Exposure and Health (2019) 11:153–165
https://doi.org/10.1007/s12403-018-00295-4

S.I. : DRINKING WATER QUALITY AND PUBLIC HEALTH

Karst Spring Protection for the Sustainable and Healthy Living: The Examples of Niangziguan Spring and Shuishentang Spring in Shanxi, China

Xiaodong He[1,2] · Jianhua Wu[1,2] · Wenyu Guo[1,2]

Received: 28 November 2018 / Revised: 24 December 2018 / Accepted: 29 December 2018 / Published online: 3 January 2019

Abstract
The karst springs, among which the Niangziguan spring and the Shuishentang spring are two typical ones, account for 24% of the total water resources in Shanxi, China and play an important role in the economic and social development of Shanxi Province. However, the spring discharge has sharply declined due to climate change and increasing anthropogenic activities. In this study, the Mann–Kendall trend test was used to analyze the trend of precipitation and spring discharge in Niangziguan spring and Shuishentang spring. Physicochemical data were also collected to delineate the karst groundwater quality variations in the two karst springs. The results show that both the precipitation and the spring discharge show a declining trend in Niangziguan spring and Shuishentang spring. Climate change is one of the critical factors that cause spring discharge attenuation. The impacts of human activities on the springs are becoming increasingly prominent, resulting in various water eco-environmental problems. TDS, TH, SO_4^{2-}, Cl^-, NH_4^+ all show increasing trend in Niangziguan spring, and the increasing concentrations of TDS and SO_4^{2-} are posing a serious threat to the safety of drinking water. In Shuishentang spring, COD_{Mn}, NO_3^-, and NO_2^- present increasing trend caused by domestic sewage and agricultural fertilizers and pesticides. Anthropogenic activities such as coal mining and quarrying, urbanization, and groundwater over exploitation should be regulated to protect the karst spring and to ensure the safety of water supply for residents.

Keywords Karst spring · Groundwater resources · Mann–Kendall trend test · Groundwater pollution · Sustainable development

Introduction

Karst areas cover 7–12% of the earth's continental area, and around 25% of the global population is completely or partially dependent on drinking water from karst aquifers (Dar et al. 2014; Hartmann et al. 2014). China is one of the countries in the world where karst is most developed and has been found in 23 provinces, covering nearly 35.8% of the total land area. Based on its basic characteristics and geographic distribution, karst in China is divided into the north China type and the south China type (He et al. 2011; Zhang et al. 2018a). Shanxi is the largest karst distribution area in northern China, which is a typical representative of karst in arid and semi-arid regions. The area of carbonate rocks covers 1.02×10^5 km^2, accounting for 65% of the total land area in Shanxi Province. The total amount of karst water is approximately 3.5×10^9 m^3/a, which accounts for 24% of the water resources in this province (Liang and Han 2013; Water Resources Department of Shanxi Province et al. 2008). Shanxi is also one of the water scarce areas in China, with few surface rivers and limited precipitation. Therefore, the economic and social development in Shanxi relies significantly on groundwater, especially karst groundwater. However, in the last 60 years, the karst springs in Shanxi have experienced various water and ecological problems due to climate change and increasing human activities (Hao et al. 2009; Jia et al. 2017). Niangziguan spring and Shuishentang spring are two typical springs facing the problems.

✉ Jianhua Wu
wjh2005xy@126.com; wujianhua@chd.edu.cn

[1] School of Environmental Science and Engineering, Chang'an University, No. 126 Yanta Road, Xi'an 710054, Shaanxi, China

[2] Key Laboratory of Subsurface Hydrology and Ecological Effects in Arid Region of the Ministry of Education, Chang'an University, No. 126 Yanta Road, Xi'an 710054, Shaanxi, China

Shanxi is rich in coal resources, the development of which requires a large amount of water resources. Due to its water scarcity, the sustainable use of water resources is particularly important to guarantee the sustainability of social development (Li et al. 2017a; Li and Qian 2018a), and the quality of groundwater is closely related to the health of local residents (Adimalla and Li 2018; Adimalla et al. 2018; Li et al. 2016, 2018a; Wu and Sun 2016; Zhang et al. 2018b). However, many groundwater problems such as spring runoff decrease, spring drying up, groundwater level decline and groundwater contamination have arisen in recent years. For example, three springs (Jinci, Lancun, Gudui) in Shanxi have completely dried up, and other springs have also experienced flow decline (Liang and Han 2013; Zhang et al. 2018a). On one hand, climate change is believed to be one of the critical factors causing spring flow attenuation. Fan and Wang (2011) found that the annual mean temperature had increased by 1.20 °C and the annual precipitation had decreased by 99.20 mm during the past 50 years in Shanxi. The decrease of precipitation directly lead to the decrease of spring flow. On the other hand, human activities have also resulted in the karst spring flow decline and karst groundwater contamination. Guo et al. (2005) deemed that spring flow attenuation of 7 karst springs including Niangziguan was controlled mainly by climate and human activities, with their contributions being about 60% and 40%, respectively. Zhang et al. (2016) studied karst water quality degradation induced by hydrogeochemical processes and coal mining activities in the Niangziguan spring, finding that coal mining activities were responsible for the change of water type from Ca·Mg-HCO_3 type in the up-stream recharge areas to Ca·Mg–HCO_3·SO_4 type in the coal mining areas. Continued groundwater pollution is threatening the safety of drinking water and the health of residents, constraining the sustainable development of the society. Because of its great abundance and regional significance, the Niangziguan spring has been studied by many researchers and institutions (Hao et al. 2006; Zhang et al. 2016, 2017), but the Shuishentang spring has received little attention. Both of the two springs are very important for the sustainable living of local residents and are the basis of water supply for irrigation, domestic and industrial purposes. However, they face serious water quantity and water quality issues, and therefore, further study is needed.

In view of above facts and findings, it is necessary to understand the status and the reasons of karst spring flow attenuation and contamination, and it is helpful to find effective measures to protect the karst spring for the sustainable and healthy living. Therefore, the objectives of this study are (1) to study the trend and relationship of spring flow with precipitation in Niangziguan spring and Shuishentang spring and to analyze the reason for karst spring flow decline, (2) to analyze the groundwater pollution based on collected karst groundwater data, and (3) to present the suggestions to protect the karst springs, safeguarding the sustainable and healthy living of residents in the area. This work may provide useful information for karst spring conservation and karst water resources management, benefiting the international community.

Study Area

Location and Climate

Niangziguan spring is one of the largest karst springs in northern China, lying in the west of the Taihang Mountain where carbonate rocks are well developed. The Niangziguan spring catchment is geographically located between east longitude from 112°35′ to 113°55′ and north latitude from 36°55′ to 38°15′, covering about 7196.19 km^2 (Fig. 1). The geomorphology of this area is mainly alluvial basin with lower elevation in the center and higher elevation in the north, west, and south of the catchment, ranging from 342 to1847 m above the mean sea level. The Niangziguan town, named after the Niangziguan spring, is located in the lowest area in the basin. The study area is characterized by a temperate continental monsoon climate with a mean annual temperature of 10.9 °C. The mean annual precipitation is approximately 533.19 mm with as much as 60–70% of precipitation in a year occurring from July to September (Hao et al. 2012; Zhang et al. 2017). The Wenhe River and the Taohe River are the main rivers around the Niangziguan spring. They converge into the Mianhe River in Niangziguan Town (Hao et al. 2015). In the south of the catchment, there are three big rivers, i.e., Songxi River, Qingzhangdongyuan River and Qingzhangxiyuan River. These rivers are sources recharging groundwater in the catchment.

Shuishentang spring is located in Guangling County, north Shanxi Province. The study area is located on the edge of the Loess Plateau, and the elevation is high in the west and low in the east. The geomorphology in Shuishentang spring catchment is divided into two main sections. In the north, some mountains lie along the boundary of the catchment, while in the south the alluvial plain is the main agricultural and residential area (Fig. 1). The main agricultural and residential area is mainly distributed along the Huliu River. The catchment stretches from east to west with a length of 34 km and extends from north to south with a width of 16 km, covering 518 km^2. The Huliu River is the only river in the Shuishentang spring catchment, running through the catchment from west to east. Atmospheric precipitation is the main recharge source of groundwater in the catchment. The annual average temperature is recorded as 6.9 °C, which the highest and the lowest temperatures being 37.5 °C and − 34.9 °C, respectively. As it is located on the edge of semi-arid regions, the mean annual precipitation is

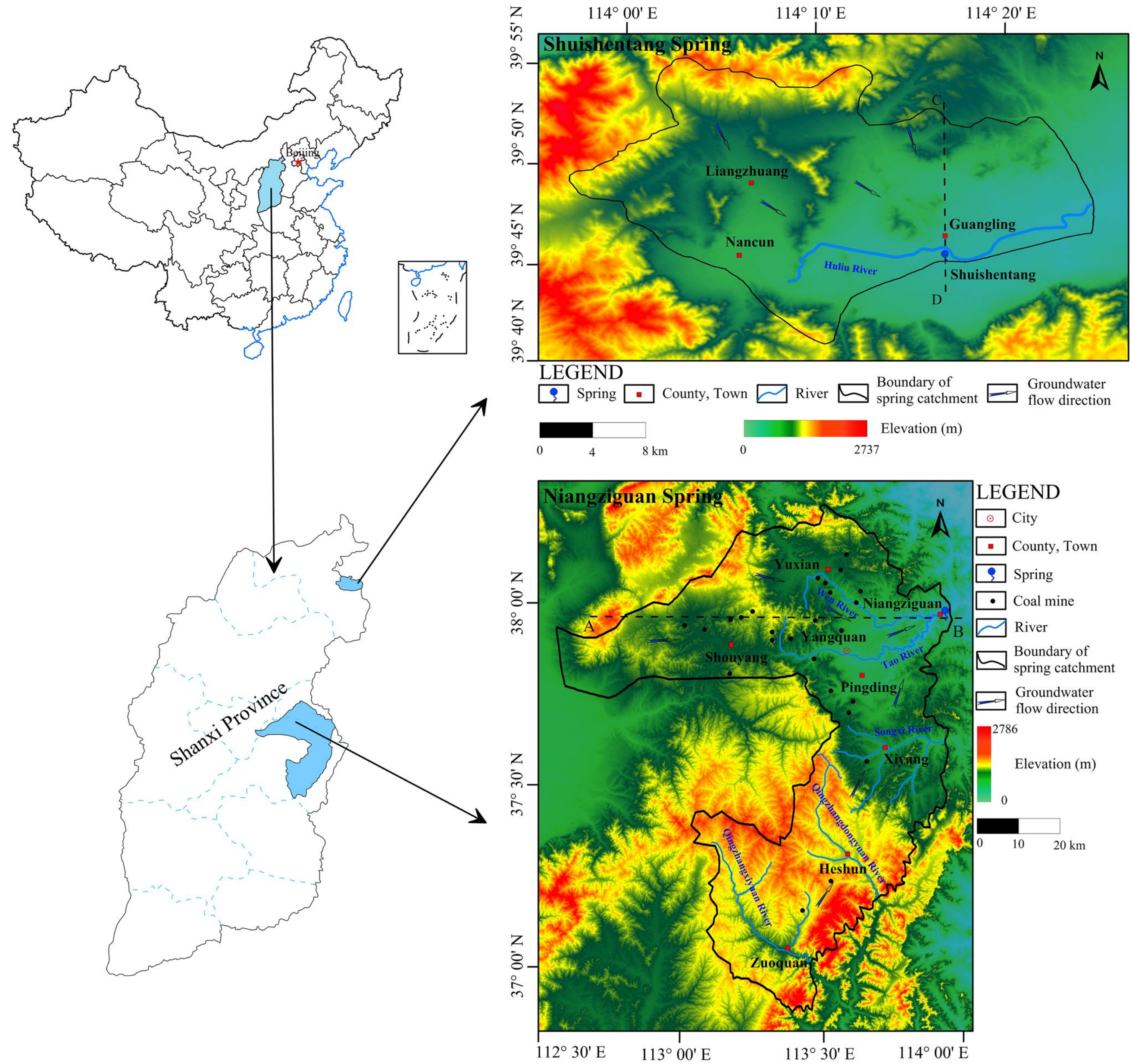

Fig. 1 Location of Niangziguan spring catchment and Shuishentang spring catchment

approximately 434 mm with over 76% of the precipitation observed from June to September (Water Resources Department of Shanxi Province et al. 2008).

Hydrogeology

The karst aquifer of Niangziguan spring is composed of Cambrian and Ordovician limestone. The Ordovician limestone aquifer is overlain by thick and relatively impermeable Carboniferous-Permian coal-bearing sandstone and shale in the west, and outcrops locally in the eastern basin area (Fig. 2a). The thickness of the Ordovician limestone is 467–628 m, providing a great space for storage and transportation of karst water. Above the Carboniferous–Permian sandstone and shale is the Quaternary deposits. Groundwater flows from west to east in the north part of the Niangziguan spring catchment and from southwest to northeast in the south part of the catchment. Precipitation is the main recharge source for groundwater, and river water percolation can also recharge groundwater locally. Affected by the faults, groundwater flow is blocked by the elevated low-permeability strata of clayed dolomite, and outcrops as spring (Gao et al. 2011; Hao et al. 2006; Liang and Han 2013). Groundwater artificial extraction

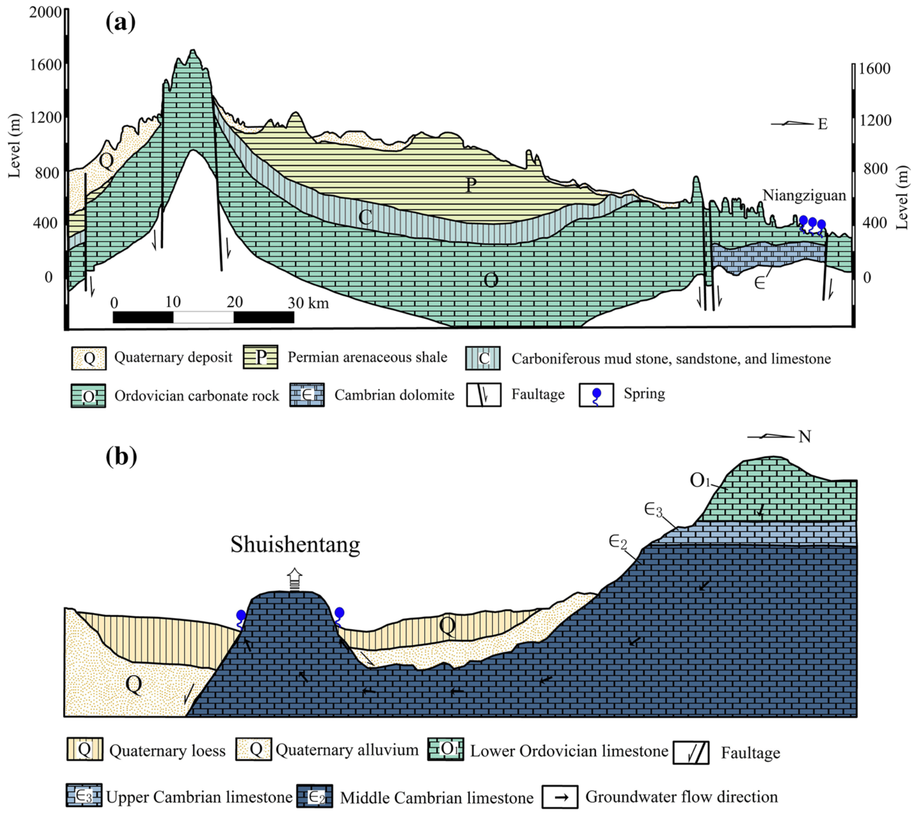

Fig. 2 Geological cross-section: **a** A–B cross-section of Niangziguan spring catchment (modified from Hao et al. 2012), **b** C–D cross-section of Shuishentang spring catchment

and natural springs are the main discharge patterns for karst water in the study area.

In the Shuishentang spring catchment, the karst aquifer is composed mainly of the Cambrian limestone and lower Ordovician flint belt dolomite. There are 30–150 m alluvial deposits and aeolian loess above the limestone (Fig. 2b). The thickness of the karst fracture aquifer in the Shuishentang spring catchment is about 290 m. Groundwater flows generally from north to south toward the Huliu River valley. Similarly, atmospheric precipitation is the main source of groundwater recharge in the area. The precipitation can directly infiltrate into the karst aquifer in the exposed area of limestone, and can also recharge karst aquifer indirectly through the Quaternary loose layers (Han et al. 1993; Water Resources Department of Shanxi Province et al. 2008). The Shuishentang Temple is located in the Huliu River valley in the central part of the basin, where there are small faults on both sides. The faults block the flow of groundwater, and form the Shuishentang spring (Fig. 2b).

Materials and Methods

Data Collection and Analysis

In this study, spring discharge and water quality data were mainly collected from published books such as *Water Resources Protection in Karst Spring Area of Shanxi Province* (Water Resources Department of Shanxi Province et al. 2008) and *Environmental Problems and Protection of Karst Groundwater in Northern China* (Liang and Han 2013). Some water quality data were collected from published articles (Han et al. 1993; Hao et al. 2006, 2009; Liu et al. 1991; Zhang et al. 2016). Collected data include spring discharge data and precipitation data from 1956 to 2015 for Niangziguan spring, and from 1956 to 2003 for Shuishentang spring. Collected physicochemical data include pH, Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-, NO_3^-, NH_4^+, TDS, and TH for Niangziguan spring in 1979, 1987, 2007 and 2013, respectively, and Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-, NO_3^-, NO_2^-, TDS, TH, and COD_{Mn} for Shuishentang spring in 1986, 2000, 2001 and 2005, respectively.

Mann–Kendall Trend Test

In this study, the Mann–Kendall trend test was used to analyze the trend of spring discharge and precipitation in the Niangziguan spring and Shuishentang spring. Water quality parameters such as SO_4^{2-}, TDS, and TH in the Niangziguan spring were also analyzed via the Mann–Kendall trend test. The Mann–Kendall test is a non-parametric statistical test recommended by the world meteorological organization, and it can effectively detect the variation trend of sequences (Hamed 2008). The procedures of Mann–Kendall trend test can be outlined as follows (Fan and Wang 2011; Jia et al. 2017; Kendall and Gibbons 1990):

(1) Suppose there is a sequence (x_1, x_2, x_3, … x_n) with no trend.
(2) S is a new sequence and conforms to normal distribution. It can be calculated by Eq. (1). In Eq. (1), sgn() is symbolic function. The average value of S is denoted as $E(S)$ and its value equals to 0, and the variance of S is Var(S), given by Eq. (2).

$$S = \sum_{i}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i) \tag{1}$$

$$\operatorname{Var}(S) = n(n-1)(2n+5)/18 \tag{2}$$

(3) The standard normal statistic Z can be acquired as follows

$$Z = \begin{Bmatrix} \frac{S-1}{\sqrt{Var(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & S < 0 \end{Bmatrix} \tag{3}$$

(4) At a given level of significance (α), if the statistic follows $|Z| \geq Z_{1-\alpha/2}$, it means that the sequence has an obvious rising or declining trend. When $Z > 0$, the series has an increasing trend; when $Z < 0$, the series has a decreasing trend. If $|Z| \geq 1.64$, 1.96, and 2.58, respectively, it will imply that the trend is significant at the 0.1, 0.05 and 0.01 levels, respectively.

At the same time, the slope β can be calculated to verify the degree of the trend change, and the calculation formula is:

$$\beta = \text{Median}\left\{ \frac{x_j - x_i}{j - i} \right\} \quad \forall j > i \tag{4}$$

The median is the median function. When $\beta > 0$, the sequence exhibits a rising trend, and when $\beta < 0$, the sequence exhibits a declining trend (Lacombe et al. 2012).

Results and Discussion

The karst spring is the vital source of water supply for domestic usage, agricultural irrigation and industrial purposes in Shanxi. However, spring discharge attenuation and groundwater level decline have become major water problems severely hampering the development of local economy and society. In addition, karst groundwater quality deterioration due to increased human activities has also been a great concern to local and national researchers. Groundwater quality research is extremely important for supporting the safety of the water supply and human health in semi-arid areas of China (Li et al. 2017b). With increasing human activities, karst groundwater quality deterioration is significantly affecting the drinking water safety of local people. Along with intense groundwater abstraction, geological disasters such as karst collapses and ground fissures become more common in this area, threatening the safety of local people and constraining the sustainable development of local society.

Spring Flow Attenuation

Niangziguan Spring

In this study, spring flow data from 1956 to 2015 were collected. As shown in Fig. 3a, the spring flow presents a significant downward trend from 1964 (15.75 m^3/s) to 2010 (5.46 m^3/s), indicating a 60% decrease over half a century. In the spring catchment, some springs have disappeared. Figure 3a demonstrates that the spring flow attenuation in the Niangziguan spring follows a certain rule: the spring discharge presents periodic fluctuation. After a long period of decline, the spring flow will have a short period of increase. It is obvious that the change of spring discharge is accompanied by the change of precipitation with, however, a certain lag before the 21st century. However, in the 21st century, their correlation became less significant. The impacts of precipitation on spring discharge are getting weaker, and intensive human activities become a more important role in affecting the spring flow.

By the Mann–Kendall test, the Z and β values for the annual spring discharge and precipitation in the Niangziguan spring region were obtained (Table 1). The values of Z and β for precipitation are − 1.77 and − 1.63, respectively. The value of Z is less than 0, but $|Z|$ is less than 1.96, with a significance at the 0.1 level. Furthermore, the value of β is also less than 0, indicating that the precipitation has a significant downward trend, and the multi-year average declining degree of precipitation is 1.63 mm/a. As for spring discharge, the values of Z and β are − 8.37 and − 0.14, respectively. $|Z|$ is greater than 2.58 with the significance at the 0.01 level. These results reveal that the spring discharge shows an even more significant declining trend, and the multi-year average declining degree of spring discharge is 0.14 m^3/a.

The karst groundwater level also shows a descending trend with the decrease of the spring discharge. In the Niangziguan spring, spring discharge and artificial groundwater abstraction through wells are the main patterns draining karst groundwater. From 1980 to 2001, the annual volume of abstracted water from wells has increased from 6.43 million to 30.8 million m^3 (Hao et al. 2006). The overall karst groundwater level has dropped by around 20 m from the

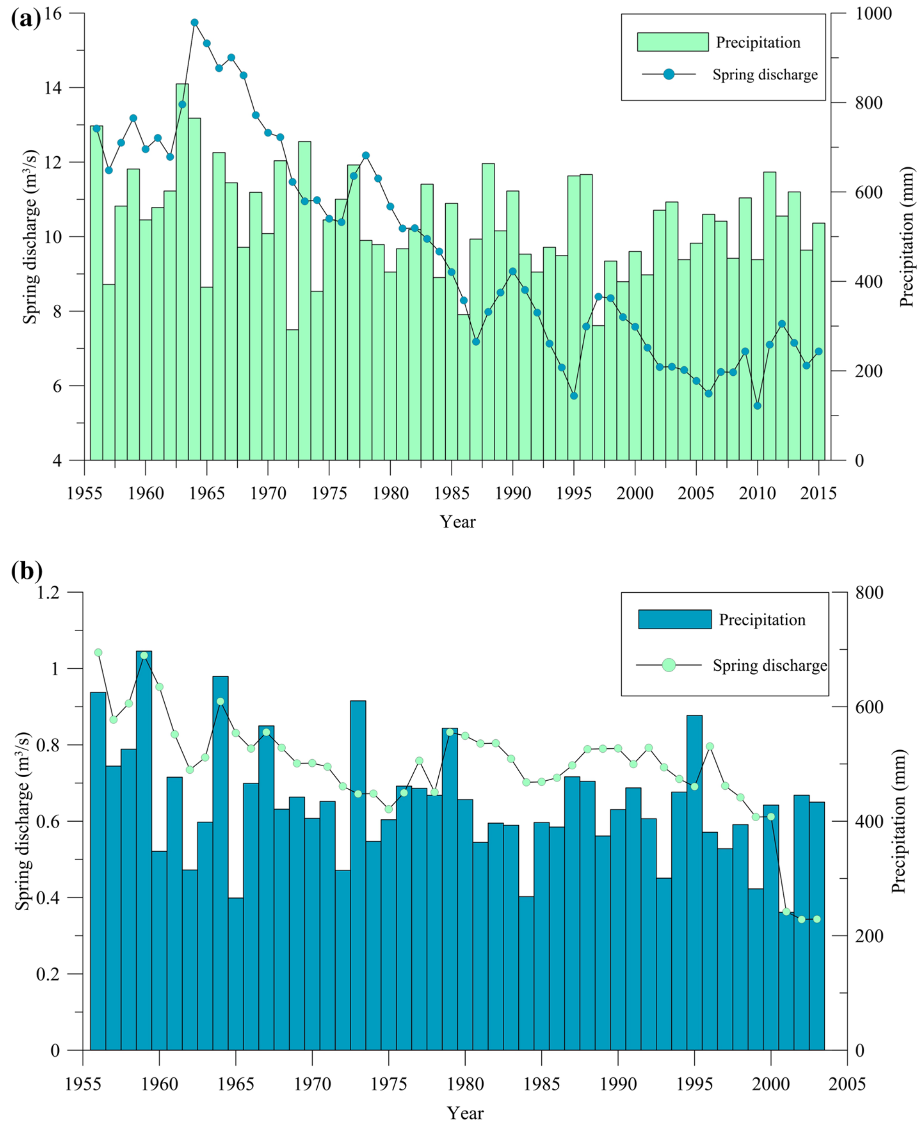

Fig. 3 Time series of the spring discharge and precipitation: **a** 1956–2015 in Niangziguan spring; **b** 1956–2003 in Shuishentang spring

Table 1 The trend test of the spring discharge, annual average precipitation, SO_4^{2-}, TDS, and TH

Spring	Element	*Z*	*β*	Trend
Niangziguan	Precipitation	− 1.77*	− 1.63	Declining
	Spring discharge	− 8.37**	− 0.14	Declining
	SO_4^{2-}	5.27**	6.72	Rising
	TDS	5.45**	11.64	Rising
	TH	4.90**	5.82	Rising
Shuishentang	Precipitation	− 1.74*	− 2.15	Declining
	Spring discharge	− 3.58**	− 0.006	Declining

*The trend is significant at the 0.1 level

**The trend is significant at the 0.01 level

1980s to the early 2000s in the Niangziguan spring system. Take the Huili deep well as an example, the groundwater level was 404.33 m in 1981, and it declined to 391.45 m in 2006. The area enclosed by the water level of 410 m expanded from 383 to 681 km^2 in 2004 and from 681 to 747.9 km^2 in 2015 (Liang and Han 2013; Liang et al. 2018). The rapid decline of groundwater level has resulted in the spring flow attenuation in the spring catchment, which can be attributed to the groundwater over exploitation for the economic and social developments in this area. The decline of groundwater level has caused many water quality and quantity problems. For example, the dramatic decrease of the underground water level has led to the leakage of the polluted river water into the groundwater, resulting in groundwater pollution, which in turn further reduces the availability of the valuable groundwater resources. In addition, in the study area, Carboniferous-Permian coal-bearing formations overlie the Ordovician karst aquifer. Many large-scale coal mining activities have also resulted in a lot of karst groundwater being drained to secure the safety of coal mining, leading to further karst groundwater level decline. The mining activities have also destroyed surface vegetation, reducing the recharge of precipitation to the karst aquifer. Nowadays, spring flow attenuation has seriously restricted the development of local economy and affected the sustainable living in this area.

Shuishentang Spring

Compared with the Niangziguan spring, the Shuishentang spring has smaller spring discharge rate, with smaller spring catchment area. In this paper, spring flow data and precipitation data from 1956 to 2003 were collected for the Shuishentang spring. Figure 3b shows that the spring discharge in the Shuishentang spring catchment also presents a decreasing phenomenon. The Huliu River is a seasonal river, and the precipitation plays a key and important role in regulating spring discharge. However, the spring discharge rate has declined sharply from 0.75 m^3/s (the mean rate from 1956 to 2003) to less than 0.2 m^3/s in 2017. The spring even dried up once in July 2014, which greatly influenced the urban water supply security and water ecological environment.

In Shuishentang spring, the values of Z and β for precipitation are − 1.74 and − 2.15, respectively, suggesting that the precipitation has a prominent downward trend, and the multi-year average declining degree of precipitation is 2.15 mm/a (Table 1). As for spring discharge, the values of Z and β are − 3.58 and − 0.006, respectively, with significance at the 0.01 level. It manifests that the spring discharge in Shuishentang spring also shows a prominent declining trend, and the multi-year average declining degree of spring discharge is 0.006 m^3/a.

The decrease of precipitation caused by global climate change is a significant reason responsible for the decline of spring flow rates, but the human activities such as population increase, urbanization, industrial and agricultural development are becoming another major factor. Figure 4 shows the carbonate and limestone exposure areas where the karst groundwater gets recharged. The precipitation in the northern mountainous area can directly infiltrate and recharge groundwater. However, the recharge area has been damaged by mining activities. Vegetation is destroyed and most of the precipitation flows out of the mountainous area as surface runoff, leading to the reduction of infiltration and reducing karst groundwater recharge. The large quantity of rain water from the northern mountains often floods into the county which is located in the low-lying area and the drainage system is relatively undeveloped. Consequently, the county is often troubled by floods in summer, and urban water accumulation eventually flows to the spring nearby, which may cause pollution to the spring. In recent years, the population of counties has increased rapidly, accompanied with the development of urbanization. In the northeast of the Shuishentang spring, a new county is under construction. The increase of population and the construction of new urban area will lead to further increase of groundwater exploitation. Similar to the Niangziguan spring catchment,

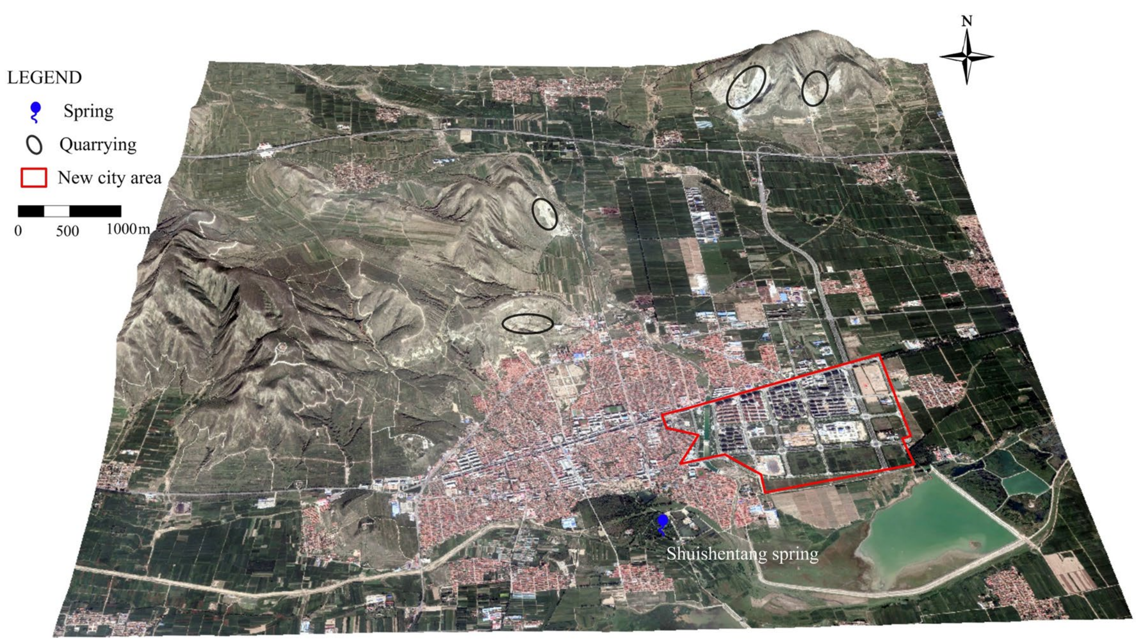

Fig. 4 Three-dimensional map of the Shuishentang spring showing the major factors influencing the spring discharge rate

over-exploitation of groundwater can bring about continuous decrease of karst groundwater level. There are 331 groundwater extraction wells in Shuishentang spring catchment. In 2011, the groundwater exploitation amount was 17.95 million m^3, of which 14 million m^3 were extracted for agriculture (Jiao 2015). A large quantity of groundwater is used for agricultural irrigation in the summer, leading to significant decrease of the spring discharge rate and continuous decline of groundwater levels. For example, the groundwater level of the well located in Zuotuan town decreased by 1.6 m from 2011 to 2013. This indicates that agriculture is the biggest water user in this catchment, and therefore, water-saving irrigation technologies should be promoted and used in agriculture in this area. Except the direct recharge of precipitation in the bare mountainous carbonate and limestone areas, pore water in loose deposit layers situated in the discharge areas of the catchment is also a significant recharge source for karst groundwater. In the discharge areas of the catchment, loose deposit layers overlie the karst aquifers. Nevertheless, the transformation of farmland into construction areas has reduced the area available for infiltration and recharge of pore water, resulting in the reduction of pore water flow to the karst aquifer.

Water Quality Issues

Niangziguan Spring

Deterioration of groundwater quality is also becoming a more and more serious issue in the Niangziguan spring. As shown in Fig. 5, the water quality parameters such as TDS, TH, SO_4^{2-}, Cl^- and NH_4^+ show an increasing trend, which indicates deteriorating water quality. Noteworthily, the concentrations of SO_4^{2-} and TDS in the karst water tend to exceed the standard for drinking water. Based on the results of the Mann–Kendall trend test, the values of Z and β for SO_4^{2-}, TDS, and TH are 5.27 and 6.72, 5.45 and 11.64, and 4.90 and 5.82, respectively, implying that SO_4^{2-}, TDS, and TH have a prominent increasing trend, and the multi-year average increasing degrees are 6.72 mg/L, 11.64 mg/L, and 5.82 mg/L, respectively (Table 1). The concentrations of water quality parameters in karst spring water and mine water in different periods are listed in Table 2. Table 2

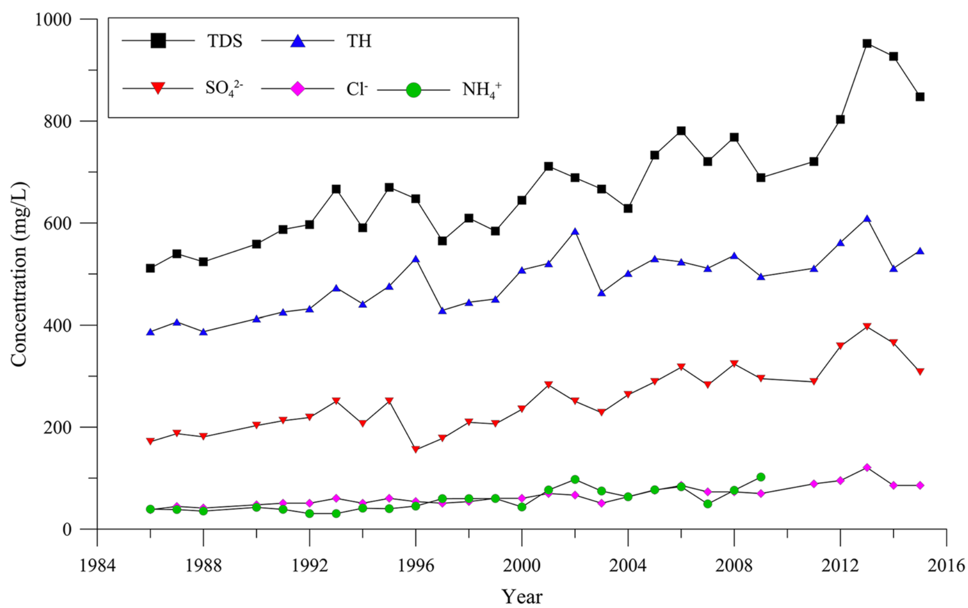

Fig. 5 Time series of major water quality parameters in Niangziguan spring

Table 2 Water quality parameters of Niangziguan spring in different years (units: mg/L except pH, Liu et al. 1991; Hao et al. 2006; Zhang et al. 2016)

Time	Type	pH	Na^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	HCO_3^-	NO_3^-	TDS	TH
1979	Karst water	–	–	–	–	22.2	59.6	–	14.7	512	291.92
1987	Mine water	7.08	–	232.25	103.34	–	1127.7	453.07	–	–	1026.63
	Karst water	7.55	–	110.98	29.09	–	179.25	263.61	–	662	397.14
2007	Mine water	7.27	324	171	88.1	40.2	1129.3	336.9	48.4	2408.8	–
	Karst water	7.67	32.8	110.5	35.4	61.3	160.9	253.7	43	771.7	–
2013	Mine water	7.34	302.92	216.57	96.23	48.73	1289.65	261.07	40.57	2258.53	–
	Karst water	7.64	25.65	119.77	36.46	46.10	195.10	259.25	39.12	721.97	–

reveals that the content of SO_4^{2-} increased from 59.6 mg/L in 1979 to 195.1 mg/L in 2013, and NO_3^- increased from 14.7 mg/L in 1979 to 43 mg/L in 2007. TDS also increased from 512 to 721.97 from 1979 to 2013 mg/L.

Coal mining activities are very common in the Niangziguan spring catchment (Fig. 1), and they have been considered as the biggest threat to karst groundwater quality (Zhang et al. 2016). Compared with the water quality parameters of spring water, it can be found that the concentrations of SO_4^{2-} and TDS are very high in the mine water, with the mean concentrations of them over 1000 mg/L and 2000 mg/L, respectively. The mean values of SO_4^{2-} and TDS in the mine water are, respectively, about 7 and 3 times higher than those of karst water. The pyrite oxidation in the coal-bearing formations and the gypsum dissolution in the middle Ordovician formations are two main sources of SO_4^{2-} in the karst groundwater of Niangziguan spring. Liang and Han (2013) estimated that 37.8% of the SO_4^{2-} in the karst water originated from the coal-bearing strata and 62.2% from gypsum dissolution. However, with the increase of coal mining activities and overexploitation of groundwater, the proportion of SO_4^{2-} originating from the coal-bearing strata is increasing. The large quantity of mine water leakage into karst aquifer leads to the increase of SO_4^{2-} and TDS in the karst groundwater. The hydraulic connectivity of aquifers is an important factor affecting groundwater quality (Wu et al. 2015, 2017), because poor quality water may leak into fresh water through various fractures and fissures occurring in the mining areas (Li et al. 2018b). The groundwater quality in mining areas requires special attention (Li et al. 2018c). Goaf water reserved in a large area of goaf may pose severe threat to the karst water quality and local ecological environment.

Shuishentang Spring

Shuishentang spring is one of a few karst springs in Shanxi without coal formation. The spring water is the main water supply to Guangling County in addition to its important role in agriculture. The quality of spring water was suitable for drinking in the 1980s. However, entering the 21st century, the spring water was contaminated by COD_{Mn}, NO_3^-, and NO_2^-. As shown in Table 3, the major ions in groundwater are not changed very much. However, NO_3-N and NO_2-N present an increasing trend from 2000 (3.97 and 0.033 mg/L, respectively) to 2005 (14 and 0.3 mg/L, respectively). This is affected by the fact that a lot of fertilizers and pesticides are used in the agricultural area. As a matter of fact, the nitrate pollution problem is becoming more and more serious in many agricultural areas (Adimalla 2018; He and Wu 2018; He et al. 2018; Zhang et al. 2018b). Based on the results tested in 2005, COD_{Mn} in groundwater has exceeded the limit for drinking recommended by the national drinking standard (3 mg/L, General Administration of Quality Supervision, Inspection & Quarantine of China, Standardization Administration of China 2017). Shuishentang spring is located at the downstream of the Guangling County and the karst water has connection with pore water in the overlying loose layers. Therefore, the karst groundwater can be easily polluted by municipal domestic sewage, industrial wastewater, and agricultural non-point pollution sources. Wastewater contains different types of contaminants such as trace metals, nitrate, organic compounds and even microbiological contaminants, and these contaminants can greatly pollute the groundwater (Li et al. 2018d). Nowadays, the government has urged less use of chemical fertilizers and pesticides in agriculture to build a green agricultural county. However, with the acceleration of urbanization, a mass of domestic sewage poses a great threat to the drinking water safety of Shuishentang spring (Jiao 2015).

Other Water Environmental Problems

In addition to spring flow attenuation and water quality deterioration, other environmental issues such as geological disasters are also serious. The continuous decrease of groundwater level evokes many geological disasters such as karst collapses and ground fractures. Further, large areas of goaf formed from mining activities poses a great threat to the safety of surface ecology, transportation, life and property of residents. There are many karst springs that are famous scenic spots of high tourist value and ecological function in Shanxi, such as Niangziguan spring and Shuishentang spring. However, spring discharge attenuation and even spring drying up have caused the loss of tourist value and ecological function in many spring scenic spots. The drying

Table 3 Water quality parameters of Shuishentang spring in different years (units: mg/L except pH, Water Resources Department of Shanxi Province et al. 2008)

Time	Type	Na^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	HCO_3^-	NO_3-N	NO_2-N	TDS	TH	COD_{Mn}
1986	Karst water	18.4	55.71	24.06	12.76	21.13	280.69	10.8	0.002	293.44	238.29	0.94
2000	Karst water	27.6	45.9	36.2	37.95	69.65	161.5	3.97	0.033	277	263.5	1.4
2001	Karst water	25	53.5	27.95	10.12	65.95	254.5	3.96	0.032	290	248.5	1.1
2005	Karst water	17.75	52.91	26.83	11.36	45.73	270.3	14	0.3	319	242.57	3.56

up of Shuiliandong spring caused the waterfall landscape to disappear, and the waterfall landscape had to be restored by hand pumping. Similarly, the abrupt drying up of Shuishentang spring has paralyzed the scenic area.

Karst Springs and Sustainable and Healthy Living

Spring flow attenuation and karst groundwater quality deterioration have become common problems in karst areas of Shanxi Province (Liang and Han 2013; Zhang et al. 2018a). The constant spring discharge decline and karst groundwater quality deterioration have severely hampered the development of local economy and society. In Niangziguan spring catchment, the karst groundwater is an important source of water supply in Yangquan City, supporting the water supply of over 700,000 people, and continued spring discharge attenuation and groundwater quality deterioration are bound to affect the drinking water safety of residents. Yangquan City is an important industrial and agricultural city in Shanxi Province. The karst groundwater level decline is restricting the development of local industry and agriculture. As for Shuishentang spring, spring discharge attenuation has affected the normal water supply for Guangling County and the local government has to make plans to establish new water sources (Jiao 2015). Karst springs also play an increasingly vital role in the ecological environment, and groundwater level decline has impacted groundwater-dependent ecosystems, causing wetlands to shrink and even disappear (Wang et al. 2018). Affected by the spring discharge attenuation, the wetland area around the Shuishentang spring is gradually shrinking and local farmers have to cultivate other crops that use less water to replace rice growth which requires more water. Due to the impact of human activities, karst groundwater deterioration caused by SO_4^{2-} and TDS in Niangziguan spring, and groundwater pollution by COD_{Mn}, NO_3^-, and NO_2^- in Shuishentang spring could be a serious threat to the health of local residents. Drinking contaminated groundwater for a long time may put local residents at high health risk. To create a sustainable and healthy living, necessary measures should be taken to protect karst springs.

Measures to Protect the Karst Springs

The karst springs are important for the sustainable development of Shanxi. To protect the karst springs from drying up and being contaminated, the following measures should be considered:

(1) Coal mining activities should be regulated with strict supervision, and small mines that do not meet completely the national regulations should be strictly banned, because unplanned energy development may induce serious environmental and geological disasters, threatening environmental biodiversity and local residents (Li and Qian 2018b). The groundwater monitoring network should be established to prevent and control further pollution of karst groundwater. Scientific research is needed to predict, prevent, and solve mine water problems (Li 2018; Li et al. 2018e). Goaf water should be controlled and treated effectively.

(2) Quarrying activities should be banned, especially in the recharge areas of the catchment. Vegetation restoration project should be carried out in the recharge area of the spring catchments to strengthen the rainfall infiltration and to avoid soil erosion and local flooding.

(3) Urbanization should be sustainably carried out by considering the availability of the water resources, especially in the arid and semi-arid areas (Li et al. 2018f). It is necessary to effectively treat urban sewage to prevent pollution of karst groundwater from sewage and industrial wastewater. Rainwater harvesting systems need to be considered for use in new residential areas and factories (Li et al. 2018a).

(4) Large volumes of groundwater are pumped for agricultural irrigation, because river water is scarce. The agricultural water takes up a great proportion of the total groundwater abstraction. Therefore, water-saving irrigation technologies should be promoted to reduce the use of groundwater for irrigation. Meantime, scientific application of fertilizers and pesticides should be strengthened to reduce the pollution of karst groundwater by agricultural activities.

(5) To protect the water resources in karst spring regions, Shanxi Province formulated regulations on the protection of water resources in the spring region of Shanxi Province in 1997. However, the decline of spring water flow and deterioration of water quality have not been effectively constrained. For specific spring areas, the regulations are not accompanied with corresponding protection measures. The corresponding effective protection measures should be formulated and must be strictly implemented for different springs.

Conclusions

Karst groundwater in Shanxi has long been an important water source for urban water supply and agricultural purposes, and plays an important role in agricultural irrigation, industrial development, ecology and tourism. However, in the last 60 years, these springs have confronted different water resources and environmental issues due to climate change and increasing human activities. To better understand the trend of karst groundwater variation and to protect the karst water for the sustainable and healthy living in this province, this study compiled data in karst groundwater flow rate, groundwater level and groundwater quality, and these data were statistically analyzed and trends were tested via the Mann–Kendall approach. The following conclusions can be summarized from this study:

(1) Based on the results of the Mann–Kendall trend test, the values of Z and β are − 1.77 and − 1.63 for precipitation and − 8.37 and − 0.14 for spring discharge in Niangziguan spring, respectively. The values of Z and β are − 1.74 and − 2.15 for precipitation and − 3.58 and − 0.006 for spring discharge in Shuishentang spring, respectively. The precipitation and spring discharge of two springs both show a declining trend. The change of spring discharge is accompanied by the change of precipitation with a certain lag, illustrating that climate change is one of the critical factors causing spring discharge attenuation.

(2) With the attenuation of spring discharge, the karst groundwater level also shows a descending trend in Niangziguan spring and Shuishentang spring. Groundwater overexploitation has led to a continuous drop in the groundwater level. The groundwater level is decreased by 12.88 m from 1981 to 2006 in the Huili deep well of the Niangziguan spring catchment. Similarly, the groundwater level of a well in Shuishentang spring catchment is decreased by 1.6 m in the 2 years from 2011 to 2013.

(3) The concentrations of SO_4^{2-}, NO_3^-, and TDS in the Niangziguan spring tend to exceed the limit for drinking water. Based on the results of the Mann–Kendall trend test, SO_4^{2-}, TDS, and TH in the Niangziguan spring present a prominent increasing trend, and the multi-year average increasing degree is 6.72, 11.64, and 5.82 mg/L, respectively. Coal mining activities widely distributed in the Niangziguan spring catchment are important factors affecting their concentrations. The contaminations from mine water and agriculture are considered as the biggest threat to karst water quality. In the Shuishentang spring, the spring water is contaminated by COD_{Mn}, NO_3^-, and NO_2^-. The domestic sewage from the urban areas poses a great threat to the water quality of Shuishentang spring.

(4) Decreasing precipitation caused by climate change is the main reason of the decrease in spring discharge. However, increasing human activities such as quarrying and coal mining, urbanization, groundwater overexploitation have also caused ecological environmental problems to the spring system. Particularly, in the spring catchment containing coal-bearing strata, coal mining and agricultural activities require special attention.

Acknowledgements Financial support has been received from various agencies for the research presented in this paper: The National Natural Science Foundation of China (41502234, 41602238, 41572236 and 41761144059), the Research Funds for Young Stars in Science and Technology of Shaanxi Province (2016KJXX-29), the Special Funds for Basic Scientific Research of Central Colleges (300102298301), the Fok Ying Tong Education Foundation (161098), the General Financial Grant from the China Postdoctoral Science Foundation (2016M590911 and 2015M580804), the Special Financial Grant from the China Postdoctoral Science Foundation (2017T100719 and 2016T90878), the Special Financial Grant from the Shaanxi Postdoctoral Science Foundation (2016BSHTDZZ03 and 2015BSHTDZZ09), and the Ten Thousand Talent Program. We are also very grateful to the anonymous reviewers and the editor for their useful and constructive comments.

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

Adimalla N, Li P, Qian H (2018) Evaluation of groundwater contamination for fluoride and nitrate in semi-arid region of Nirmal Province, South India: a special emphasis on human health risk assessment (HHRA). Hum Ecol Risk Assess. https://doi.org/10.1080/10807039.2018.1460579

Dar FA, Perrin J, Ahmed S, Narayana AC (2014) Review: carbonate aquifers and future perspectives of karst hydrogeology in India. Hydrogeol J 22:1493–1506. https://doi.org/10.1007/s10040-014-1151-z

Fan X, Wang M (2011) Change trends of air temperature and precipitation over Shanxi Province, China. Theor Appl Climatol 103:519–531. https://doi.org/10.1007/s00704-010-0319-2

Gao X, Wang Y, Ma T, Hu Q, Xing X, Yu Q (2011) Anthropogenic impact assessment of Niangziguan karst water. Water Manag 164:495–510. https://doi.org/10.1680/wama.1000070

General Administration of Quality Supervision, Inspection & Quarantine of China, Standardization Administration of China (2017) Standards for groundwater quality (GB/T14848-2017). Standards Press of China, Beijing **(in Chinese)**

Guo Q, Wang Y, Ma T, Li L (2005) Variation of karst spring discharge in the recent five decades as an indicator of global climate change: a case study at Shanxi, northern China. Sci China Ser D Earth Sci 48(11):2001–2010. https://doi.org/10.1360/04yd0113

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—a study on big karst springs in Shanxi. Geological Publishing House, Beijing **(in Chinese)**

Hao Y, Yeh TCJ, Hu C, Wang Y, Li X (2006) Karst groundwater management by defining protection zones based on regional geological structures and groundwater flow fields. Environ Geol 50:415–422. https://doi.org/10.1007/s00254-006-0220-6

Hao Y, Wang Y, Zhu Y, Lin Y, Wen J, Yeh TCJ (2009) Response of karst springs to climate change and anthropogenic activities: the Niangziguan Springs, China. Prog Phys Geogr 33(5):634–649. https://doi.org/10.1177/0309133309346651

Hao Y, Liu G, Li H, Li Z, Zhao J, Yeh TCJ (2012) Investigation of karstic hydrological processes of Niangziguan Springs (North China) using wavelet analysis. Hydrol Process 26:3062–3069. https://doi.org/10.1002/hyp.8265

Hao Y, Huo X, Duan Q, Liu Y, Fan Y, Liu Y, Yeh TCJ (2015) A Bayesian analysis of nonstationary generalized extreme value distribution of annual spring discharge minima. Environ Earth Sci 73:2031–2045. https://doi.org/10.1007/s12665-014-3552-7

Hartmann A, Goldscheider N, Wagener T, Lange J, Weiler M (2014) Karst water resources in a changing world: review of hydrological modeling approaches. Rev Geophys 52:218–242. https://doi.org/10.1002/2013RG000443

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. https://doi.org/10.1007/s12403-018-0289-7

He K, Jia Y, Wang F, Lu Y (2011) Overview of karst geo-environments and karst water resources in north and south China. Environ Earth Sci 64:1865–1873. https://doi.org/10.1007/s12665-011-0998-8

He X, Wu J, He S (2018) Hydrochemical characteristics and quality evaluation of groundwater in terms of health risks in Luohe aquifer in Wuqi County of the Chinese Loess Plateau, northwest China. Hum Ecol Risk Assess. https://doi.org/10.1080/10807039.2018.1531693

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

Jiao X (2015) Water environment problems and water resources protection measures in Shuishentang spring catchment. Shanxi Water Resources 6:9–10 **(in Chinese)**

Kendall MG, Gibbons JD (1990) Rank correlation methods, 5th edn. Griffin, London

Lacombe G, McCartney M, Forkuor G (2012) Drying climate in Ghana over the period 1960–2005: evidence from the resampling-based Mann–Kendall test at local and regional levels. Hydrol Sci J 57(8):1594–1609. https://doi.org/10.1080/02626667.2012.728291

Li P (2018) Mine water problems and solutions in China. Mine Water Environ 37(2):217–221. https://doi.org/10.1007/s10230-018-0543-z

Li P, Qian H (2018a) Water resources research to support a sustainable China. Int J Water Resour Dev 34(3):327–336. https://doi.org/10.1080/07900627.2018.1452723

Li P, Qian H (2018b) Water resource development and protection in loess areas of the world: a summary to the thematic issue of water in loess. Environ Earth Sci 77(24):796. https://doi.org/10.1007/s12665-018-7984-3

Li P, Li X, Meng X, Li M, Zhang Y (2016) Appraising groundwater quality and health risks from contamination in a semiarid region of northwest China. Expo Health 8(3):361–379. https://doi.org/10.1007/s12403-016-0205-y

Li P, Qian H, Zhou W (2017a) Finding harmony between the environment and humanity: an introduction to the thematic issue of the Silk Road. Environ Earth Sci 76(3):105. https://doi.org/10.1007/s12665-017-6428-9

Li P, Tian R, Xue C, Wu J (2017b) 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 (2018a) 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, Wu J, Tian R, He S, He X, Xue C, Zhang K (2018b) Geochemistry, hydraulic connectivity and quality appraisal of multilayered groundwater in the Hongdunzi Coal Mine, Northwest China. Mine Water Environ 37(2):222–237. https://doi.org/10.1007/s10230-017-0507-8

Li P, Tian R, Liu R (2018c) Solute geochemistry and multivariate analysis of water quality in the Guohua Phosphorite Mine, Guizhou Province, China. Expo Health. https://doi.org/10.1007/s12403-018-0277-y

Li P, He S, He X, Tian R (2018d) Seasonal hydrochemical characterization and groundwater quality delineation based on matter element extension analysis in a paper wastewater irrigation area, northwest China. Expo Health 10(4):241–258. https://doi.org/10.1007/s12403-17-0258-6

Li P, Qian H, Wu J (2018e) Conjunctive use of groundwater and surface water to reduce soil salinization in the Yinchuan Plain, North-West China. Int J Water Resour Dev 34(3):337–353. https://doi.org/10.1080/07900627.2018.1443059

Li P, He S, Yang N, Xiang G (2018f) Groundwater quality assessment for domestic and agricultural purposes in Yan'an City, northwest China: implications to sustainable groundwater quality management on the Loess Plateau. Environ Earth Sci 77(23):775. https://doi.org/10.1007/s12665-2018-7968-3

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

Liang Y, Gao H, 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 26:1371–1385. https://doi.org/10.1007/s10040-018-1792-4

Liu Z, Yuan D, Shen Z (1991) Effect of coal mine waters of variable pH on spring water quality: a case study. Environ Geol Water Sci 17(3):219–225

Wang Y, Zheng C, Ma R (2018) Review: safe and sustainable groundwater supply in China. Hydrogeol J 26:1301–1324. https://doi.org/10.1007/s10040-018-1795-1

Water Resources Department of Shanxi Province, Institute of Karst Geology (CAGS), Water Resources Management Committee of Shanxi Province (2008) Water resources protection in karst spring area of Shanxi Province. China Water & Power Press, Beijing **(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, Li P, Qian H (2015) Hydrochemical characterization of drinking groundwater with special reference to fluoride in an arid area of China and the control of aquifer leakage on its concentrations. Environ Earth Sci 73(12):8575–8588. https://doi.org/10.1007/s12665-015-4018-2

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

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 23:6286–6299. https://doi.org/10.1007/s11356-015-5838-z

Zhang J, Hao Y, Hu B, Huo X, Hao P, Liu Z (2017) The effects of monsoons and climate teleconnections on the Niangziguan karst spring discharge in North China. Clim Dyn 48:53–70. https://doi.org/10.1007/s00382-016-3062-2

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

Zhang Y, Wu J, Xu B (2018b) Human health risk assessment of groundwater nitrogen pollution in Jinghui canal irrigation area of the loess region, northwest China. Environ Earth Sci 77(7):273. https://doi.org/10.1007/s12665-018-7456-9