Exposure and Health (2020) 12:513–525
https://doi.org/10.1007/s12403-019-00317-9

ORIGINAL PAPER

Quantitative Study on the Changes of Karst Groundwater Level and Hydrochemistry in Jinci Spring Catchment, Shanxi, China

Zhixiang Zhang[1,2] · Zhaoliang Wang[2] · Yongxin Xu[2,3] · Yongbo Zhang[1] · Liangliang Guo[1] · Qiang Zheng[1] · Li Tang[1]

Received: 23 February 2019 / Revised: 19 May 2019 / Accepted: 28 June 2019 / Published online: 5 July 2019

Abstract

Since Jinci spring ceased to flow on April 30, 1994, it has never been reflowed, which seriously affects the sustainable utilization of karst groundwater. The purpose of this paper is to provide the basis for the reflow of Jinci spring and the sustainable protection for karst groundwater. Based on the long-term monitoring data from 1994 to 2014, this paper accurately quantifies the changes in the quantity and hydrochemistry of karst groundwater resources. By means of the Mann–Kendall trend test method, this paper analyzes the variation trends of karst groundwater level, EC, and SO_4^{2-} in Jinci spring catchment. Monitoring data show that the groundwater level in the karst aquifer declined by 2.32 m from 1994 to 2008, which is equivalent to a loss of 3.3 Mm^3 in aquifer storage, while the groundwater level rose by 17.67 m from 2009 to 2014, which constitutes a gain of 25.2 Mm^3. The results indicate that (1) karst groundwater level showed a rising trend, which was mainly controlled by the rainfall, exploitation of karst groundwater, and the Fenhe River leakage; (2) groundwater salinity varied greatly and showed an increasing trend: increasing order of 47.83% for the six major ions, 37.52% for EC, and 3.34% for pH; (3) the increase of groundwater salinity is governed by the increase in rainfall salinity, the increase in groundwater runoff time, the recharge of the Fenhe River to groundwater, the increase of sewage in spring catchment, and the ease of solubility of carbonate rocks. The results of this study are of great significance for predicting the groundwater level and salinity of karst aquifer and ensuring the safety of drinking water in Jinci spring catchment.

Keywords Groundwater level · Hydrochemistry · Jinci spring · Overexploitation · Salinity

✉ Zhaoliang Wang
wzliang0501@126.com

Zhixiang Zhang
zhangzhixiang@tyut.edu.cn

Yongxin Xu
xuyongxin@tyut.edu.cn

Yongbo Zhang
zfstzhang@sina.com

Liangliang Guo
guoliangliang@tyut.edu.cn

Qiang Zheng
tyutzhengqiang@163.com

Li Tang
Li370336892@163.com

[1] College of Water Resources Science and Engineering, Taiyuan University of Technology, Taiyuan 030024, China

[2] Department of Earth Sciences, University of the Western Cape, Cape Town 7535, South Africa

[3] Institute of Africa Water Resources and Environment, Hebei University of Engineering, Handan 056038, China

Introduction

Groundwater is a valuable resource in arid and semi-arid regions of the world. It plays a vital role in local agricultural, industrial, and domestic water uses. With global warming, it will further intensify the shortage of groundwater resources in arid and semi-arid areas (Scanlon et al. 2010). In addition, due to the increasing demand for water resources in economic and social development, overexploitation of groundwater (Custodio 2002), coupled with the drainage of sewage resulting from the acceleration of industrialization, has brought a very serious negative impact on groundwater resources; the declines of groundwater level and groundwater contamination and pollution in aquifers are very common, threatening the sustainable use of groundwater and the health of residents. In many water source areas, the monitoring wells have been explored and drilled, and many valuable groundwater monitoring data have been obtained. In order to avoid the shortage of groundwater resources and deterioration of water quality, it is very necessary for researchers to analyze the changes in the quantity and hydrochemistry of groundwater resources in aquifers based on groundwater monitoring data, and to identify and quantitate the relevant trends to draw reliable conclusions. This not only gives us a clear understanding of the current state of groundwater resources, but also allows us to predict the future changes of groundwater based on the status quo. It is of great significance for the protection of the quality and quantity of groundwater resources and the sustainable utilization of groundwater.

Many researches have been carried out on the quantity and quality of groundwater resources, and many valuable results have been obtained. For example, Ajdary and Kazemi (2014) concluded that the overexploitation and decrease in rainfall aggravated the downward trend of groundwater level in Shahrood, northeastern Iran, with a loss of 216 Mm^3 from the aquifer storage from 1993 to 2009. Khezzani and Bouchemal (2018) pointed out that the decline of groundwater level in the Souf oasis of Algerian Sahara was accompanied by the dramatic increase in electric conductivity. Boukhari et al. (2015) found that the enrichment of chlorides and sulfates caused the change in groundwater salinity from east to west in large alluvial aquifer of Morocco. Ghouili et al. (2018) evaluated the water quality of the phreatic aquifer in the northeastern Tunisia, and regarded that the cumulative evaporative effect of rainwater infiltration into groundwater led to the increase in groundwater salinity. Li et al. (2019) pointed out that TH, TDS, NO_3^-, and SO_4^{2-} had affected the groundwater quality in Yan'an, China, and nearly half of the residents were facing noncarcinogenic health risks. Although the previous studies provide important references for comprehensive understanding of the sustainable use of local groundwater resources and the safety of drinking water, the multifactor comprehensive analysis on the changes in the quantity and hydrochemical status of groundwater resources needs to be further studied.

Some scholars have reviewed the factors affecting the groundwater quantity and quality. For example, Fan et al. (2016) reported that the intensified coal mining is the main driving factor for the decline of groundwater level in the Yushenfu mining area. Under the anthropogenic influence, the groundwater level in Jinan spring catchment has a significant downward trend of −0.694 m/10a, and the precipitation has an insignificant upward trend of 23.941 mm/10a (Qi et al. 2015). Due to the impact of overexploitation, the total amount of water resources in Beijing area has been greatly reduced, and the groundwater quality has been deteriorated (Wang et al. 2017). Groundwater in Guanzhong Plain Irrigation Area is mainly composed of micro-salt water and medium-salt water; the electric conductivity varies with time, and the larger the electrical conductivity, the greater the change over time (Liu et al. 2018). However, the changes in the quantity and quality of groundwater were not described, and the potential health risks of groundwater quality exceeding the national standard were not quantitated in the previous researches, which might restrict the sustainable use and management of local groundwater.

China is one of the countries where karst is extensively developed in the world. In terms of the geographical distribution and basic characteristics, karst in China is divided into the southern type and the northern type (Zhang et al. 2018). In the northern karst of China, the area of carbonate rocks in Shanxi covers 1.02×10^5 km^2, and the total karst groundwater resources are estimated to be 3.5×10^9 m^3/a (Liang and Han 2013). Due to its location in arid and semi-arid regions, the water resources in Shanxi are very scarce, and the development of groundwater is significantly dependent on karst groundwater. In the last 60 years, problems such as the decline of groundwater level and groundwater contamination and pollution have occurred in Shanxi karst springs, and these problems have attracted great attentions by scholars. Karst spring flows have been found to have continuously decreased for the past many years (Liang et al. 2018). In particular, Lancun spring, Jinci spring, and Gudui spring dried up in 1988, 1994, and 1999, respectively, and they have no reflows so far (Zhang et al. 2018). The researchers concluded that the climate change and human activities were the causes for the decrease of Shanxi karst spring flows (Zhang et al. 2018; He et al. 2019). Zhang et al. (2016a) proposed that the coal mining and hydrogeochemical processes caused the degradation of karst groundwater quality in Niangziguan spring. The scholars have accumulated some experiences, methods, and achievements in the study of karst springs and karst groundwater, and promoted the karst groundwater science to a higher level. All these provide research ideas and references for future generations. However, due to the differences in hydrogeological conditions among karst spring catchments in Shanxi, and the problems of serious water quantity and quality, study on karst groundwater needs to be further strengthened.

Jinci spring is a typical representative of the 19 major karst springs in Shanxi region, northern China. It is located in the Jinci Temple (the earliest Royal Garden in China), and it is the concentrated discharge point of karst groundwater in Jinci spring catchment. The Jinci Temple is famous for Jinci spring and its unique humanity architecture, with a long history and culture, and it has been awarded as a national key cultural unit. Since Jinci spring ceased to flow on April 30, 1994, it has never been reflowed, which seriously affects the sustainable utilization of karst groundwater in Jinci spring catchment and the tourism value of the Jinci Temple. In addition, karst groundwater quality plays a vital role in the health of local residents (Wu and Sun 2016; Li et al. 2018). Due to the important historical and regional significances of Jinci spring, researchers have studied the dynamics of karst groundwater level, groundwater quality, and vulnerability (Zhao 2014; Gao 2012; Zhang et al. 2016b), and obtained beneficial results. However, the comprehensive research of the karst groundwater level and hydrochemistry was not conducted in Jinci spring catchment, and the effect of water quality on the safety of drinking water was not discussed in the previous studies, which might restrict the reflow of Jinci spring and the protection of karst groundwater.

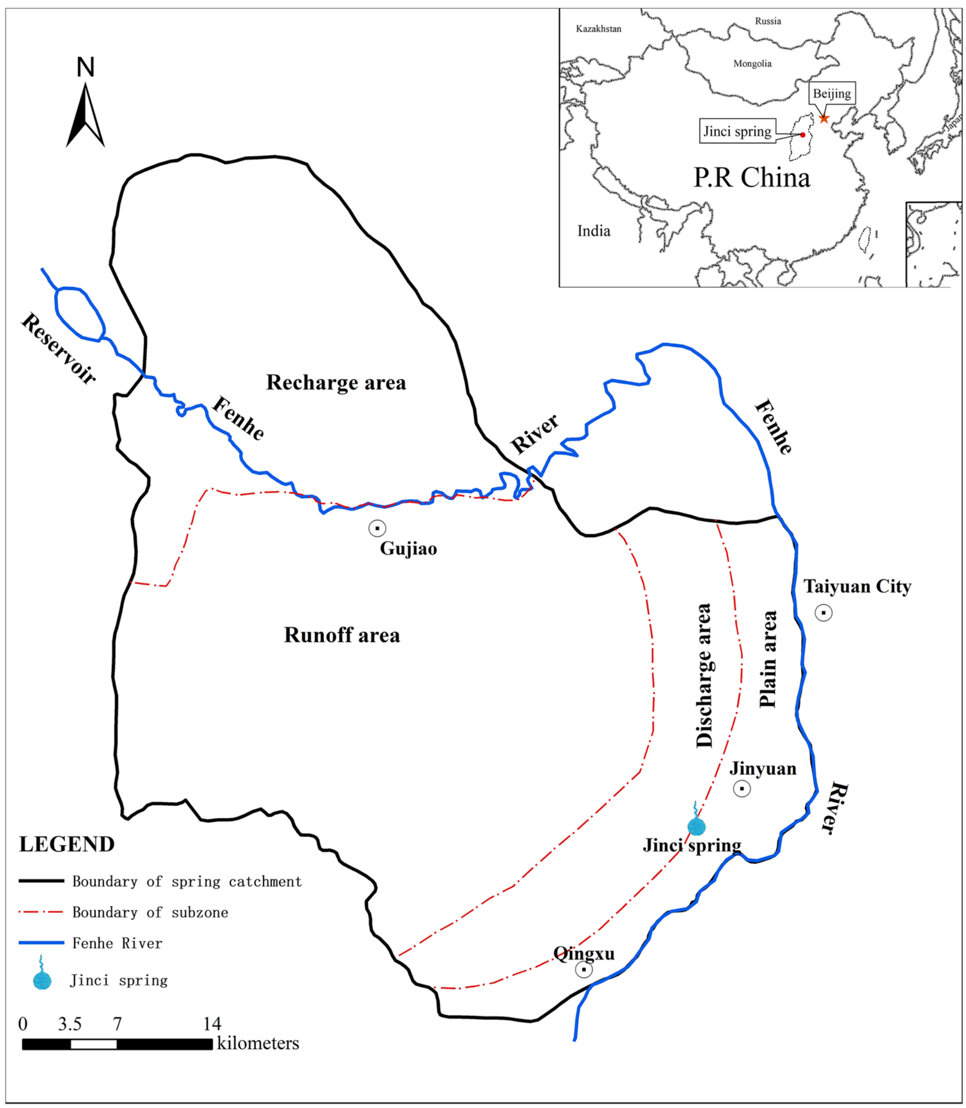
Hence, the purpose of this paper is to provide the basis for the reflow of Jinci spring and the sustainable protection for the quantity and quality of karst groundwater. Based on the long-term monitoring data from 1994 to 2014, this paper accurately quantitates the changes in the quantity and hydrochemistry of karst groundwater resources after the cessation of Jinci spring. By means of the Mann–Kendall trend test method, this paper analyzes the variation trends of karst groundwater level, EC, and SO_4^{2-} in Jinci spring catchment. The results of this study can provide an important reference for the decision makers of karst groundwater management and protection in Jinci spring catchment.

Description of Study Area

Location and Climate

Jinci spring catchment is located in West Mountain area of Taiyuan, Shanxi, China. It is in 37°32′–38°12′N. latitude and 111°54′–112°38′E. longitude, with an area of 2030 km^2 (Fig. 1). The study area is semi-arid monsoon climate. Local average annual rainfall in the form of rain and snow is 464.49 mm; average annual temperature is 8 °C. The Fenhe River is the largest one in the region, passing through the area from west to east, and then turning southward after

Fig. 1 Location of study area



flowing out of the West Mountain. The major water supply aquifer is the Middle Ordovician (O_2) karst fissure aquifer. The groundwater is mainly used for agricultural, industrial, and domestic waters. The average annual groundwater exploitation is 1.54 m^3/s (1994–2014). The exposed and semi-exposed areas of the north are 600 km^2, the central buried area is 1171 km^2, and the plain area in the southeast is 259 km^2.

Geology and Hydrogeology

From a geological point of view, the mountain area is composed of Archean (Ar) metamorphics, Cambrian (€) carbonates, Ordovician (O) carbonates, Carboniferous (C) clastics and coal-bearing layer, Permian (P) and Triassic (T) clastics, and Quaternary (Q) sediments. The Taiyuan fault basin region in Jinci spring catchment is covered by a very thick Cenozoic stratum. Detailed description of the geological conditions of Jinci spring catchment is given by Zhao and Cai (1990).

Limestone and dolomite of the Majiagou formation and Fengfeng formation in the Middle Ordovician (O_2) are the main aquifers of regional water supply significance. According to the previous geological records and pumping test data, the average specific storage is 2.44E−05/m. Groundwater recharge is dominated by the precipitation infiltration and leakage of the Fenhe River. Groundwater discharge includes spring, well pumping, lateral discharge to the Quaternary aquifer and dewatering of karst groundwater in coal mines. The flow of groundwater is from the northwest to the southeast.

Materials and Methods

Data Acquisition and Analysis

The karst groundwater level, groundwater chemistry, groundwater exploitation and river leakage data which are used in this study were collected from the local water administration. Groundwater level data were recorded in 7 piezometers (OB1, OB2, OB3, OB4, OB5, OB6, and OB7). Hydrochemical data were recorded at 6 groundwater sampling points (SP1, SP2, SP3, SP4, SP5, and SP6). These monitoring wells (Fig. 2) are maintained and monitored by the local water administration. In fact, three monitoring wells (OB1, OB3, and OB7 correspond to SP1, SP2, and SP5, respectively) are intended for both water level and water quality. The data of precipitations were acquired from the local meteorological administration. In addition, data published in some literatures were also used as supplementary. Compared with the larger area of Jinci spring catchment, it must be admitted that the data of seven water-level monitoring wells and six groundwater sampling points are obviously insufficient. As Jinci spring catchment is located in the West Mountain region, the monitoring wells and monitoring data are relatively scarce. In order to basically grasp the evolution of karst groundwater, this study can only use the existing monitoring data to quantitate the changes in the quantity and hydrochemical status of karst groundwater resources after the cessation of Jinci spring. This is helpful to the reflow protection of Jinci spring and the health of local residents.

Mann–Kendall Trend Test

The Mann–Kendall trend test method is a nonparametric statistical test method. It is very effective for detecting the variation trend of sequences (Hamed 2008). By means of the Mann–Kendall trend test, this paper analyzes the trend of karst groundwater level in Jinci spring catchment. Karst groundwater quality parameters such as EC and SO_4^{2-} in Jinci spring catchment area were also analyzed through the Mann–Kendall trend test. Detailed descriptions of the procedures of the Mann–Kendall trend test are available in the literatures of Jia et al. (2017a) and He et al. (2019).

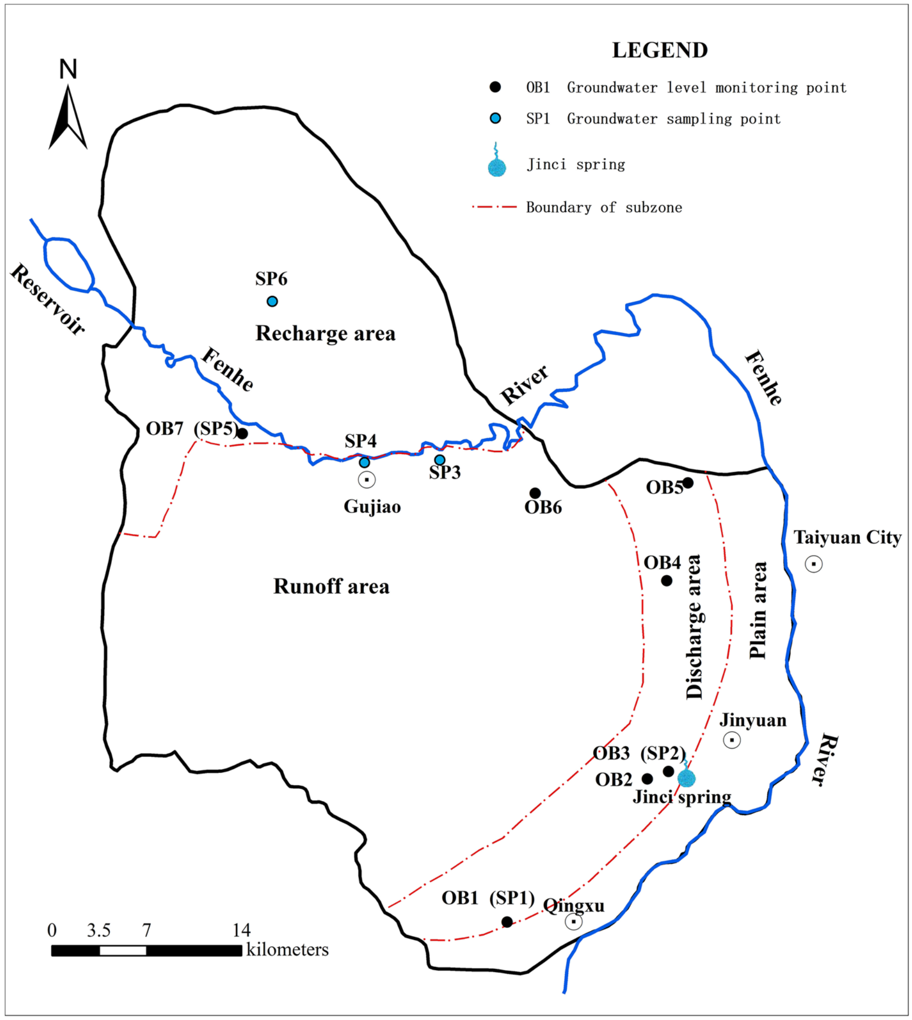
Results and Discussion

Variations in Groundwater Level

Figure 3 shows the groundwater level of karst aquifer in Jinci spring catchment from 1994 to 2014. It is based on the area-weighted average groundwater level of April (end of dry season) and October (end of rainy season). This is because the groundwater levels in April and October are the most representative of the fluctuations in the groundwater level of Jinci spring catchment. In the calculation of the weighted groundwater level, the recharge area (600 km^2), the runoff area (851 km^2) and the discharge area (320 km^2) of karst aquifer in Xishan Mountain area were mainly considered (Fig. 1), excluding the plain area (259 km^2).

As can be seen from Fig. 3, the groundwater level in karst aquifer is declining at a slower rate from 1994 to 2008; while the groundwater level is rising at a steep rate from 2009 to 2014. It indicates that the groundwater level has declined by 2.32 m from 1994 to 2008, equivalent to 16.57 cm/year of drawdown; the groundwater level has increased by 17.67 m from 2009 to 2014, equivalent to 294.5 cm/year of rise. During the period from 1994 to 2008, the loss of karst aquifer storage equals 3.3 Mm^3, i.e. 1171 $km^2 \times 0.0000244/m \times 50\ m \times 2.32\ m$; during the period from 2009 to 2014, the gain of karst aquifer storage equals 25.2 Mm^3, i.e. 1171 $km^2 \times 0.0000244/m \times 50\ m \times 17.67\ m$. It must be emphasized that the “50 m” used in both calculations

Fig. 2 Locations of groundwater level monitoring wells and groundwater sampling points



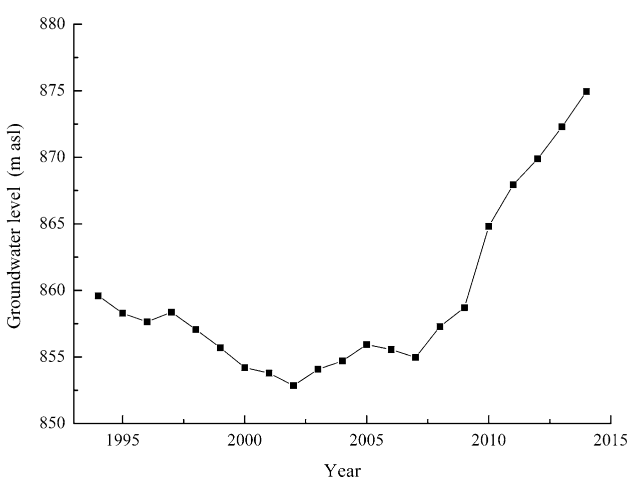


Fig. 3 Groundwater level of karst aquifer based on 7 piezometers

refers to the average thickness of the Middle Ordovician (O_2) karst aquifer in Jinci spring catchment.

In Fig. 4, the groundwater levels of three different piezometers are presented. OB1–OB5 is located in the discharge area, followed by OB6 in the runoff area and OB7 in the recharge area. This clearly indicates that the response of groundwater level in different zones of karst aquifer to various groundwater stresses is different. The shorter the groundwater flow path is, the faster the response of groundwater level to the stress, such as OB7 and OB6.

Figure 5 shows the drawdown of groundwater level in 7 piezometers during the research period (underlying data points are presented in Table 1). With regard to Fig. 5, the following points need to be discussed:

1) After 20 years of change (1994–2014), the groundwater levels of various piezometers have dropped from 7.71 to

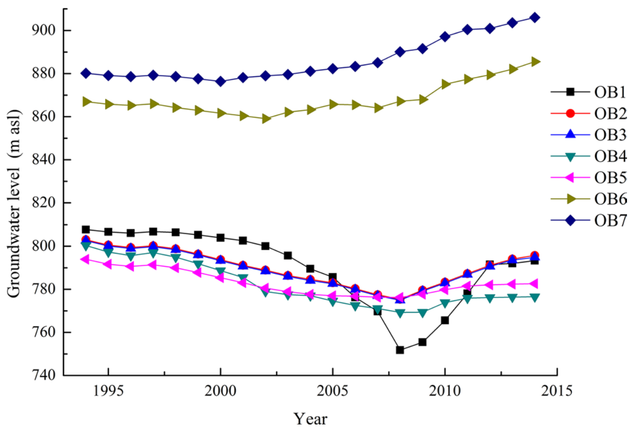


Fig. 4 Groundwater levels of 7 piezometers in the recharge, runoff, and discharge areas

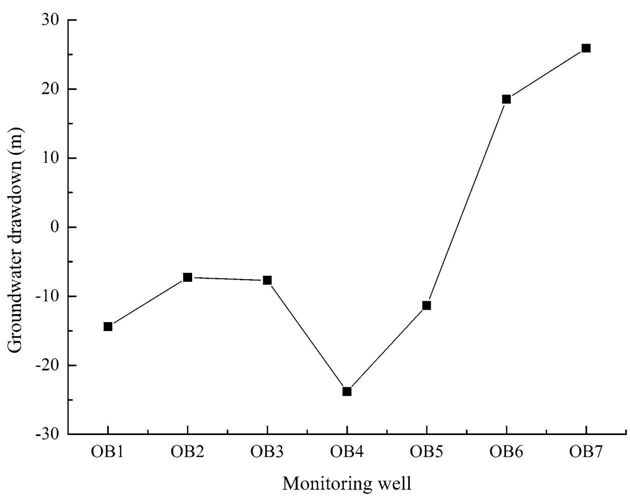


Fig. 5 Drawdown of groundwater level in 7 piezometers

− 25.90 m. The groundwater levels in the recharge and runoff areas increased, while the groundwater level in the discharge area decreased. The rise of groundwater level in the recharge area was the largest, followed by the runoff area. The drawdown of OB4 in the discharge area was the highest, followed by OB1.

2) If the groundwater levels of five piezometers in the discharge area are averaged, and averaged with the groundwater levels in the recharge and runoff areas, then the average rise of groundwater level during the research period would be 10.51 m. There is a difference of 4.84 m from the weighted groundwater level rise of 15.35 m. This result is mainly because of the runoff area, the recharge area, and the discharge area measuring 851 km^2, 600 km^2, and 320 km^2, respectively; the differences in weighted areas resulted in the weighted groundwater level to rise higher than the average groundwater level rise. The weights of the runoff area and the discharge area are 48% and 34%, respectively, both of which are more than 1/3 and significantly larger than the weight of 18% in the discharge area; therefore, both play dominant roles in the calculation of the weighted groundwater level rise.
3) Figure 5 illustrates that three piezometers (OB1, OB4, and OB5) experienced a drop of more than 10 m. In contrast, OB6 and OB7 each showed an increase of more than 18 m; they represent a larger areas of the recharge and runoff zone compared with the discharge zone, which means that most aquifers experienced a faster rate of rising in groundwater level.

Trend of Groundwater Level Variation

In order to determine the varying trend of karst groundwater level after the cessation of Jinci spring, and based on the rise of the karst groundwater level induced by the implementation of the artificial recharge of the Fenhe River and the decrease of exploitation after 2008, the research period was divided into two segments, 1994–2008 and 2009–2014. The drop of groundwater level in the first segment is 2.32 m, while the rise of groundwater level in the second segment is 17.67 m (Fig. 3). This clearly indicates that the previous decline rate is constant. If the strict measures are not taken to prevent the groundwater level from falling, the groundwater level will continue to decline, and the loss of groundwater storage in the karst aquifer will be further increased. In the later period, due to the measures taken for the reduction

Table 1 Annual groundwater level and drawdown in 7 piezometers

Monitoring well No	Groundwater level (m asl)			Drawdown (m)		
	1994	2008	2014	1994–2008	2008–2014	1994–2014
OB1	807.72	751.8	793.32	− 55.92	41.52	− 14.40
OB2	803.04	775.36	795.76	− 27.68	20.4	− 7.28
OB3	802.59	774.94	794.88	− 27.65	19.94	− 7.71
OB4	800.36	769.28	776.55	− 31.08	7.27	− 23.81
OB5	793.95	776.24	782.62	− 17.71	6.38	− 11.33
OB6	866.99	867.16	885.52	− 0.17	− 18.36	18.53
OB7	880.13	890.11	906.03	9.98	15.92	25.90

of groundwater exploitation and artificial recharge of the Fenhe River, the gain of groundwater storage in the karst aquifer was achieved, and the groundwater level was continuously rising. In addition, the following two points are worth mentioning:

1) If the groundwater exploitation after 2008 remains at the average of 1994–2008 over time, the groundwater level would experience a faster rate of decline. This is because Jinci spring catchment is located in the syncline of West Mountain, an axial south–north syncline that is inclined to the south. With the decline of karst groundwater level, the water supply area of the aquifer would decrease. For the constant groundwater exploitation, it would inevitably lead to a large drop in the groundwater level. Therefore, the rate of decline in the groundwater level would increase.
2) By carefully analyzing the groundwater levels of the karst aquifer after 2002 (Fig. 3), it is clear that, from 2003 to 2008, the groundwater levels were higher than that in 2002, but the annual fluctuations were relatively obvious. This is because the karst groundwater exploitation was reduced in this period, but the leakage of the Fenhe River also showed a decreasing trend, reducing the amount of groundwater recharge. The groundwater storage in the karst aquifer cannot be effectively replenished, thus increasing the annual fluctuation of the groundwater level. The groundwater level gradually increased from 2009 to 2014, but the annual fluctuation in groundwater level was greatly reduced. This is because the artificial recharge of the Fenhe River was implemented, the karst groundwater exploitation was further reduced, and the leakage from the Fenhe River was larger than that of the previous period (1994–2008) and maintained at around 0.93 m^3/s. This can prevent the groundwater level from falling, that is, it forces the groundwater level to rise. The result of the reduced exploitation and larger river leakage is the minimum fluctuation in groundwater level.

The Z and β values of the annual karst groundwater level in Jinci spring catchment were obtained via the Mann–Kendall trend test (Table 2). The values of Z and β for the karst groundwater level are 1.96 and 0.68, respectively. It indicates that the karst groundwater level has a significant rising trend, and the multiyear average upward degree is 0.77 m. The variation trend is significant at the 0.05 level.

Table 2 The trend tests of the karst groundwater level, EC, and SO_4^{2-} in Jinci spring catchment

Element	Z	β	Trend
Groundwater level	1.96	0.68	Rising
EC	5.10	21	Rising
SO_4^{2-}	5.89	5.80	Rising

The Relationship Between Groundwater Level Drawdown and Rainfall

Rainfall data from 1994 to 2014 have been superimposed on the groundwater level data in Fig. 6. As evident from Fig. 6, there is a certain correlation between rainfall and groundwater level, that is, the declining and the rising trend of the groundwater level are also affected by fluctuations in rainfall. This could be caused by the following two reasons.

1) The study area belongs to semi-arid area, the recharge area is 600 km^2, and the coefficient of rainfall infiltration is 0.275 (Han et al. 1993). The average rainfall from 1994 to 2008 is 443.22 mm, while the average rainfall from 2009 to 2014 is 531.83 mm. When the rainfall decreases, the groundwater recharge decreases, causing the falling of groundwater level; when the rainfall increases, the groundwater recharge increases, causing the rising of groundwater level. In addition, groundwater exploitation and the Fenhe River leakage during the study period are shown in Fig. 7. Because of the large amount of groundwater exploitation and the reduction of the Fenhe River leakage, coupled with the average rainfall of 413.82 mm, the decline of groundwater level was further aggravated from 1994 to 2002. After 2002, due to the reduction of groundwater exploitation and the increase of the Fenhe River leakage caused by the implementation of artificial recharge since 2008, coupled with the average precipitation of 509.58 mm, the groundwater level overall increased from 2003 to 2014, but the groundwater level rose faster from 2008 to 2014. From here we see that, the decrease of rainfall, overex-

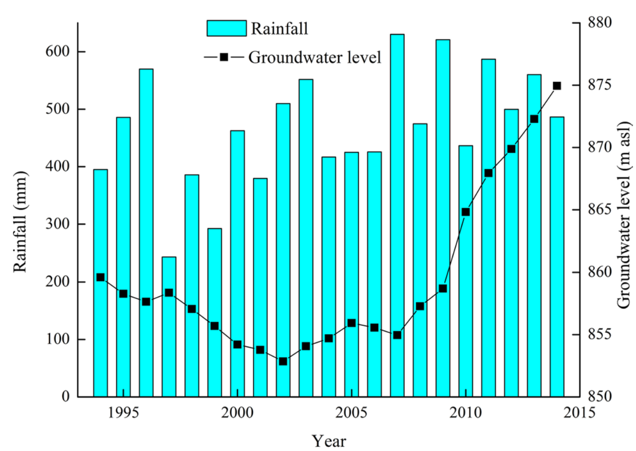


Fig. 6 The relationship between groundwater level and rainfall

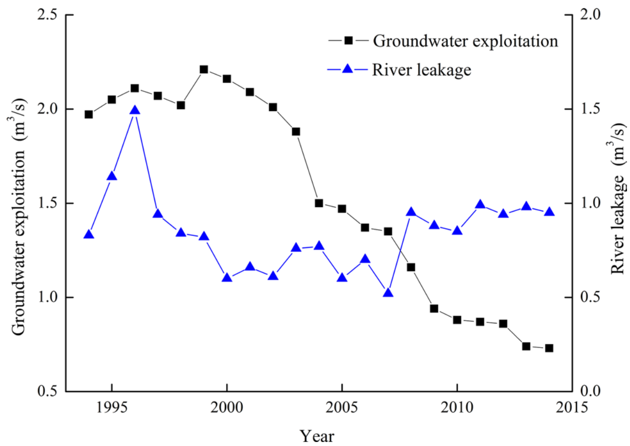


Fig. 7 Groundwater exploitation and the Fenhe River leakage in 1994–2014

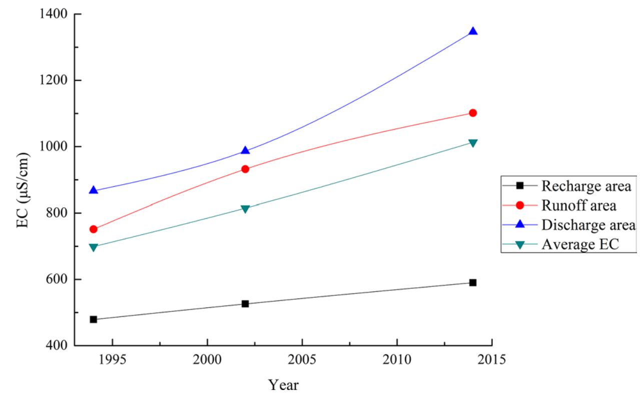


Fig. 8 EC values in recharge, runoff, and discharge areas and average EC values

ploitation of karst groundwater and the decrease of the Fenhe River leakage lead to the decline of groundwater level; on the contrary, the increase of rainfall, reduction of groundwater exploitation and the increase of the Fenhe River leakage cause the rise of groundwater level.

2) Under natural conditions, the groundwater level reacted strongly to the rainfall recharge. Regarding the drop of groundwater level from 1994 to 2002, it was only 6.75 m, but it was superimposed on the drawdown of groundwater level during the previous period (1961–1994), which led to a larger groundwater level drop. However, the decline of groundwater level inevitably led to the prolongation of the rainfall recharge to the groundwater level. As a result, the response of the groundwater level to the rainfall recharge lagged behind the rainfall. Due to the small rainfall during this period (1994–2002), the influence of rainfall recharge was eventually attenuated by the deepening of the groundwater level.

Temporal Change in the EC of Groundwater

The EC values of the recharge, runoff, and discharge areas and the average values of EC in Jinci spring catchment in 1994, 2002, and 2014 are shown in Fig. 8 (underlying data points are presented in Table 3).

It is obvious that for the same year, the change in the EC presents the order: the recharge area < runoff area < discharge area. Compared with Fig. 3, the change in the EC is quite different from that of the groundwater level. The groundwater level first decreased, and then increased. However, the EC values in the recharge, runoff, and discharge areas and the average EC values all display slightly increasing trend. Regarding the average EC of groundwater in the karst aquifer, it has increased by 16.59% from 699 μS/cm in 1994 to 815 μS/cm in 2002, and correspondingly it has increased by 24.29% from 815 μS/cm in 2002 to 1013 μS/cm in 2014. The general increase in groundwater salinity (electrical conductivity or EC) is governed by the following natural and anthropogenic factors.

1) The increase in rainfall salinity: there has been an exponential increase in the number of cars on the streets and consequently, the fuel consumption in Taiyuan City over the last two decades. This has negatively impacted the quality of rainfall in the region (Ajdary and Kazemi 2014; Mimura et al. 2016). With rapid urbanization and industrialization of Taiyuan in recent years, fossil fuels are still one of the main sources of energy. Coal combustion, gasoline combustion, and vehicles-related emissions are common for producing large amounts of sulfur dioxide, nitrogen oxides, and so on. According to relevant data, the dominant ionic species in rainfall in Taiyuan were SO_4^{2-}, NO_3^-, Cl^-, Ca^{2+}, Mg^{2+}, and Na^+, accounting for 90% of the total ions. These characteristics are similar to those of previous studies in China (Zhang et al. 2011, 2012; Xiao 2016). Severe pollution from anthropogenic sources led to high concentrations of EC in rainwater of Taiyuan. As a result, the salinity of karst groundwater increased with the recharge of rainfall.
2) The increase in groundwater runoff time: regarding Jinci spring catchment, due to the continuous pumping in the

Table 3 EC values in different areas and average EC values

Time	EC of recharge area	EC of runoff area	EC of discharge area	Average EC
1994	479	751.5	866.5	699
2002	526	932	986.5	815
2014	590	1101.5	1346.5	1013

discharge area during the study period, the groundwater level drawdown was larger than that of the recharge and runoff areas (Fig. 5). After the groundwater in the north was recharged by rainfall and the Fenhe River, it needs to flow for a distance of more than 30 km to reach the water table in the discharge area. Coupled with the drop in groundwater level, the runoff time of groundwater was further increased, which increased the interaction time of groundwater and rocks, resulting in the increase of groundwater salinity. Figure 9 illustrates a negative correlation between karst groundwater level and EC ($R^2 = 0.178$), which can fully support this statement.

3) The recharge of the Fenhe River to groundwater: the Fenhe River has a long-term recharge of groundwater in the limestone leakage section. Since 2008, in order to speed up the reflow of Jinci spring, artificial recharge of the Fenhe River has been carried out, and the river leakage was maintained at about 0.93 m^3/s; due to the high salinity of surface water, the degree of salinity contamination in groundwater was high.
4) The increase of sewage in spring catchment: according to the survey, with the development of economy and society, there are 23 drainage outlets for industrial and domestic sewage and coal mining drainage in Jinci spring catchment, including 17 industrial sewage outlets, 1 domestic sewage outlet, and 5 industrial and domestic sewage outlets. The drainages at some sewage outlets include mine drainage. The main pollutants in sewage were CODcr and ammonia nitrogen. Due to the lack of necessary sewage treatment system, the sewage drainage outlets are mainly in the tributaries of the Fenhe River, and the sewage was eventually discharged into the Fenhe River. Groundwater was recharged by sewage at the leakage section of the Fenhe River, resulting in the increase of groundwater salinity. In addition, there are local infiltrations of sewage in individual places.
5) The ease of solubility of carbonate rocks: the groundwater replenishment in the Jinci spring catchment mainly comes from the recharge of the northern carbonate rock exposed area. After a long-drawn path flow, the reaction time between groundwater and carbonate rocks was increased, and many salty substances such as the calcite in unsaturated zone, and the dolomite and gypsum in saturated zone were dissolved. As a result, TDS, Ca^{2+}, and Mg^{2+} gradually increased, and the farther it is from the north, the higher the groundwater salinity. That is to say, groundwater salinity presents in the order: discharge area > runoff area > recharge area.

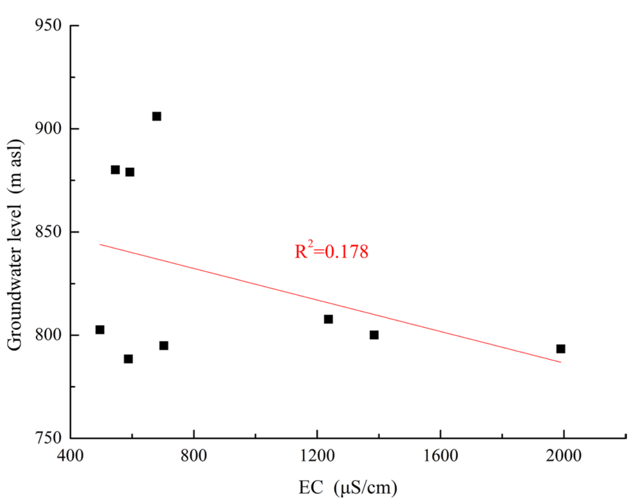


Fig. 9 The relationship between groundwater level and the EC

According to the results of the Mann–Kendall trend test, the Z and β values of the EC are 5.10 and 21, respectively (Table 2). It shows that the EC has a prominent rising trend, and the multiyear average upward degree is 15.7 μS/cm. The variation trend is significant at the 0.01 level.

Spatial Change in the EC of Groundwater

Figure 10 shows the changes in the EC at 6 groundwater sampling points (underlying data points are presented in Table 4). It can be seen that the EC values of the six sampling points have increased, and the EC values at two sampling points have increased by more than 60%. The huge differences between different sampling points are illustrated based on the temporal change in the EC, as shown in Fig. 11.

Figure 11 implies that the higher EC value in 1994 showed significant increase in EC during the study period. For example, two sampling points with EC values above 800 μS/cm showed an increase in EC of more than 60%. However, four sampling points with EC below 600 μS/cm showed an increase in EC of less than 42%. In the process of runoff and discharge of karst water, although calcites were precipitated in most areas, in special areas with high EC values (SP1, SP4), there were potential contamination and pollution sources such as village domestic wastewater, agricultural activities and livestock and poultry breeding, the direct infiltration of sewage may also be one of the causes for the increase in the percentage change of EC. In addition, it is also possible that the calcites in these areas were in a dissolved state, causing a greater increase in salinity than that in the general areas.

Changes in Groundwater Chemistry and Acidity

Figure 12 shows the quantitative changes in the six major ions (Na^+, Ca^{2+}, Mg^{2+}, HCO_3^-, SO_4^{2-}, and Cl^-) and pH during the study period. As can be seen from the figure, the major ions and pH as a whole show an increasing trend.

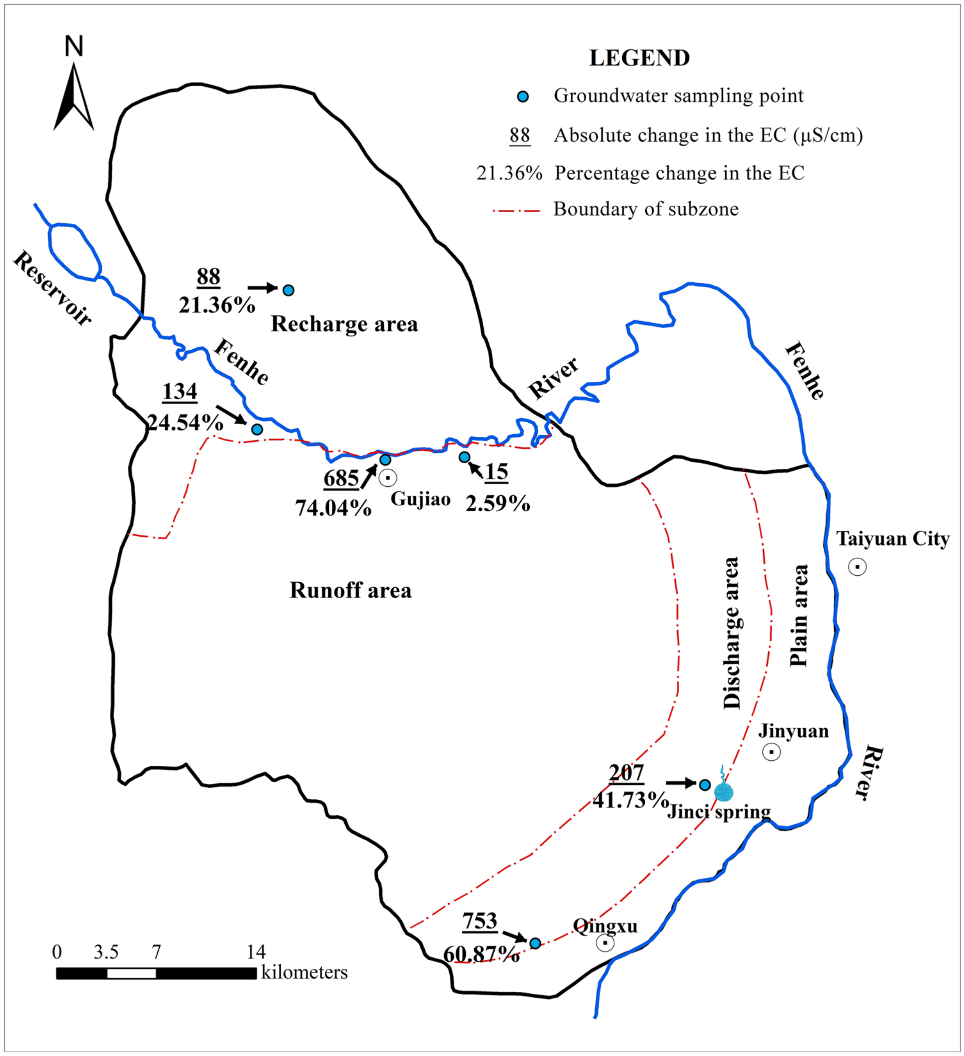


Fig. 10 Absolute increase and percentage increase in the EC between 1994 and 2014

Table 4 Absolute increase and percentage increase in the EC from 1994 to 2014

Zone	Sampling well	Absolute increase in EC (μS/cm)	Percentage increase in EC (%)
Discharge area	SP1	753	60.87
	SP2	207	41.73
Runoff area	SP3	15	2.59
	SP4	685	74.04
Recharge area	SP5	134	24.54
	SP6	88	21.36

Compared the major ions and pH of 1994 with that in 2014, the percentage increase is shown in Table 5.

It is seen from Table 5, Na^+ (203.96%) increased the most, followed by SO_4^{2-} (31.75%), Mg^{2+} (23.99%), Ca^{2+} (18.85%), HCO_3^- (7.23%), and Cl^- (1.19%). The average increase of the three cations was 82.27%, and the average

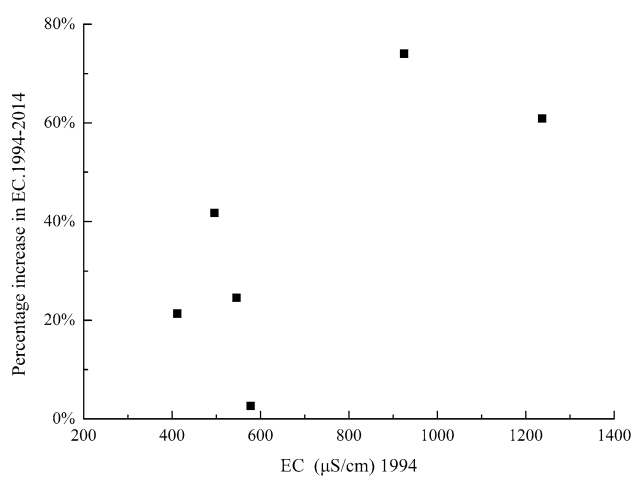


Fig. 11 The relationship between percentage increases in EC during 1994–2014 and EC in 1994

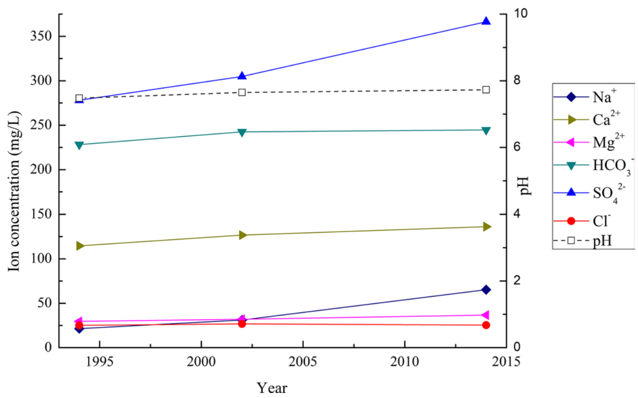


Fig. 12 Changes in major ions and pH

Table 5 Percentage increases in the major ions, from 1994 to 2014

Ions	Percentage increase (%)
Na^+	203.96
Ca^{2+}	18.85
Mg^{2+}	23.99
HCO_3^-	7.23
SO_4^{2-}	31.75
Cl^-	1.19
pH	3.34

increase of the three anions was 13.39%. Therefore, the average increase of all six ions was 47.83%. The percentage increase in average ion concentration was almost 1.27 times higher than that of 37.52% in the EC. The differences may be because some ions were not measured by the local water authority, especially phosphates and nitrates, which have been reduced significantly in recent years due to the conversion of cultivated land to forests in many areas of Jinci spring catchment. The other reason is that different ions have different effects on the EC value. For example, cation Na^+ exerts lower weight in the EC value.

In terms of acidity, the pH increased by 3.34%. This may be related to the increase in the concentrations of Ca^{2+}, Mg^{2+}, and Na^+. These cations generally make groundwater turn basic (Ajdary and Kazemi 2014). However, it is expected that the acidity would increase with the increasing sulfate concentration in groundwater of Jinci spring catchment.

Based on the results of the Mann–Kendall trend test, the Z and β values of SO_4^{2-} are 5.89 and 5.80, respectively (Table 2). It implies that SO_4^{2-} also has a prominent rising trend, and the multiyear average upward degree is 4.42 mg/L. The variation trend is also significant at the 0.01 level.

According to the analysis of the monitoring data, the hydrochemical types of karst groundwater have obvious variations in Jinci spring catchment ranging from the recharge area, the runoff area and to the discharge area. The evolution law reveals change from HCO_3–Ca·Mg (recharge area), HCO_3·SO_4–Ca·Mg (runoff area) and to SO_4–Ca·Mg (discharge area). This is mainly related to the rainfall, dissolutions of dolomite and gypsum, ion exchange, and leakage of coal mining drainage. In addition, geological structures and hydrodynamic fields have obvious controlling effects on the hydrogeochemical reactions occurring within groundwater (Jia et al. 2017a, b). It can be seen that the variations of hydrochemical type in Jinci spring catchment result from both natural and human factors (Wu et al. 2017; Adimalla and Li 2018).

It is well known that the deterioration of groundwater quality has become a global problem that hampers the sustainable living of the people in the world (Li et al. 2017), and it is also a challenge that we have to face. In many developing countries, poor drinking water quality has led to many waterborne diseases (Li and Wu 2019). Especially for people in arid and semi-arid regions, drinking contaminated groundwater increases the risk of an outbreak of water-borne diseases (Li et al. 2014), which will induce more serious water issues and people's health problems.

With regard to Jinci spring catchment, when people are exposed to drinking water containing high concentrations of sulfate, the most important physiological response is diarrhea, that is, people suffer from gastrointestinal effects (Backer and Lorraine 2000). Once the nitrate in drinking water exceeds the mandatory national "Standards for Drinking Water Quality" (GB5749-2006), it can be reduced to nitrite in the stomach and intestines, and this carcinogen can cause esophageal cancer (Zhang et al. 2014). In addition, excessive nitrite poses a higher risk to children's health (He and Wu 2018; Adimalla 2018). When more polycyclic aromatic hydrocarbons (PAHs) are released into the karst groundwater environment, potential risks might be posed to the safety of drinking water and human health (Gavrilescu et al. 2015). In rural areas, if the drinking water is pumped directly from the wells without proper treatment, intestinal diseases will occur when bacteria and viruses exceed the standard (Joshi et al. 2018). Therefore, the sewage and pollution sources in Jinci spring catchment must be effectively treated to prevent the karst groundwater from being contaminated again. In addition, the sustainable management of karst groundwater resources in Jinci spring catchment must be further strengthened.

Conclusions

By quantitating the changes in the quantity and hydrochemistry of karst groundwater resources in Jinci spring catchment after the cessation of Jinci spring, the main results of this study can be summarized as follows:

(1) Based on the monitoring data from 1994 to 2014, the groundwater level of the karst aquifer in Jinci spring catchment continued to decline by 2.32 m from 1994 to 2008, which is equivalent to a loss of 3.3 Mm^3 in aquifer storage, while the groundwater level continued to rise by 17.67 m from 2009 to 2014, which constitutes a gain of 25.2 Mm^3 in aquifer storage. Compared with the groundwater level in 1994, it overall increased by 15.35 m by 2014, and the average rate of increase was 76.75 cm/year.

(2) Based on the results of the Mann–Kendall trend test, the values of Z and β for the karst groundwater level are 1.96 and 0.68, respectively. The karst groundwater level shows a significant rising trend, which was mainly controlled by the rainfall, exploitation of karst groundwater, and the Fenhe River leakage. The results also indicate that the groundwater level rise in the recharge area is the largest, followed by the runoff area.

(3) From 1994 to 2014, groundwater salinity varied greatly. Over the same 20 years, two sampling points showed an increase in EC of more than 60%; four sampling points showed an increase in EC of less than 42%. For six major ions, Na^+ (203.96%) increased the most, followed by SO_4^{2-} (31.75%), Mg^{2+} (23.99%), Ca^{2+} (18.85%), HCO_3^- (7.23%), and Cl^- (1.19%). The average increase of all six ions was 47.83%. The percentage increase in average ion concentration was almost 1.27 times higher than that of 37.52% in the EC. The differences may be because some ions were not measured by the local water authority, especially phosphates and nitrates, which have been reduced significantly in recent years as the conversion of cultivated land to forests in many areas of Jinci spring catchment. Based on the results of the Mann–Kendall trend test, the values of Z and β are 5.1 and 21 for the EC and 5.89 and 5.80 for SO_4^{2-}, respectively. Both EC and SO_4^{2-} show a prominent rising trend.

(4) The results also show that the pH increased by 3.34% during the study period. This may be related to the increase in the concentrations of Ca^{2+}, Mg^{2+}, and Na^+. These cations generally make groundwater turn basic.

(5) The increase of groundwater salinity is governed by natural and anthropogenic factors, including the increase in rainfall salinity, the increase in groundwater runoff time, the recharge of the Fenhe River to groundwater, the increase of sewage in spring catchment, and the ease of solubility of carbonate rocks. Under the combined effects of these factors, the salinity of karst groundwater was increased, and consequently, the safety of groundwater quality was also affected.

(6) Artificial recharge of the Fenhe River and reduction of groundwater abstraction are effective for the increase of karst groundwater level, and the reflow of Jinci spring is expected to be realized. The sewage and pollution sources in Jinci spring catchment must be effectively treated to prevent the karst groundwater from being contaminated again. The results of this study are of great significance for predicting the groundwater level and salinity of karst aquifer and ensuring the safety of drinking water in Jinci spring catchment.

Acknowledgements This study was supported in part by the National Natural Science Foundation of China 41572221, 41807195, and the Natural Science Foundation of Shanxi Province 201801D221049. The data were kindly provided by the Water Authority Departments of Shanxi region, who are greatly thanked and acknowledged. The authors gratefully appreciate all the valuable comments and suggestions from the anonymous reviewers and editors, which helped to improve the quality of the manuscript greatly.

Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Adimalla N (2018) Groundwater quality for drinking and irrigation purposes and potential health risks assessment: a case study from semi-arid region of South India. Expo Health. https://doi.org/10.1007/s12403-018-0288-8

Adimalla N, Li P (2018) Occurrence, health risks and geochemical mechanisms of fluoride and nitrate in groundwater of the rock-dominant semi-arid region, Telangana State, India. Hum Ecol Risk Assess. https://doi.org/10.1080/10807039.2018.1480353

Ajdary K, Kazemi GA (2014) Quantifying changes in groundwater level and chemistry in Shahrood, Northeastern Iran. Hydrogeol J 22(2):469–480. https://doi.org/10.1007/s10040-013-1042-8

Backer LC (2000) Assessing the acute gastrointestinal effects of ingesting naturally occurring, high levels of sulfate in drinking water. Crit Rev Clin Lab Sci 37(4):389–400. https://doi.org/10.1080/10408360091174259

Boukhari K, Fakir Y, Stigter TY, Hajhouji Y, Boulet G (2015) Origin of recharge and salinity and their role on management issues of a large alluvial aquifer system in the semi-arid Haouz plain Morocco. Environ Earth Sci 73(10):6195–6212. https://doi.org/10.1007/s12665-014-3844-y

Custodio E (2002) Aquifer overexploitation: what does it mean? Hydrogeol J 10(2):254–277. https://doi.org/10.1007/s10040-002-0188-6

Fan L, Xiang M, Pen J, Li C, Li Y, Wu B, Bian H, Gao S, Qiao X (2016) Groundwater response to intensive mining in ecologically fragile area. J China Coal Soc 41:2672–2678 **(In Chinese)**

Gao Q (2012) Evaluation of karst groundwater quality of Jinci spring area. Shanxi Water Resour 9:18–20 **(In Chinese)**

Gavrilescu M, Demnerová K, Aamand J, Agathos S, Fava F (2015) Emerging pollutants in the environment: present and future challenges in biomonitoring, ecological risks and bioremediation. New Biotechnol 32(1):147–156. https://doi.org/10.1016/j.nbt.2014.01.001

Ghouili N, Hamzaoui-Azaza F, Zammouri M, Zaghrarni MF, Horriche FJ, Melo MT (2018) Groundwater quality assessment of the Takelsa phreatic aquifer (Northeastern Tunisia) using geochemical and statistical methods: implications for aquifer management and end-users. Environ Sci Pollut Res 25(36):36306–36327. https://doi.org/10.1007/s11356-018-3473-1

Hamed KH (2008) Trend detection in hydrologic data: the Mann-Kendall trend test under the scaling hypothesis. J Hydrol 349:350–363. https://doi.org/10.1016/j.jhydrol.2007.11.009

Han X, Lu R, Li Q (1993) Karst water system: study on karst springs in Shanxi. Geological Publishing House, Beijing, p 227 **(In Chinese)**

He S, Wu J (2018) Hydrogeochemical characteristics, groundwater quality, and health risks from hexavalent chromium and nitrate in groundwater of Huanhe formation in Wuqi County, Northwest China. Expo Health 1:1–10. https://doi.org/10.1007/s12403-018-0289-7

He X, Wu J, Guo W (2019) Karst spring protection for the sustainable and healthy living: the examples of Niangziguan spring and Shuishentang spring in Shanxi, China. Expo Health. https://doi.org/10.1007/s12403-018-00295-4

Jia Z, Zang H, Hobbs P, Zheng X, Xu Y, Wang K (2017) Application of inverse modeling in a study of the hydrogeochemical evolution of karst groundwater in the Jinci spring region, Northern China. Environ Earth Sci 76(8):312. https://doi.org/10.1007/s12665-017-6631-8

Jia Z, Zang H, Zheng X, Xu Y (2017) Climate change and its infuence on the karst groundwater recharge in the Jinci spring region Northern China. Water 9(4):267. https://doi.org/10.3390/w9040267

Joshi YP, Kim JH, Kim H, Cheong HK (2018) Impact of drinking water quality on the development of enteroviral diseases in Korea. Int J Environ Res Public Health 15(11):2551. https://doi.org/10.3390/ijerph15112551

Khezzani B, Bouchemal S (2018) Variations in groundwater levels and quality due to agricultural over-exploitation in an arid environment: the phreatic aquifer of the Souf oasis (Algerian Sahara). Environ Earth Sci 77:142. https://doi.org/10.1007/s12665-018-7329-2

Li P, Wu J (2019) Drinking water quality and public health. Expo Health. https://doi.org/10.1007/s12403-019-00299-8

Li P, Wu J, Qian H, Lyu X, Liu H (2014) Origin and assessment of groundwater pollution and associated health risk: a case study in an industrial park, Northwest China. Environ Geochem Health 36(4):693–712. https://doi.org/10.1007/s10653-013-9590-3

Li P, Tian R, Xue C, Wu J (2017) Progress, opportunities and key fields for groundwater quality research under the impacts of human activities in China with a special focus on Western China. Environ Sci Pollut Res 24(15):13224–13234. https://doi.org/10.1007/s11356-017-8753-7

Li P, He X, Li Y, Xiang G (2018) Occurrence and health implication of fluoride in groundwater of loess aquifer in the Chinese Loess Plateau: a case study of Tongchuan, Northwest China. Expo Health. https://doi.org/10.1007/s12403-018-0278-x

Li P, He X, Guo W (2019) Spatial groundwater quality and potential health risks due to nitrate ingestion through drinking water: a case study in Yan'an City on the Loess Plateau of Northwest China. Hum Ecol Risk Assess. https://doi.org/10.1080/10807039.2018.1553612

Liang Y, Han X (2013) Environmental problems and protection of karst groundwater in Northern China. Geological Publishing House, Beijing **(in Chinese)**

Liang Y, Gao X, Zhao C, Tang C, Shen H, Wang Z, Wang Y (2018) Review: characterization, evolution, and environmental issues of karst water systems in Northern China. Hydrogeol J 26(5):1371–1385. https://doi.org/10.1007/s10040-018-1792-4

Liu G, Li Z, Xu G, Yang Y, Cheng Y, Yao J (2018) Analysis on variation of groundwater electrical conductivity over time in Guanzhong plain irrigation district. Res Soil Water Conserv 25:216–220 **(In Chinese)**

Mimura AMS, Almeida JM, Vaz FAS, de Oliveira MAL, Ferreira CCM, Silva JCJ (2016) Chemical composition monitoring of tropical rainwater during an atypical dry year. Atmos Res 169:391–399. https://doi.org/10.1016/j.atmosres.2015.11.001

Qi X, Li W, Li C, Li Yan, Ma Y (2015) Trends and Persistence of groundwater table and precipitation of Ji'nan karst springs watershed. J Irrigat Drainage 34:98–104 **(In Chinese)**

Scanlon BR, Mukherjee A, Gate J, Reedy RC, Sinha AK (2010) Groundwater recharge in natural dune systems and agricultural ecosystems in the Thar Desert region, Rajasthan India. Hydrogeol J 18(4):959–972. https://doi.org/10.1007/s10040-009-0555-7

Wang X, Zhang Y, Sun Y, Li P (2017) Impacts of human activities on the groundwater in Beijing Plain. Yellow River 39:77–81 **(In Chinese)**

Wu J, Sun Z (2016) Evaluation of shallow groundwater contamination and associated human health risk in an alluvial plain impacted by agricultural and industrial activities, Mid-west China. Expo Health 8(3):311–329. https://doi.org/10.1007/s12403-015-0170-x

Wu J, Wang L, Wang S, Tian R, Xue C, Feng W, Li Y (2017) Spatiotemporal variation of groundwater quality in an arid area experiencing long-term paper wastewater irrigation, Northwest China. Environ Earth Sci 76(13):460. https://doi.org/10.1007/s12665-017-6787-2

Xiao J (2016) Chemical composition and source identification of rainwater constituents at an urban site in Xi'an. Environ Earth Sci 75:209. https://doi.org/10.1007/s12665-015-4997-z

Zhang Y, Lee X, Cao F (2011) Chemical characteristics and sources of organic acids in precipitation at a semi-urban site in Southwest China. Atmos Environ 45(2):413–419. https://doi.org/10.1016/j.atmosenv.2010.09.067

Zhang X, Jiang H, Zhang Q, Zhang X (2012) Chemical characteristics of rainwater in Northeast China, a case study of Dalian. Atmos Res 116:151–160. https://doi.org/10.1016/j.atmosres.2012.03.014

Zhang X, Zhuang D, Ma X, Jiang D (2014) Esophageal cancer spatial and correlation analyses: water pollution, mortality rates, and safe buffer distances in China. J Geogr Sci 24(1):46–58. https://doi.org/10.1007/s11442-014-1072-8

Zhang P, Zheng X, Zang H (2016) Assessment of karst groundwater vulnerability in Jinci spring area based on revised PI model. Yellow River 38(8):47–51 **(In Chinese)**

Zhang X, Li X, Gao X (2016) Hydrochemistry and coal mining activity induced karst water quality degradation in the Niangziguan karst water system China. Environ Sci Pollut Res 23(7):6286–6299. https://doi.org/10.1007/s11356-015-5838-z

Zhang Z, Xu Y, Zhang Y, Cao J (2018) Review: karst springs in Shanxi, China. Carbonates Evaporites 1:1–10. https://doi.org/10.1007/s13146-018-0440-3

Zhao W (2014) Groundwater dynamic of Jinci spring area and its protection measures. Shanxi Water Resour 6:18–19 **(In Chinese)**

Zhao Y, Cai Z (1990) Researches on groundwater system in karst areas: a case study in Taiyuan Region, Shanxi Province, China. Science Press, Beijing, p 229 **(In Chinese)**