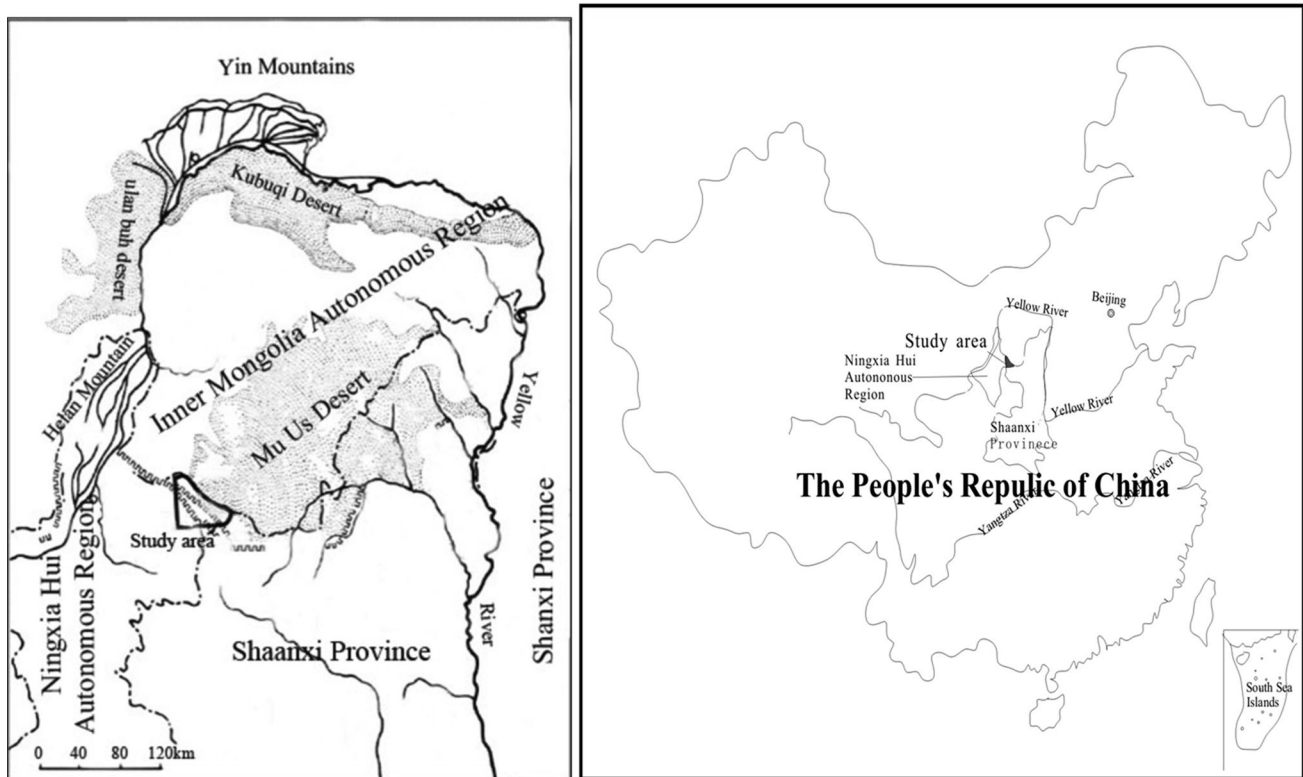
## Materials and methods

### Outline of the study area

Located in the transition zone from the Ordos Platform to the Loess Plateau, the study area (geodetic coordinates of  $X = 18,700,000$ – $18,733,000$  and  $Y = 4,191,000$ – $4,210,000$ ) has a shape of a right trapezoid with the maximum east–west length of 33 km, the maximum north–south length of 20 km and an area of approximately 400 km<sup>2</sup> (Fig. 1). The area is a wavy plateau with a relatively gentle terrain at altitudes of 1300–1500 m, high in the west and south and low in the east and north. The climate is a typical continental arid and semiarid monsoon with the average annual evaporation of 2293.07 mm which is 8 times the average annual precipitation of 277.11 mm (Xu et al. 2013). The study area is an endorheism of Yanchi with no perennial surface water flow.

The Cretaceous Huanhe formation ( $K_1h$ ) consists of a set of interbedding between brownish red/brownish yellow silty fine sandstones and mudstones/sandy mudstones with locally developed cross-bedding. Often covered by the quaternary system, the formation is distributed throughout the whole area with a total thickness of 255–420 m (Zhang and Wang 2003). With a thickness of 190–255 m, the Cretaceous Luohandong formation ( $K_1lh$ ) comprises nacarat/light brownish red fine arkose interspersed by brownish red/brownish purple mudstones and sandy mudstones, mainly outcropping and distributed in the top layer of the Liuyangbao-Zuojiwan area in the west. The eolian diluvium of quaternary Holocene series ( $Q_4^{col+pl}$ ) comprises of sandy silt/clayey silt interspersed by thin layers of sand, distributed along Guojiagou-Nanwangquan in the south and Liuyangbao-Zuojiwan in the west with a thickness of approximately 10–20 m. For the 7 m thick diluvial chemical deposition layer of Holocene series ( $Q_4^{1+ch}$ ) which is distributed throughout Yanchi, the upper part is light yellow, grey yellow or dark brown silt and silty sand and the lower part is black/gray black sludge interbedded by salt deposit and mirabilite. Mainly distributed along Guojiagoushuili-Xishabianzi-Sandaochuan in the north and several to 10 m thick with a maximum thickness of 45 m, the aeolian sand of the upper Holocene series ( $Q_4^{col}$ ) is loose, consists of light yellow silty fine sands and often forms travelling dunes or semifixed dunes.

Fissure-pore water of Cretaceous clastic rock is widely distributed in the entire area. Water-bearing formations such as the Luohe formation and the Huanhe formation are extremely thick. The lithology is mainly interbedded fine sandstone and siltstone interspersed locally by argillaceous sandstone and sandy mudstone, and water quality, as a whole, is relatively poor. Quaternary pore water is only distributed in the south of Beidachi and the wind-sand



**Fig. 1** Location of the study area

grass land in the southeast. The aquifer is several meters to tens of meters thick. The lithology is light yellow/brownish yellow silty-fine sand. With the depth of 1.35–25.8 m, the groundwater has good quality and forms a unified and connected water-bearing system with the underlying Cretaceous aquifer (Fig. 2) (Hou and Zhang 2006).

The groundwater is mainly recharged by the lateral runoff from outside the area and the atmospheric precipitation with the latter being 70 % of the total recharge. It is mainly discharged through soil surface evaporation, vegetation evapotranspiration, overflow to surface water body such as lakes and artificial exploitation, and 87 % of the total discharge is through the first two ways (Zhou 2013). As the study area is high in the south, the groundwater flows northwards after being recharged. That in Liushu-liangshuili in the east flows westwards while that in the west flows eastwards and northeastwards. In the end, the groundwater converges centripetally towards the two final discharge places of Beidachi lake and Xiaochi pond within the study area (Fig. 3) (Xu et al. 2013).

**Data source**

The 110 sets of groundwater dynamics, hydrochemistry data, the lithology and soluble salt data from the 5 drill holes (LK3, LK4, LK5, LK6 and LK7) were provided by

Xi’an Center of China Geological Survey. In addition, 35 sets of vadose zone samples were taken from typical soil profiles during field survey in August 2012. Particle size of soil and core samples was analyzed with the sieving method and a laser particle size analyzer, respectively. Mineral composition was determined with X-ray diffraction spectrometer (XRD) according to national standard (SY/T 5163-2010). Chemical analyses were performed according to *Chemical Analytical Methods for Nonmetallic Minerals and Rocks* (JC/T1021-2007). Soluble salt experiment was conducted as described in *Standard for Soil Test Method* (GB/T-50123-1999). The above determinations were performed by the Xi’an Center of China Geological Survey who has first class quality certification.

**Research methods**

**Leaching experiment**

Soil column leaching experiment was conducted to quantitatively evaluate the contribution of the salts in the Vadose zone to the chemical composition of the groundwater. The soils used in the experiment were of the quaternary aeolian sand and of the Cretaceous Huanhe formation with lithology of silty-fine sand and sandy silt,

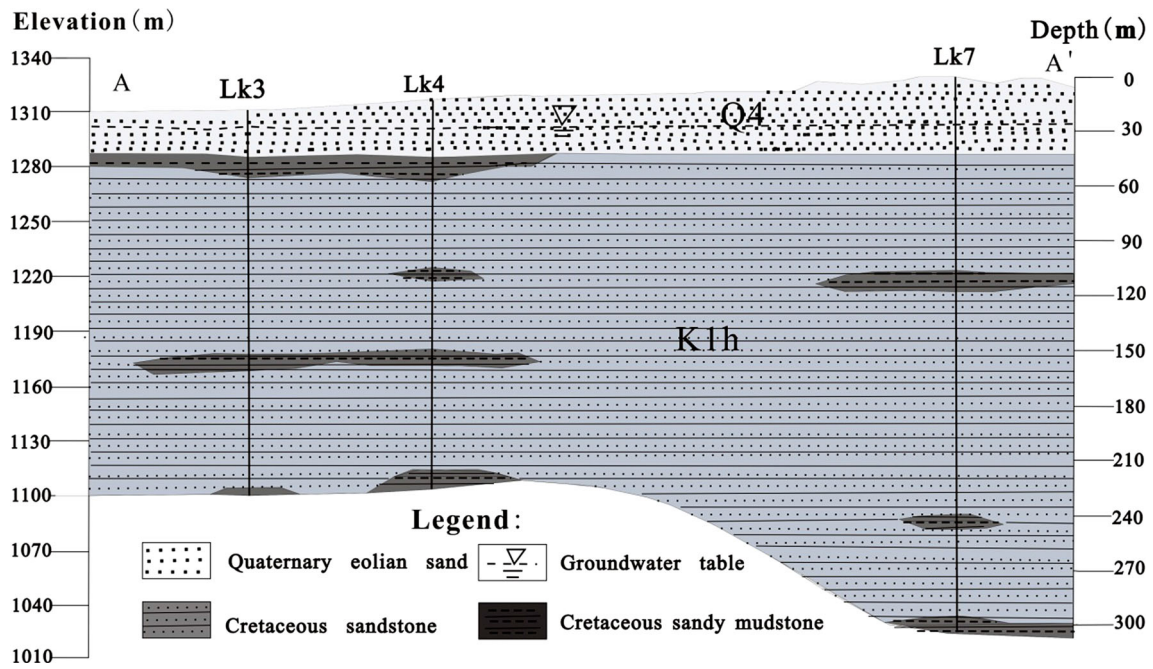


Fig. 2 Schematic hydrogeological profile in study area

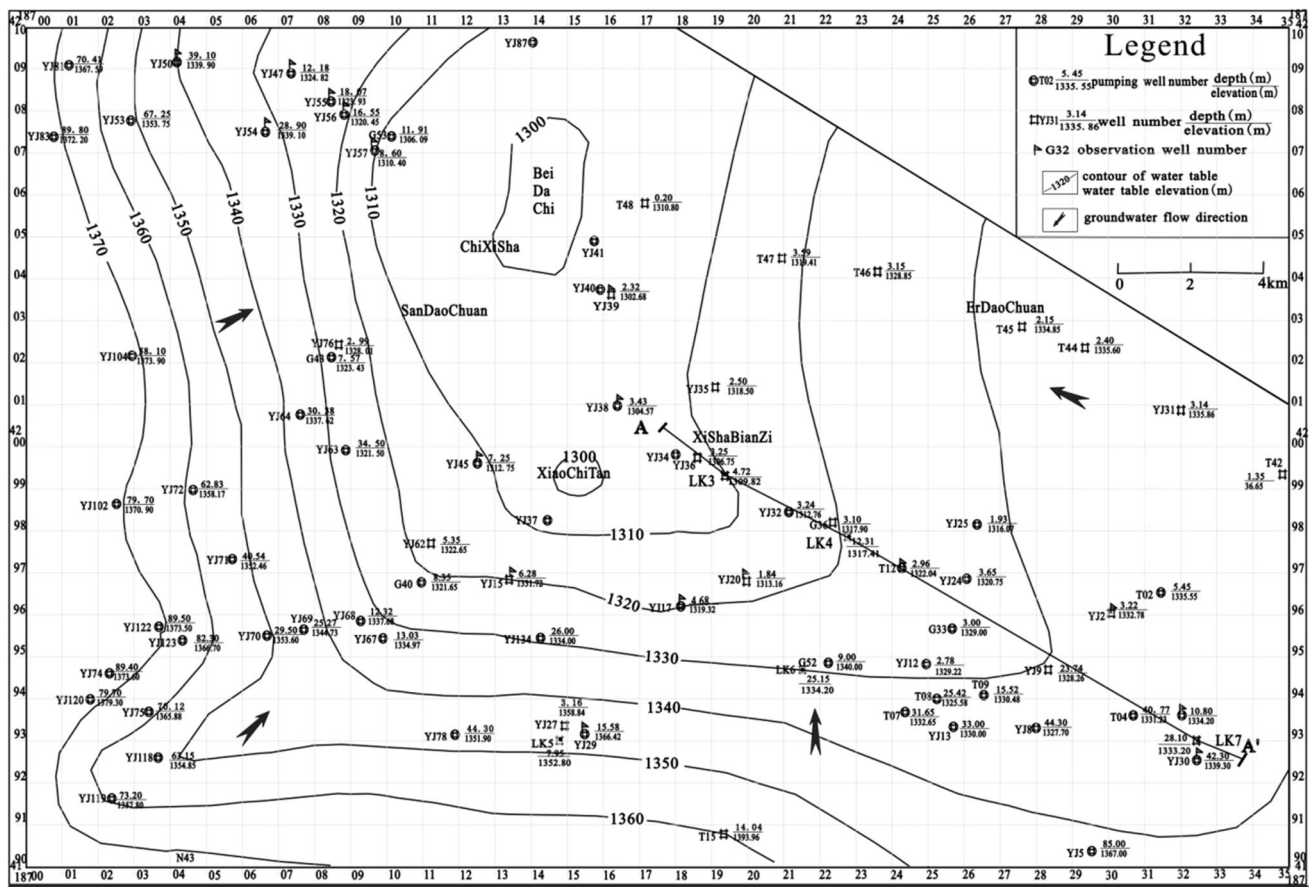


Fig. 3 Contour of shallow groundwater table in study area

respectively. Polymethyl methacrylate columns with inner diameter of 15 cm were used. Before filled with soils, the columns were pasted with waterproof abrasive paper on the inner walls to prevent predominant current and then filled with silica sand to a height of 3 cm on top of a sheet of fibermesh. After filled with soils, the columns were filled again with silica sand of 1 cm height and finished with another sheet of fibermesh. Distilled water was used for the leaching to simulate atmospheric precipitation. Water was first slowly supplied from the bottom of the column to saturate the soil, and then supplied from the top with a constant waterhead for continuous leaching. The time when water began to come out from the bottom was recorded as time 0 and the leachate (approximately 250 mL) was collected for determination of pH, Eh, electrical conductivity (EC),  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{CO}_3^{2-}$ ,  $\text{HCO}_3^-$ ,  $\text{NO}_3^-$ ,  $\text{K}^+$ ,  $\text{Na}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$  and  $\text{F}^-$ . The leaching was continued until the EC was stable. For each group of soil samples, heights of 30, 60 and 90 were set up in soil column, respectively.

*Water/salt balance*

The recharge and discharge of groundwater not only affect the water balance but also decide the salt balance in the aquifer system. Therefore, the water and salt balances in an area dedicate the evolution trend of the groundwater quality in that area. To elucidate the formation mechanism of the fresh groundwater in the Yanchi area, a water and salt balance model was developed. Salt balance calculation was based on water balance and the two balances have the following relationship:

$$\text{Water balance : } \sum_{i=1}^n Q_i - \sum_{j=1}^m Q_j = \Delta Q \tag{1}$$

$$\text{Salt balance : } \sum_{i=1}^n S_i - \sum_{j=1}^m S_j = \Delta S \tag{2}$$

where  $Q_i$  (in  $\text{m}^3/\text{a}$ ) is the amount of the  $i$ th water recharge,  $Q_j$  (in  $\text{m}^3/\text{a}$ ) is the amount of the  $j$ th water discharge,  $\Delta Q$  (in  $\text{m}^3/\text{a}$ ) is the change amount of the groundwater storage,  $S_i$  (in  $\text{g}/\text{a}$ ) is the amount of salt brought to the groundwater system by the  $i$ th water recharge,  $S_j$  (in  $\text{g}/\text{a}$ ) is the amount of salt taken away from the groundwater system by the  $j$ th water discharge, and  $\Delta S$  (in  $\text{g}/\text{a}$ ) is the change amount of salt storage in the groundwater system.

For the Yanchi area, groundwater recharge sources include atmospheric precipitation ( $P$ ) and lateral runoff from outside ( $Q$ ), while groundwater discharge includes evaporation and evapotranspiration ( $E$ ), artificial exploitation ( $W$ ) and overflow to the surface water bodies ( $R$ ). Thus, the water balance model is:

$$(P + Q) - (E + W + R) = \Delta Q \tag{3}$$

Corresponding to water recharge, salt recharge includes from atmospheric precipitation, the leachate through the vadose zone ( $S_P$ ) and from the lateral runoff ( $S_Q$ ); salt discharge includes through artificial exploitation ( $S_W$ ) and through overflow to surface water body ( $S_R$ ). During evaporation and evapotranspiration, only water is taken away, while the corresponding salts are left in the vadose zone and can return to the groundwater system with atmospheric precipitation. Therefore, it is taken that the evaporation and evapotranspiration of phreatic water has no effects on the salt discharge in the groundwater system. So the salt balance model for the aquifer system is:

$$(S_P + S_Q) - (S_W + S_R) = \Delta S. \tag{4}$$

**Results**

**The distribution and hydrochemical characteristics of saltwater and freshwater**

According to the *Hygienic Standard for Drinking Water* (Ministry of Health of the People’s Republic of China 2007), the total dissolved solid (TDS) in drinking water should not be higher than 1000 mg/L and chloride should not be higher than 250 mg/L. In this study, the study area was divided into saltwater area and freshwater area as shown in Fig. 4 using chloride of 250 mg/L and TDS of 1000 mg/L as the threshold values.

The samples depth of saltwater is mostly less than 30 m while that in freshwater mainly lies in 1–5 m. Analysis of the nine hydrochemical parameters of different groundwater quality in the study area is summarized in Table 1. The groundwater samples were weakly alkaline with pH range of 7.1–8.6. Concentrations of the principal parameters varied greatly, with coefficients of variation varying from 0.28 to 1.11, especially TDS,  $\text{Na}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{SO}_4^{2-}$  and  $\text{Cl}^-$ . For example, the concentration of TDS varied from 215.64 to 7930.74 mg/L. The concentrations of all parameters are almost inferior to the National Standard for Drinking Water in fresh groundwater zone (Ministry of Health of the People’s Republic of China 2007). However, the concentrations of all parameters practically exceed the National Standard for Drinking Water in saline groundwater zone, implying they are unsuitable for drinking.

In the east–west direction, the saltwater–freshwater boundary lay along Macanghao-Xishabianzi while in the north–south direction, the boundary lay along Shuangduizi-Liushuliang-Shabianzi wood farm. In the north aeolian sand dune area, the groundwater from the soil surface to

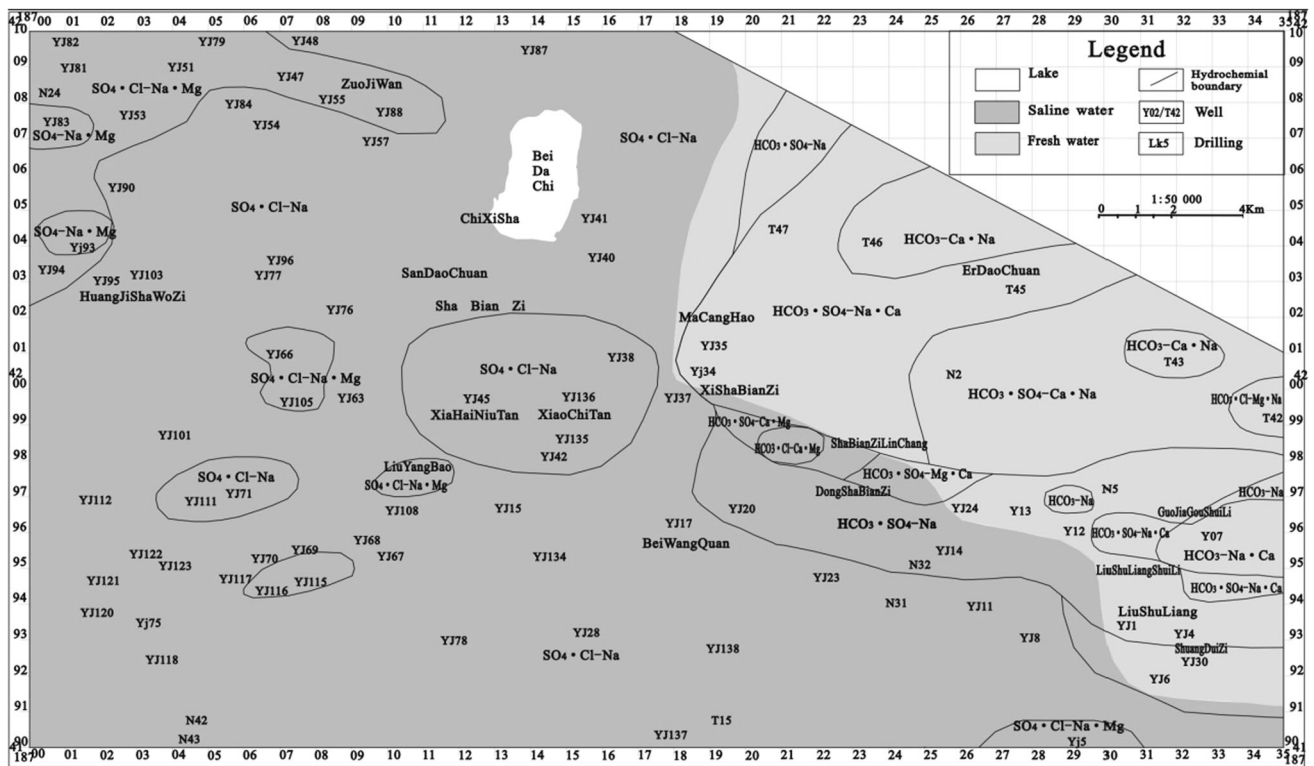


Fig. 4 Hydrochemical type and Water quality partition in the study area

Table 1 Descriptive statistics of hydrochemistry in fresh and saline groundwater

Parameters	Unit	Sample quantity	Minimum	Maximum	Mean	SD	CV	National standard
Fresh groundwater								
pH		20	7.4	8.1	7.64	0.19	0.025	6.5–8.5
TDS	mg/L	20	215.64	1038.94	592.32	272.7	0.46	1000
Na <sup>+</sup>	mg/L	20	22.32	229.37	103.17	66.88	0.65	200
Ca <sup>2+</sup>	mg/L	20	3.06	124.67	52.47	33.16	0.63	–
Mg <sup>2+</sup>	mg/L	20	16.54	96.08	35.17	22.58	0.64	–
Cl <sup>-</sup>	mg/L	20	8.86	163.08	71.28	57.46	0.81	250
SO <sub>4</sub> <sup>2-</sup>	mg/L	20	27.09	282.9	144.46	86.19	0.60	250
HCO <sub>3</sub> <sup>-</sup>	mg/L	20	147.05	395.15	278.92	78.59	0.28	–
F <sup>-</sup>	g/L	20	0.2	1.0	0.49	0.25	0.51	1.0
Saline groundwater								
pH		90	7.1	8.6	7.84	0.25	0.032	6.5–8.5
TDS	mg/L	90	375.7	7930.74	2309.4	1511.3	0.65	1000
Na <sup>+</sup>	mg/L	90	105.73	1922.84	580.81	350.16	0.60	200
Ca <sup>2+</sup>	mg/L	90	9.78	484.09	80.74	89.41	1.11	–
Mg <sup>2+</sup>	mg/L	90	13.05	416.38	101.38	85.96	0.85	–
Cl <sup>-</sup>	mg/L	90	15.56	2783.31	506.79	481.23	0.95	250
SO <sub>4</sub> <sup>2-</sup>	mg/L	90	68.15	3569.06	824.33	637.89	0.77	250
HCO <sub>3</sub> <sup>-</sup>	mg/L	90	49.0	585.03	315.7	127.06	0.4	–
F <sup>-</sup>	g/L	90	0.37	7.5	2.66	1.44	0.54	1.0

30 m below soil surface had a salinity <1.04 g/L, Cl<sup>-</sup> < 250 mg/L, F<sup>-</sup> < 1.0 mg/L with pH range of 7.4–8.1 (Table 1). The hydrochemical types were HCO<sub>3</sub> and HCO<sub>3</sub>-SO<sub>4</sub>, and the main cations were Ca<sup>2+</sup>·Na<sup>+</sup>, Na<sup>+</sup>·Ca<sup>2+</sup>, Mg<sup>2+</sup>·Ca<sup>2+</sup> and Ca<sup>2+</sup>·Mg<sup>2+</sup> (Fig. 4).

Along Guojigou-Nanwangquan-Liuyangbao-Huangjisha-wozi-Zuojiwan in the west and south of the study area, brackish groundwater with salinity of 1–3 g/L was widely distributed. Cl<sup>-</sup> was commonly higher than 250 mg/L, F<sup>-</sup> was 1–3 and >3.0 mg/L in some places with pH range of 7.1–8.6 (Table 1). The predominant hydrochemical type was SO<sub>4</sub>-Cl-Na with SO<sub>4</sub>-Cl-Na-Mg sporadically distributed. In the Xiaochi pond and Xiahainiutan near the groundwater discharge area, saltwater with salinity >3.0 g/L even up to 5.0 g/L was distributed. F<sup>-</sup> was 1–3.0 mg/L and the main hydrochemical types were Cl-SO<sub>4</sub>-Na and SO<sub>4</sub>-Cl-Na (Fig. 4).

**The leaching ability of vadose zone**

As can be seen from the mineral and chemical analysis results (Table 2), the main minerals in the soil samples from vadose zone were quartz, anorthose, potassium feldspar, calcite, illite and chlorite. Hornblende and kaolinite

**Table 2** The contents (%) of mineral and chemical composition of the aquifer medium

Sample	Silty-fine sand	Sandy silt
<b>Mineral composition</b>		
Quartz	63.00	36.78
Anorthose	20.75	33.67
Potassium feldspar	5.15	9.06
Calcite	4.13	4.51
Hornblende	0.82	1.34
Pyrite	–	0.18
Apatite	–	0.19
Analcite	–	1.07
Gypsum	–	0.38
Montmorillonite	–	1.61
Dolomite	–	0.21
Illite	2.67	6.14
Chlorite	2.67	4.86
Kaolinite	0.33	–
<b>Chemical composition</b>		
SiO <sub>2</sub>	77.31	64.17
Al <sub>2</sub> O <sub>3</sub>	8.39	11.97
Fe <sub>2</sub> O <sub>3</sub>	2.15	3.39
CaO	3.05	5.81
MgO	0.97	1.60
K <sub>2</sub> O	1.98	2.30
Na <sub>2</sub> O	1.78	2.99

were also detected in the silty-fine sand. Montmorillonite, hornblende, analcite, and dolomite were found in the sandy clay from the Huanhe formation and gypsum in some samples. It can be seen that predominated by quartz, the silty-fine sand had a simpler mineral composition than the sandy silt from the Huanhe formation. Chemical composition analysis results also showed that the silty-fine sand contained mainly SiO<sub>2</sub> with low contents of other components. Both the mineral composition and chemical composition analysis results demonstrated that the silty-fine sand contained far less salt than the sandy silt.

From the leaching experiment results, it can be observed that the salt deliverability of the vadose zone media of different lithologies. As shown in Table 3, for a same lithology, the higher the soil column, the larger the salinity and Cl<sup>-</sup> concentration in the leachate. For a same height, leachate through the sandy silt column had larger salinity and Cl<sup>-</sup> concentration than that through the silty-fine sand column. When leaching became stable, the leachates from the silty-fine sand columns of 30, 60 and 90 cm height have salinity of 28.93, 39.07 and 49.97 mg/L, respectively and the leachates from the sandy silt had salinity of 163.93, 226.87 and 340.50 mg/L, respectively. The silty-fine sand had an average salt deliverability of 15.97 mg/L of which Cl<sup>-</sup> was 0.04 mg/L while the sandy silt had an average salt deliverability of 220.42 mg/L of which Cl<sup>-</sup> was 0.44 mg/L. Therefore, the salt deliverability of the silty-fine sand covering the aeolian sand aquifer was far smaller than that of the sandy silt covering the aquifer of the Huanhe formation.

**Discussion**

**The major factors influencing on the quality of groundwater**

*The effects of the chemical composition of vadose zone on the quality of groundwater*

When the minerals such as silicate, carbonate and sulfate in vadose zone and aquifer medium contact with groundwater, hydrogeochemical reactions such as dissolution, leaching and cation exchange generally happen. These hydrogeochemical processes will change the chemical component contents and distribution characteristics of the groundwater (Kumar et al. 2009; Sonkamble et al. 2012; Kraiem et al. 2013). When atmospheric precipitation moves down through vadose zone, it will bring the soluble salts out from the vadose zone into the groundwater, influencing the chemical properties of the groundwater. Table 4 shows the soluble salt contents in the vadose zone samples and the chemical characteristics of the

**Table 3** Soluble salt deliverability of each lithology

Column height (cm)	The silty-fine sand		The sandy silt	
	TDS (mg/L)	Cl <sup>-</sup> (mg/L)	TDS (mg/L)	Cl <sup>-</sup> (mg/L)
30	5.57	0.03	140.58	0.43
60	15.72	0.04	203.52	0.44
90	26.62	0.06	317.15	0.46
Mean	15.97	0.04	220.42	0.44

**Table 4** The relation between the chemical properties of Vadose zone soil and groundwater

Sampling site	Vadose zone soil				Groundwater				
	No.	Soluble salt content (g/kg)	F <sup>-</sup> (mg/L)	Chemical type	Well No.	TDS (g/L)	F <sup>-</sup> (mg/L)	Chemical type	Depth (m)
Nanwangquan	1	0.55	0.24	HCO <sub>3</sub> -Ca·Mg·Na	YJ29	5.548	1.20	Cl·SO <sub>4</sub> -Na	15.58
Beiwangquan	2	19.01	1.54	Cl·HCO <sub>3</sub> ·SO <sub>4</sub> -Na	YJ17	7.02	1.44	SO <sub>4</sub> ·Cl-Na	4.68
Xishabianzi	3	0.23	0.11	HCO <sub>3</sub> -Ca·Mg	YJ35	0.282	0.24	HCO <sub>3</sub> ·SO <sub>4</sub> -Ca·Na	2.50
Dongshabianzi	4	19.15	7.70	HCO <sub>3</sub> -Cl-Na·Ca	YJ126	1.038	0.62	HCO <sub>3</sub> ·SO <sub>4</sub> -Mg·Ca	2.96
Liushuliang	5	0.69	0.15	SO <sub>4</sub> ·HCO <sub>3</sub> -Na·Ca	Y02	0.346	0.55	HCO <sub>3</sub> ·SO <sub>4</sub> -Na·Ca	3–5
Liushuliangshuili	6	0.93	0.73	HCO <sub>3</sub> ·SO <sub>4</sub> -Na·Ca	Y01	0.334	0.65	HCO <sub>3</sub> -Na	3–5

groundwater in corresponding area. The salt and F<sup>-</sup> contents in vadose zone soils were highly consistent with the salinity and F<sup>-</sup> concentration in the groundwater of the corresponding area. That is, the higher the salt/F<sup>-</sup> content in vadose zone will promote the higher the salinity/F<sup>-</sup> concentration in the corresponding groundwater. Such consistence was related to the groundwater depth. As the depth of groundwater is the shallower, the chemical properties of vadose zone and groundwater will be the closer. This indicates that the chemical materials in vadose zone have important influence on the chemical composition of the groundwater and are the important sources of the chemical materials in groundwater.

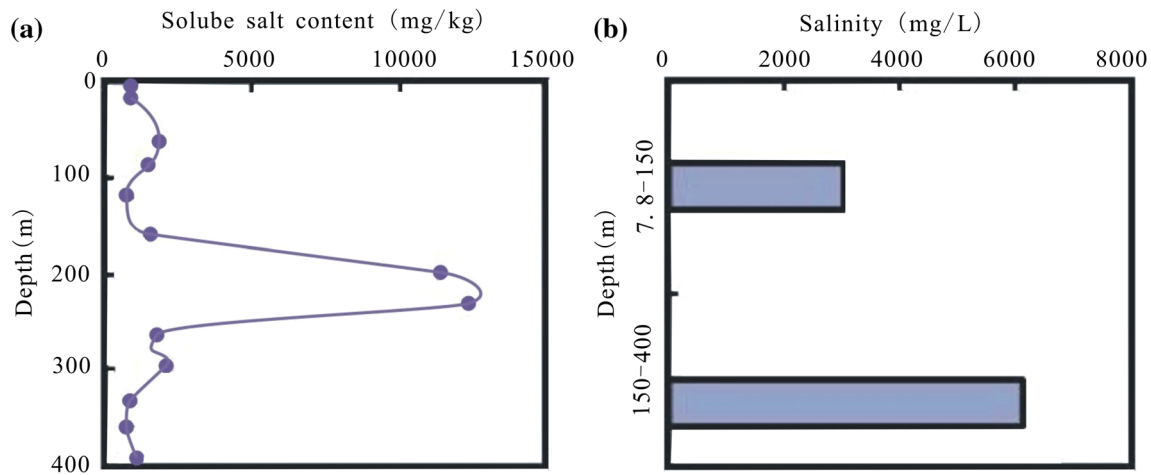
Hydrogeochemical simulation is currently a commonly used method throughout the world for studying the formation and evolution of the chemical composition of groundwater (Parkhurst and Appelo 1999; Rosenthal et al. 2007; Sung et al. 2012). In this study, hydrogeochemical simulation method was employed to simulate the leaching processes. The results showed that water–rock interaction occurred between water and soil, which was indicated by the dissolution of calcite, CO<sub>2</sub>, fluorite, gypsum, rock salt and potassium feldspar, the precipitation of dolomite, illite and quartz, and cation exchange. The mineral dissolution/precipitation between water and the silty-fine sand was relatively weak while that between water and sandy silt was relatively strong and cation exchange between NaX/CaX<sub>2</sub> was significant. This is the main reason why the salt deliverability of the silty-fine sand over the aeolian sand aquifer was far smaller than that of the sandy silt over the aquifer of the Huanhe formation.

The lithology of the vadose zone in the freshwater area is quaternary aeolian sand. Soluble salt contents are low and most of the mineral components are indissolvable minerals. Water–rock interaction is weak. When atmospheric precipitation infiltrates downward through the vadose zone, small amount of chemical materials is leached from the vadose zone to groundwater. As a result, the groundwater with relatively low salinity is formed.

#### *The effects of the chemical composition of aquifer medium on groundwater quality*

The soluble salts and chemical composition of the drill hole LK5 were used as an example to analyze the relation between the geochemical properties of aquifer medium and the chemical properties of the groundwater. Corresponding stratification of the groundwater was made according to the stratification of the drill hole LK5: 7.8–150 m as the upper layer and 150–400 m as the lower layer. As shown in Fig. 5, the upper layer of the rock–soil had lower soluble salt contents than the lower layer and correspondingly. Accordingly, the upper layer of the groundwater had lower salinity than the lower layer. In addition, Table 5 shows that there were very good correlations between soluble salt content, salinity and major ions in the aquifer medium and those in the groundwater, respectively. This implies that the chemical composition of aquifer medium is also one of the important factors influencing the chemical composition of groundwater and that the material transfer between aquifer medium and the groundwater also affects and changes the original chemical properties of groundwater.





**Fig. 5** The soluble content in drill hole LK5 (a) and the salinity in groundwater (b)

**Table 5** The chemical compositions of the rock–soil of drill hole LK5 and of the groundwater

Depth	pH	Salinity	F <sup>-</sup>	K <sup>+</sup> +Na <sup>+</sup>	Ca <sup>2+</sup>	Mg <sup>2+</sup>	Cl <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	HCO <sub>3</sub> <sup>-</sup>
The upper layer (7.8–150 m)									
Rock–soil (mg/kg)	9.2	1144.6	2.5	324.9	65.9	18.4	117.4	388.7	338.6
Groundwater (mg/L)	8.1	3010.5	2.6	800.4	141.8	77.1	733.9	1054.7	297.1
The lower layer (150–400 m)									
Rock–soil (mg/kg)	8.7	3885.4	1.2	395.1	795.3	29.1	221.6	2269.2	294.3
Groundwater (mg/L)	7.9	6111.2	0.8	1454.6	533.0	112.7	2109.5	1863.4	49.0

*The influence of hydrodynamic conditions*

Hydrodynamic conditions reflect how quickly groundwater moves through aquifer medium and it is one of the important factors influencing water–rock interaction. Therefore, hydrodynamic condition is the vital factor influencing hydrogeochemical processes and the zoning of groundwater chemical constituents (Guo and Wang 2004; Cao et al. 2009; Iggy et al. 2010; Maurice et al. 2011). The study area is located in the depressed zone of Yanchi, and the terrain is high in the west and south but low in the east and north with weak incision. The groundwater flows towards low-lying places or surface lakes (e.g., Xiaochi pond, Beidachi pond). According to calculation, the groundwater flowed relatively slow, at approximately 0.1 m/d, in the saltwater zone while it flowed at about 0.25 m/d in the freshwater zone (Zhou 2013). Ion equivalent ratio,  $\gamma\text{Cl}^-/\gamma\text{Ca}^{2+}$ , can indirectly reflect hydrodynamic features. The smaller the ratio is, the better the hydrodynamic condition is. On the contrary, the high ratio indicates slow flow of the groundwater (Chidambaram et al. 2005; Belkhiri et al. 2012). The  $\gamma\text{Cl}^-/\gamma\text{Ca}^{2+}$  is 3.68–7.41 in the saltwater zone while that is approximately 0.72 in the freshwater zone. Therefore, both ion equivalent ratio and flow rate indicate a better hydrodynamic condition for the groundwater in the freshwater zone. In other words, in the freshwater zone, as the interaction time between the aquifer medium and the

groundwater is short, there is no enough time for water–rock interaction. As a result, relatively small amount of chemical materials in the aquifer medium will go into the groundwater.

*The recharge ability of precipitation infiltration and the discharge ability of evaporation*

1. Atmospheric precipitation infiltration

The recharge ability of atmospheric precipitation infiltration is influenced and controlled by many factors such as landform, surface vegetation, lithologic structure of vadose zone, precipitation characteristics and the buried conditions of groundwater. In the west and south of the study area, the landform fluctuates greatly, and the groundwater is buried deeply. The lithology of the vadose zone is not uniform with mudstone interlayer, resulting in an unfavorable coefficient of 0.08–0.10 for precipitation infiltration recharge. In the north of the study area adjacent to the Mu Us Desert in Inner Mongolia, the vadose zone is an extremely thick layer of eolian sand which has loose structure, developed pores, very good water permeability with coefficient of 0.2–0.4 for precipitation infiltration recharge (Hou and Zhang 2006). As the distribution of precipitation within a year is extremely nonuniform and precipitation is often in the form of rainstorm, the eolian

sands are easy for rainstorms to infiltrate, freshwater bodies with good water abundance and good water quality readily developed. Moreover, the quaternary aquifer and the Cretaceous aquifer had close hydraulic connection. Therefore, atmospheric precipitation not only becomes the freshwater in the quaternary aquifer but also dilutes the groundwater in the Huanhe formation underneath in the freshwater zone.

## 2. Groundwater evaporation

Groundwater evaporation concentrates the chemical components in the groundwater. Generally, shallow brackish water and saline water of high salinity readily form in the middle of an arid and semiarid basin with strong evaporation (Ren and Yan 1999; Li and Hao 1999; Duan et al. 2007). However, in the study area with the same evaporation intensity, the co-occurrence of shallow brackish water, saline water and freshwater indicated that the shallow groundwater has different evaporative power. Generally speaking, in coarse particle medium, the capillary water ascends less, which is unfavorable for evaporation, while the opposite is true in fine particle medium. Previous research showed that the maximum evaporation depth is about 0.5 m in the aeolian sand of the Ordos Basin and about 5 m in sandy loam (Wang et al. 2011). Laboratory determination showed that capillary water rose for 53 cm in the aeolian sand sample taken from the study area, in line with the maximum evaporation depth of the aeolian sand. This demonstrates that in the north aeolian sand area, when the groundwater depth is 3–5 m which is far larger than 53 cm, the evaporative power of the groundwater is weakened greatly. Therefore, even though the ground evaporation was strong, the evaporation effect the groundwater was subjected to small.

However, along Liushuliangshuili-Shabianzi-Beiwangquan-Xiahainiutan in the west and south of the study area, the soil type in the vadose zone was sandy loam, and the groundwater depth was 3–5 m. The groundwater

evaporation was so strong that the chemical components in the groundwater had been concentrated and accumulated, resulting in high salinity groundwater.

## Groundwater and salt balances

Table 6 shows the water and salt balances in the freshwater zone. The annual total water recharge was  $2.7685 \times 10^7$  m<sup>3</sup>/a of which  $2.13953 \times 10^7$  m<sup>3</sup>/a or 77.28 % was from atmospheric precipitation and  $6.2897 \times 10^6$  m<sup>3</sup>/a or 22.72 % from lateral runoff. The annual total salt recharge was  $1.07477 \times 10^6$  kg/a of which  $8.6 \times 10^2$  kg/a or 0.08 % was from atmospheric precipitation,  $2.7917 \times 10^5$  kg/a or 25.97 % from lateral runoff through the east boundary, and  $7.9474 \times 10^5$  kg/a or 73.95 % from lateral runoff through the saltwater–freshwater boundary in the south. The last was the major salt source for the freshwater zone.

The annual water discharge of the freshwater zone was  $2.61314 \times 10^7$  m<sup>3</sup>/a of which  $1.67618 \times 10^7$  m<sup>3</sup>/a or 64.14 % was through evapotranspiration and evaporation, the major discharge way in the freshwater zone,  $1.5938 \times 10^6$  m<sup>3</sup>/a or 6.10 % through artificial exploitation, and  $7.7758 \times 10^6$  m<sup>3</sup>/a or 29.76 % through lateral runoff. The annual total salt discharge was  $1.07758 \times 10^6$  kg/a of which  $1.5226 \times 10^5$  kg/a or 14.13 % was through artificial exploitation and  $9.2532 \times 10^5$  kg/a or 85.87 % through lateral runoff. The recharge–discharge difference for water was  $1.5534 \times 10^6$  m<sup>3</sup>/a while that for salt was  $-2.81 \times 10^3$  kg/a.

As can be seen from Table 6, although atmospheric precipitation contributed 77.28 % of the total water recharge, the salt recharge contributed by its infiltration through the vadose zone was only 0.08 % of the total salt recharge, indicating that contribution of local atmospheric precipitation to the salts in groundwater was negligible. The lateral runoff from the south boundary contributed only 12.48 % of the total groundwater recharge, but it

**Table 6** The water and salt balances in the freshwater zone

Recharge	Water		Salt		Discharge	Water		Salt	
	10 <sup>4</sup> m <sup>3</sup> /a	%	10 <sup>3</sup> kg/a	%		10 <sup>4</sup> m <sup>3</sup> /a	%	10 <sup>3</sup> kg/a	%
Precipitation	2139.53	77.28	0.86	0.08	Evapotranspiration and evaporation	1676.18	64.14	0	0
Lateral runoff									
East boundary	283.43	10.24	279.17	25.97	Artificial exploitation	159.38	6.10	152.26	14.13
South boundary	345.54	12.48	794.74	73.95	Lateral discharge	777.58	29.76	925.32	85.87
Total recharge	2768.50		1074.77		Total discharge	2613.14		1077.58	
Water recharge–discharge difference	$155.34 \times 10^4$ m <sup>3</sup> /a				Salt recharge–discharge difference	$-2.81 \times 10^3$ kg/a			
Total water resource	$1.25 \times 10^{10}$ m <sup>3</sup> /a								

contributed 73.95 % of the total salt recharge, highly suggesting a huge potential threat of the southern saltwater zone to the fresh groundwater. In addition, the annual salt recharge–discharge difference in the freshwater zone was  $-2.81 \times 10^3$  kg/a, indicating that the salt did not accumulate in the fresh groundwater. In other words, salt concentration in the groundwater can decrease 0.23  $\mu\text{g/L}$ , count on  $\text{Cl}^-$ , annually which can be negligible when compared with the average  $\text{Cl}^-$  concentration of 110.5 mg/L in the groundwater. Therefore, salt balance in the freshwater zone was basically in a balanced state. Currently, seawater or saline water intrusion has occurred in many freshwater areas due to excessive exploitation of fresh groundwater, resulting in salinization occurrence of the limited fresh groundwater resources (Kim et al. 2003; Misut and Voss 2007; Ghiglieri et al. 2012; Han et al. 2014). Therefore, in the future exploitation of the fresh groundwater in study area, water quality and quantity constraint should be taken into account to optimize related exploitation schemes to ensure that water quality will not deteriorate.

**The formation mechanism of the fresh groundwater**

On the basis of previous research on geological and hydrogeological conditions, the formation mode chart as shown in Fig. 6 was developed for the fresh groundwater in the Yanchi area by analyzing material source, hydrodynamic condition, precipitation infiltration and evaporation coupling the results of water/salt balance analyses.

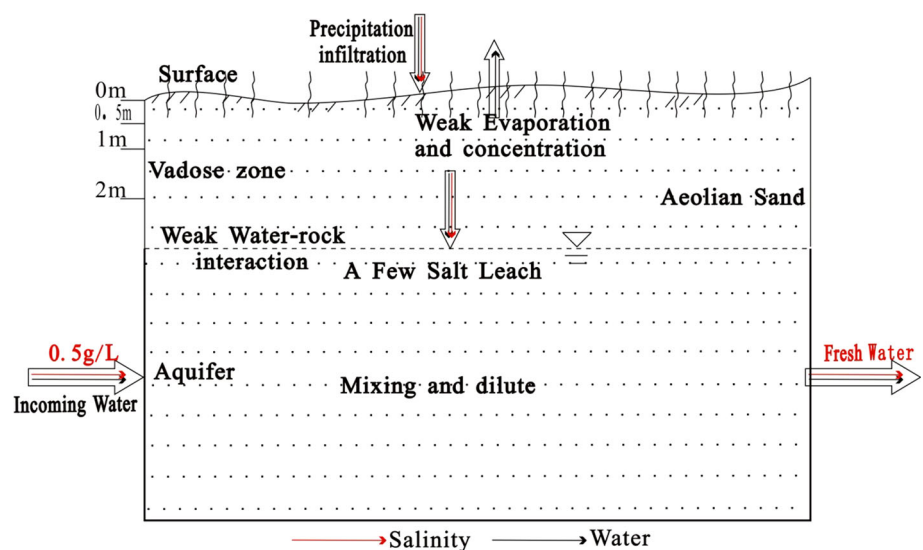
In the north area near the Mu Us Desert, the main landform is aeolian sand dune and the ground is covered by a thick layer of quaternary aeolian sand. The aeolian sand in the vadose zone has loose structure, developed pores,

and very good water permeability. In addition, the groundwater is buried shallowly. Therefore, precipitation can go through the vadose zone quickly to recharge the groundwater. As the aeolian sand in the vadose zone has low contents of soluble salt, the eluviations is weak during the infiltration process of precipitation. Salts leached by precipitation was  $0.86 \times 10^3$  kg/a, only 0.08 % of the annual total salt recharge. The shallow aquifer in the north of the study area is quaternary aeolian sand. Leaching experiments demonstrated weak water–rock interaction and that the chemical material supply ability for the groundwater was low which was unfavorable for the rise of the groundwater salinity. The capillary rise ability of the aeolian sand in the vadose zone was weak, the maximum evaporation depth was 0.5 m while the groundwater depth was 3–5 m. Therefore, the aeolian sand effectively prevented the evaporation of groundwater, slowed down the concentration effects of the chemical components in the groundwater. Evidently, the special physico-chemical properties of the aeolian sand rendered a high amount of recharge from precipitation infiltration, a low amount of leached salts, and weak water–rock interactions and effectively prevented the groundwater from evaporation. Therefore, those serve as a vital role in the formation of fresh groundwater.

Besides, the north of the study area received a large amount of freshwater recharge from the Mu Us Desert, which was approximately 10.24 % of the total recharge for the freshwater zone. The incoming freshwater had a salinity of about 0.5 g/L. It mixed and diluted the groundwater in the study area, also playing an important role in the formation of the freshwater.

Generally, formation lithology and landform control the chemical composition and movement of the materials in

**Fig. 6** Formation pattern of shallow fresh groundwater



groundwater, the arid climate with strong evaporation inevitably leads to material accumulation, and the hydro-geochemical processes affect the distribution pattern of the chemical components in groundwater while human activities drive the evolution process of groundwater quality (Shen 1986; Cao et al. 2009; Jing et al. 2014). However, in the arid north area of Yanchi area, the strong evaporation hardly played a role in the formation and evolution of the fresh groundwater in the aeolian sand area, which subverts our traditional knowledge that strong evaporation and concentration would result in shallow saline groundwater. This suggests that even in arid and semiarid areas with strong evaporation, shallow fresh groundwater resources are possible to be found. Therefore, the findings of this study are of significance for the groundwater exploration and exploitation in other arid and semiarid areas.

## Conclusions

Based on the presented results, the following conclusions can be drawn:

1. The geochemical characteristics of the groundwater in the study area had the evident feature of zonation. In the north aeolian sand area, the groundwater was fresh water with low salinity and the major hydrochemical type of  $\text{HCO}_3\text{-SO}_4$ . In the west and south areas, the Cretaceous groundwater was brackish or saline water with high salinity and the major hydrochemical type of  $\text{SO}_4\text{-Cl-Na}$ .
2. The chemical materials in vadose zone and aquifer medium have vital influence on the compositions of groundwater. Hydrodynamic conditions is one of the important factors influencing water-rock interaction which can contribute the amount of chemical materials into the groundwater. Meanwhile, the ability of precipitation infiltration and evaporation is the significant effect on the groundwater quality in the study area.
3. The water and salt balances are developed to analyze the recharge and discharge amount of water and salt in the freshwater zone, which implies salt concentration can annually decrease  $0.23 \mu\text{g/L}$ , count on  $\text{Cl}^-$  in the groundwater. The lateral runoff from the south boundary contributed 73.95 % of the total salt recharge in the freshwater zone, highly suggesting a huge potential threat of the southern saltwater zone to the fresh groundwater.
4. Due to the special physic-chemical properties of aeolian sand, the condition for precipitation infiltration recharge was good, the water-rock interaction was weak, the amount of salts leached was small, and the evaporation intensity of the groundwater was weak in the shallow fresh groundwater area. This played a deciding role in the formation of the fresh groundwater. In addition, the large amount of lateral runoff recharge of fresh groundwater from the Mu Us Desert played a role of mixing and diluting during the formation of the fresh groundwater.

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