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REVIEW

Review: karst springs in Shanxi, China

Zhixiang Zhang[1,2] · Yongxin Xu[1,2] · Yongbo Zhang[2] · Jianhua Cao[3]

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Abstract

China is one of a few countries in the world where karst is intensively developed and karst water is heavily utilized as water supply sources. Shanxi is such a Province with the largest karst distribution in places in Northern China, where 19 large karst springs and their catchments are identified to provide important sources of the water supply and ecosystem functioning in Shanxi. Over the years, many problems associated with utilization of karst springs in Shanxi cropped out, including the decrease in spring flow, decline of groundwater level, groundwater contamination and pollution, etc., which severely restrict the sustainable utilization of karst water resources in Shanxi. Through the retrieval and analysis of some 200 local and international publications, this paper critically reviews the research results of karst springs in the region from the perspective of spring flow trend, precipitation recharge and time-lag, evaluation of karst water resources, water chemistry and environmental isotopes with purposing assession, and further evaluates the integrity of the aquifer system including vulnerability, impacts of coal mining and engineering activities on karst groundwater, delineation of spring catchment sub-systems, protection and management measures. It is concluded that human activities and climate change are the primary and secondary factors negatively affecting karst springs, respectively. The impacts of human activities on karst springs are mainly facilitated by intensive development of karst water, mining drainage, engineering construction and other activities. While karst water in parts of Shanxi spring catchments is polluted to various degrees, hence it is recommended to mainstream the protection of karst spring water in the areas of strategic importance. This paper will contribute towards the establishment of sustainable development and utilization of karst water in Shanxi and even in Northern China.

Keywords Karst spring · Karst water · Spring catchment · Water resources · Shanxi

Introduction

China is one of the countries where karst is widely distributed. The total karstic area of China is approximately 344×10^4 km^2, equalling 35.8% of the total land area. The area of exposed karst is about 90.7×10^4 km^2, equaling 9.5% of the total land area (Han 2015). The karst water resource is 2034.24×10^8 m^3/a (Han et al. 1993), which is about 1/4 of the total groundwater resources in China (Yuan et al. 1994). According to statistics, more than 25% of the world population uses karst water as a source of drinking water (Ford and Williams 1989). Therefore, karst water has become an important area in hydrogeology. In terms of the karst system, the effects of karst features on circulation of water in carbonate rocks were investigated in coastal areas of the Bahamas and Yugoslavia (Stringfield and Legrand 1971); Yuan (1982) pointed out that the law of karst development must be mastered by the thorough research of the typical site; hence hydrogeological and hydrological analyses were used to identify the karst system (Bonacci and Jelin 1988); the geochemical and kinetic evolution of a karst flow system in West Virginia were evaluated by the use of the mass balance calculation (Groves 1992). In the aspect of karst springs, the relationships between reservoir water level and spring discharge were used to study karst hydrology (Alpaslan 1981); the hydrogeology, hydrology, and hydraulic properties were examined to research the groundwater circulation in the karst spring (Bonacci 1995); Niangziguan Spring flows were simulated using an artificial neural

✉ Yongxin Xu
xuyongxin@tyut.edu.cn; yxu@uwc.ac.za

[1] Department of Earth Sciences, University of the Western Cape, Bellville, South Africa

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

[3] Institute of Karst Geology, Chinese Academy of Geological Sciences, Guilin, China

network model (Hu et al. 2008); the response of Niangziguan karst spring to climate change and anthropogenic activities was studied (Hao et al. 2009a); the effect of annual precipitation amount on the characteristics of spring hydrograph was researched by Mohammadi and Shoja (2014). In consideration of isotopes, variations in the isotopic composition of water were used to explain the recharge mechanism of the karst spring in Greece (Kallergis and Leontiadis 1983); the environmental isotope methods were used to evaluate the groundwater in the Paleogene limestone aquifer in northeastern Syria (Kattan 2001); the recharge in dolomitic aquifers in South Africa was estimated by the use of natural isotopes (Bredenkamp 2007); isotopic analysis was used to characterize the flow system in the carbonate aquifer at Taiyuan area, Northern China (Sun et al. 2016). In the research of karst water contamination and pollution, the pollution of whole hydrosystem in karst terrains was related with an increasingly industrial society (George 1973); land use was not the primary control on groundwater contamination (Scanlon 1990); coal mine waters of variable pH had an effect on spring water quality (Liu et al. 1991); the impact of a landfill leachate on underlying aquifer water or spring discharge was assessed (Kogovsek and Petric 2013). For a karst aquifer, the controlling factors of the development of karst and permeability are climate, topography, soluble rocks, geological structure, groundwater circulation, base level and meteoric water (Stringfield et al. 1979); karst water quality depends on the development of the channels and the permeability of the carbonate rocks (Dodge 1984); the hydrology of the karst aquifer at the experimental site of Guilin was investigated (Yuan et al. 1990); groundwater level fluctuation in the large fractured-karst aquifer system in the Jinan Spring field was simulated (Qian et al. 2006); groundwater balance of the Jadro Spring aquifer was estimated using the conceptual rainfall-runoff model (Jukic and Denic-Jukic 2009); the response of large karst aquifers in the Mediterranean area to the recharge input variation was evaluated (Fiorillo et al. 2015). Overall, investigators have made some practical results in the research of karst springs and karst water, which provide references for the development and protection of the local karst water resources.

Karst water occupies an important place in the water supply of China's urban and industry, and it plays an important role in ensuring the rapid development of the country's economy. However, due to original sedimentary environment, geological conditions, and paleo-climate, karst features in the North and South of China are manifested differently. In Southern China, the distribution of carbonate rocks is larger with a higher degree of karstification in forms of karst fissures and channels at various scales (including karst caves), and the storage of karst water is mostly unreliable. In Northern China, the distribution of carbonate rocks is also large, but mostly is of the buried type, the degree of karstification is lower in the forms of karst fissures and cave fissures, and the storage of karst water is mostly reliable (He and Zhou 1996). Located in the eastern margin of the China's second-stage ladder, Shanxi Province is situated on a plateau between the western part of the North China plain, the eastern part of the Loess plateau, and the middle reaches of the Yellow River. The Province, in its own right, forms the largest karst distribution area among three Provinces in Northern China, with an exposed karst area of 2.6×10^4 km^2, and a covered karst area of 8.7×10^4 km^2, resulting in a total area of up to 11.3×10^4 km^2, which accounts for 75.2% of the total area of Shanxi Province (Fan 2005). Shanxi is surrounded by mountains with significant topographic relief with a mean annual precipitation of 494.9 mm (Li et al. 2015). In this semi-arid karst area, the formation of many karst springs with relatively stable flow form clusters of springs at base level of the spring catchments. Each spring catchment consisting of the springs and their contributing areas is a complete karst water system (Han et al. 1993). According to statistics, there are 86 karst springs in Shanxi with the spring flow rate greater than 0.1 m^3/s (Han et al. 1993). Among them, there are 19 spring catchments with original spring flow at a rate of greater than 1 m^3/s (Fig. 1). According to the decreasing sizes of spring catchments, the 19 springs are listed as Xin'an Spring (10,950 km^2), Tianqiao Spring (10,192 km^2), Niangziguan Spring (7217 km^2), Guozhuang Spring (5600 km^2), Shentou Spring (4756 km^2), Liulin Spring (4729 km^2), Pingshang Spring (3035 km^2), Sangu Spring (2814 km^2), Yanhe Spring (2575 km^2), Lancun Spring (2500 km^2), Longzici Spring (2250 km^2), Jinci Spring (2030 km^2), Chengtouhui Spring (1672 km^2), Huoquan Spring (1272 km^2), Majuan Spring (754 km^2), Hongshan Spring (632 km^2), Shuishentang Spring (518 km^2), Gudui Spring (460 km^2) and Leimingsi Spring (377 km^2), respectively (Water Resources Management Committee Office of Shanxi Province 1998). These karst spring flows have stable quantity and good quality, which used to provide important sources of water supply and ecoscape in Shanxi. Since the 1950s, due to the impact of natural and man-made factors, many problems in most parts of spring catchments occurred, including the decrease in spring flow rates, and the decline of groundwater level. (Hao et al. 2006a, 2007). Among these being affected the Lancun Spring, Jinci Spring, and Gudui Spring ceased to flow in 1988, 1994, and 1999, respectively (Chen 2006a; Jin et al. 2005; Zhang 2014a), and there is still no reflow yet. Owing to contamination and pollution in some spring catchments, the water quality became deteriorated (Shi et al. 2004; Wang et al. 2008). These problems imposed constraints on the development and utilization of karst water resources where affected.

Shanxi Province is well known for its rich coal resources. There are six coalfields: Datong, Ningwu, Hedong, Xishan, Qinshui and Huoxi. The Datong coalfield has been mining

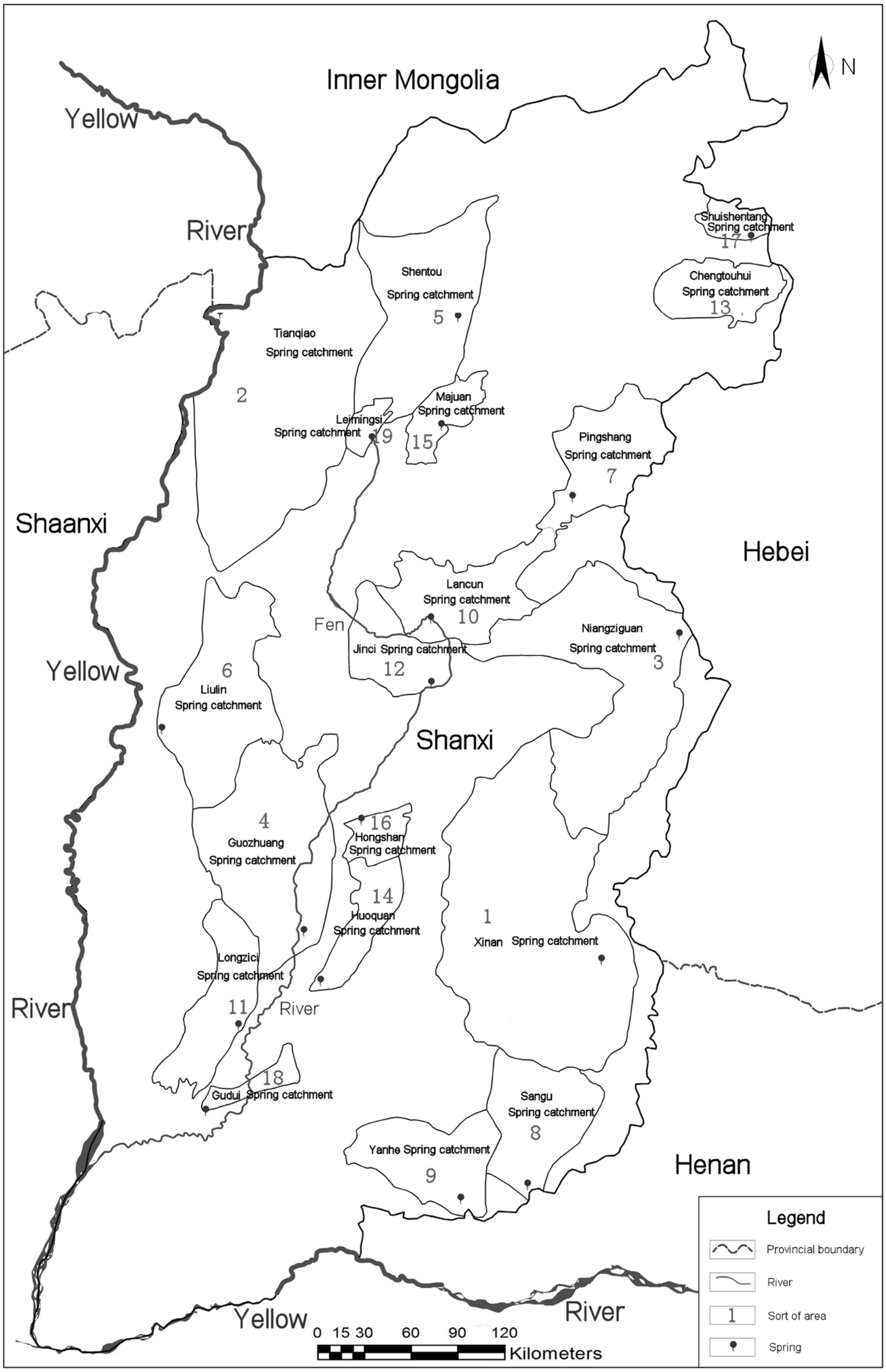

Fig. 1 Nineteen big karst springs in Shanxi Province, China

coal deposits of Jurassic age, while most of the other coalfields are mining the Carboniferous and Permian coal seams. Due to the sedimentary formation of the coal-bearing strata overlying carbonate rocks, and the control of regional tectonics, it constitutes the coexistence of water and coal resources (Lu 1992). There are many coal mines being mined out within the spring catchments, and in places, coal mining has produced a large amount of acid mine drainage (AMD). To ensure safety in production, mine inflow was often discharged during the mining process. But after the coal mines were closed and the dewatering discharge stopped, the water level of AMD in the gob gradually rose. At the same time, the AMD characterized by the coal-mining pollutants seeped into the underlying karst aquifer through the coal seam floor fissures, faults, and induced fractures, and contaminated the karst aquifer water. With the continuous increase in the number of abandoned coal mines in Shanxi spring catchments, AMD problems is increasingly becoming serious, which threatens the health and normal life of local residents. This phenomenon is similar to AMD problems in many other countries such as South Africa. South Africa is a country with extensive mining experience, due to intensified exploitation of mining in many areas, which has caused serious AMD problems for many years. For example, mining at Middelburg Colliery in the Witbank Coalfield has shown a marked deterioration of groundwater quality in the area due to the seepage of AMD (Bullock and Bell 1997), and the impact of AMD in South Africa is likely to persist for centuries rather than decades (McCarthy 2011). Although the AMD in both countries have caused karst water contamination and pollution, there is a certain difference in AMD problems between China and South Africa. The polluted AMD in Shanxi is often discharged into surface water courses and/or is leaked downward into the underlying karst aquifer as well. In South Africa, AMD rose into the upper karst aquifer after the cessation of drainage, and eventually decanted to the surface, which caused the pollution of karst water and surface water (Durand 2012). Shanxi Province is a region with a serious shortage of water resources, the water resources per capita is 381 m^3 (Zhang and Zhao 2009), which not only below the internationally recognized 1700 m^3 per capita water tight line, but is also far below the internationally recognized 1000 m^3 per capita water shortage warning line. Once the AMD on karst water pollution is aggravated, it is bound to increase the tensions of water supply in Shanxi. A lot of surface water in Shanxi cannot be utilized due to its outflow to the outside, combining with the damage of pore water and fissure water caused by coal mining, the water for industrial and agricultural production and drinking in most regions mainly depends on the development of karst water. Therefore, karst water has an important strategic position in the development and utilization of water resources in Shanxi.

In the light of climate change and human activities, the impacts on development and utilization of karst water in Shanxi are getting more and more tangible. This is a great challenge faced for the development of karst water in Shanxi. The cessation of Lancun Spring in 1988 and that of Jinci Spring in 1994 triggered the promulgation of "Water Resources Protection Regulations of Lancun Spring Catchment in Taiyuan City" in 1990 and "Water Resources Protection Regulations of Jinci Spring Catchment in Taiyuan City" in 1995 by the Standing Committee of the People's Congress of Taiyuan City (Chen 2006b; Jin et al. 2005). "Water Resources Protection Regulations of Spring Catchments in Shanxi Province" was also issued in 1997 by the Standing Committee of the People's Congress of Shanxi Province, which provides a legal basis for the protection for the karst water. Thus, it is of special significance for karst water protection to be codified at a provincial level. Coal and karst water coexist in 19 karst spring catchments of Shanxi Province, the area of any spring catchment is vast. These spring catchments have their own uniqueness and profound cultural backgrounds. The karst springs are scenic tourist spots and have become a lot of temple resorts (Han 2015). All these indicate that Shanxi karst area has its own characteristics and regionalism in the Northern China karst. Therefore, it is of great significance to review the research findings on karst springs in Shanxi. To protect the precious karst water resources in Shanxi, and to prevent or reduce the occurrence of karst water contamination and pollution. This paper aims to review the research results of karst springs in Shanxi for the past decades, to analyze the problems and difficulties in the research, and to point out the way forward of the research on karst springs, hoping that the fact that karst springs have been seriously affected will draw public attention for the sustainable utilization of karst springs in Northern China in general and in Shanxi in particular.

Overview karst spring studies in Shanxi

Karst areas in Northern China include all areas of Shanxi Province, Hebei Province, Shandong Province, Beijing City, Tianjin City, some parts of Liaoning Province, the Inner Mongolia Autonomous Region, Shaanxi Province, Gansu Province, Ningxia Province, Anhui Province, Jiangsu Province, and Henan province (Xie and Li 1983). The total area of the carbonate rocks is 68.5×10^4 km^2 (Hou et al. 2008). In terms of climate, Shanxi is a transition zone from the inland arid, semi-arid climate to the southeast humid, semi-humid monsoon climate; in the aspect of hydrology, Shanxi is the watershed between the inland surface water system and the coastal external water system (Guo et al. 2005). Thus, it can be seen that Shanxi karst is a typical representative in Northern China karst. Shanxi karst springs are of significance not only in Shanxi karst areas but also in the field of Northern China karst, the value of its development and utilization is great, and it is the main water supply source for Shanxi City and its energy base. Over the years, investigators have carried out a lot of research on Shanxi karst springs, especially investigators such as Han Xingrui et al. at the Institute of Karst Geology, Chinese Academy of Geological Sciences, who paid special attention to the karst springs in Northern China. They made a thorough study of Shanxi karst springs in the collaboration with Shanxi water conservancy departments for many years, and achieved many important results. Such a report, named "Study on karst water resources evaluation and exploitation of Niangziguan Spring catchment", was completed in 1983, from which the karst water resources in Niangziguan Spring catchment was evaluated. Using system theory method, and system analysis method, Han et al. (1993) reported their evaluation of the origin, flow dynamic and water resources of Shanxi karst springs, giving a systematic summary of the study of karst water in Shanxi over a period of two decades. By combining geological structure with water chemistry, isotope, and hydrodynamic analysis, Han et al. (1994a) further outlined the Danhe karst water system of Shanxi, and evaluated the natural resources of karst water of interest. These results have good practical value, forming a basis for the development and utilization of karst spring resources in Shanxi.

Spring flow trend

Dynamic record of spring flow

Over the years, the dynamics of karst spring flows in Shanxi have changed in various degrees (Table 1). According to the decreasing sizes of spring catchments, the 19 springs from No. 1 to No. 19 are numbered as seen in Fig. 1. Xin'an Spring (No. 1) flow has decreased significantly since 1980 (Chen et al. 2015). Niangziguan Spring (No. 3) flow showed a downward trend (Yan 2013). Guozhuang Spring (No. 4) flow was in a state of fluctuation before 1980, and it showed a downward trend in 1980 (Chong 2008). Shentou Spring (No. 5) flow was relatively stable before 1968, and it was in a state of decrease from 1969 to 2006 (Cao 2008). Liulin Spring (No. 6) flow was in a state of fluctuation before the 1980s, and it showed a downward trend in 1990 (Bai et al. 2012). Pingshang Spring (No. 7) flow

Table 1 The change of karst spring flows in Shanxi for many years

Item	The mean annual flow (m^3/s)	The mean annual flow in the 1950s (m^3/s)	The mean annual flow in the 1960s (m^3/s)	The mean annual flow in the 1970s (m^3/s)	The mean annual flow in the 1980s (m^3/s)	The mean annual flow in the 1990s (m^3/s)	The mean annual flow in the 21 st century (m^3/s)
Xin'an Spring	9.29 (1957–2000)	–	–	–	–	–	–
Niangziguan Spring	10.65 (1956–2000)	13.42	13.90	11.23	9.36	9.09	–
Guozhuang Spring	7.14 (1956–2000)	–	–	–	–	–	–
Shentou Spring	7.84 (1958–2006)	8.47	8.65	7.50	5.76	5.11	4.74
Liulin Spring	3.38 (1957–2005)	–	–	3.67	2.88	2.16	1.37
Pingshang Spring	4.67 (1956–2000)	–	–	–	–	–	–
Sangu Spring	3.91 (1956–2000)	4.83	4.56	3.35	3.68	3.61	–
Yanhe Spring	2.96 (1956–2000)	3.59	3.64	2.39	3.12	2.37	–
Lancun Spring	1.88 (1954–1988)	–	–	–	–	–	0
Longzici Spring	5.018 (1955–2007)	5.90	6.14	5.11	5.31	3.94	3.65
Jinci Spring	–	1.95	1.61	1.21	0.52	0	0
Chengtouhui Spring	–	–	–	–	2.93	2.19	
Huoquan Spring	3.899 (1956–1997)	–	–	–	–	–	–
Majuan Spring	0.83 (1956–2009)	–	–	–	–	–	–
Hongshan Spring	1.156 (1955–2000)	1.54	1.39	1.14	1.02	0.86	–
Shuishentang Spring	–	–	0.9	0.6	–	–	0.2

displayed a gentle downward trend (Li 2007). Sangu Spring (No. 8) flow showed an overall downward trend (Zhang et al. 2010). Yanhe Spring (No. 9) flow was in a state of fluctuation before 1986, it remained in fluctuation with a slight decline from 1986 to 1995, and the decline amplitude increased from 1996 to 2000 (Liu 2004). Lancun Spring (No. 10) flow showed a downward trend year by year, and it eventually ceased to flow in 1988 (Chen 2006b). Longzici Spring (No. 11) flow showed an overall downward trend (Wang et al. 2010). Jinci Spring (No. 12) flow was relatively stable from 1954 to 1960, it was in a state of decrease from 1961 to 1994, and ceased to flow in 1994 (Jin et al. 2005) (Fig. 2). Chengtouhui Spring (No. 13) flow was relatively stable before 2010, but from the beginning of 2010, it could not maintain a flow rate of 1.50 m^3/s (Wang 2015). Huoquan Spring (No. 14) flow showed an overall downward trend (Zheng et al. 1999). The change trend of Majuan Spring (No. 15) flow remained unchanged as its flow rate was in a relatively stable state (Liu 2012). Hongshan Spring (No. 16) flow showed an overall downward trend (Zhang and Song 2002). The mean annual flow of Shuishentang Spring (No. 17) from 1980 to 2000 declined 12.5% of what it was from 1956 to 1979 (Jiao 2015).

Combined Table 1 with the previous investigations, it is evident that the majority of spring flows in question have been decreasing in general. As shown in Fig. 2, the extent of decrease in a total flow of 15 springs was smaller prior to the 1980s, the extent of the decrease became larger after the 1980s. Jinci Spring, Lancun Spring, and Gudui Spring ceased to flow for many years (Chen 2006a; Jin et al. 2005; Zhang 2014b), these springs are still dry. Majuan Spring did not decrease as its flow is the most stable among all the karst springs in Shanxi. There are few literatures on Leimingsi Spring and Tianqiao Spring, but according to the fact that most of karst spring flows have already decreased, it is deduced that the flows of Leimingsi Spring and Tianqiao Spring may well be decreased. The decrease in the spring flows has intensified the shortage of public water supplies to various degrees, which has brought a series of environmental problems such as the decrease in tourist turnout and the degradation of ecological function to the tourist resorts surrounding karst spring catchments in Shanxi (Han 2015). For instance, the cessation of Jinci Spring flow has reduced the tourism income and cultural value of Jinci Temple, which is a famous tourist destination in China. The government departments had to take remedial measures to prevent the situation from deteriorating beyond control, namely by artificial recharge to aquifer. The worst is that due to the limitation of artificial recharge water source, the karst groundwater level of Jinci Spring catchment has still not fully recovered, which leads to Jinci Spring failing to discharge as usual. Therefore, it is necessary to pay adequate attention to the dynamic changes of the karst spring flows in Shanxi.

Causes of the decrease of spring flow

In recent years, investigators paid much attention to the causes of the decrease of karst spring flow in Shanxi, and obtained some valuable results. The decrease of Shanxi spring flows is attributed to the reduction of precipitation and human factors (Han et al. 1993). The decrease of Chengtouhui Spring flow in certain years was due to the reduction of precipitation in corresponding years (Wang 2015). The decrease of Shuishentang Spring flow was related to the reduction of precipitation and over-abstractions (Jiao 2015). The decrease of Shentou Spring flow was attributed to the reduction of precipitation, abstraction for water supply, industrial purposes and coal mining activities (Cao 2008). Among them, the reduction of precipitation was the main cause, whereas anthropogenic impact was the secondary cause (Ma et al. 2001, 2004). The reduction of precipitation was the main factor for the decrease of Lancun Spring

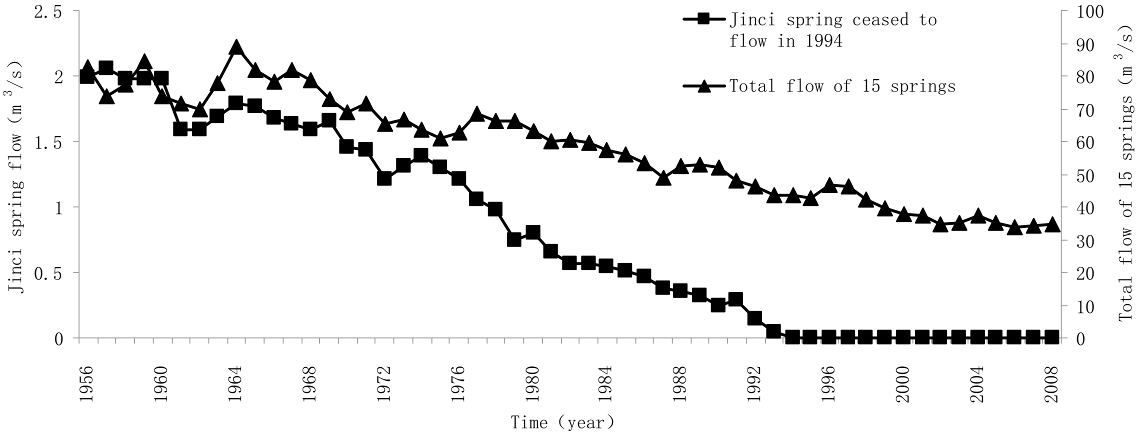

Fig. 2 The annual flow of Jinci spring and the total of 15 springs

flow before the 1970s, and the over-exploitation of karst water was the main cause for its decrease after the 1970s (Chen 2006b). The cessation of Jinci Spring was caused by the reduction of precipitation, the decrease of leakage from Fenhe River, the increase of over-exploitation (including dewatering of coal mines) and the increase of development stress exerted within a Quaternary unconsolidated aquifer in Taiyuan basin. Among them, the karst water development was the main factor for the decrease of Jinci Spring flow (Jin et al. 2005; Hao et al. 2009b). The reduction of precipitation was the main cause of the decrease of Liulin Spring flow prior to 1990, and it was due to the combined effect of the reduction of precipitation and the over-exploitation after 1990 (Bai et al. 2012). But the latter plays a main role in the decrease of Liulin Spring flow (Hao et al. 2009c). The decrease of Niangziguan Spring flow was mainly related to the reduction of precipitation, the decrease of the leakage from Taohe River, the increase of karst water abstraction and the reduction of underflow recharge on the periphery (Liang et al. 2005); as a result, it caused the imbalance of discharge more than recharge (Cao 2007). Groundwater abstraction accounts for only about 34–52% of the declines, the remainders of the declines were related to other human activities (Hao et al. 2009a). To have a closer examination of the decrease of Niangziguan Spring flow, Liang et al. (2011) discussed the effect of time scale on the leakage from Taohe River. The decrease of Guozhuang Spring was related to the increase of karst water utilization, the reduction of precipitation, and the drainage of karst water by coal mining (Gao 2002). The changes in rainfall over many years, the over-exploitation of groundwater, coal mining and local economic activities were the key reasons that caused the decrease of Hongshan Spring flow (Zhang and Song 2002). The decrease of Huoquan Spring flow was related to the reduction of precipitation, the increase of karst water abstraction, coal mining dewatering and the reduction of recharge from surface water (Chai 2011). The decrease of Longzici Spring flow was related to the reduction of precipitation, the increase of karst water exploitation, and the drainage of karst water by coal mining (Ye 2006). The decrease of Xin'an Spring flow was related to the change of precipitation and groundwater development (Chen et al. 2015). The main factors in the decrease of Sangu Spring flow were the reduction of precipitation, karst water development, and coal mining drainage (Zhang et al. 2010). The decrease of Yanhe Spring flow was related to the reduction of precipitation, the increase of karst water abstraction, the reduction of river leakage, and coal mining drainage (Liu 2004). The cessation of Gudui Spring was due to the excessive exploitation of karst groundwater (Zhang 2014a).

In general, the karst spring flows in Shanxi were affected by multi-factors and their combination. The decrease in the karst spring flows as discussed above was mainly controlled by the climate and human activities (Han et al. 1994b). At present, the investigators are more concerned about Shentou Spring, Lancun Spring, Jinci Spring, Niangziguan Spring, Chengtouhui Spring, Shuishentang Spring, Liulin Spring, Guozhuang Spring, Hongshan Spring, Huoquan Spring, Longzici Spring, Xin'an Spring, Sangu Spring, Yanhe Spring, and Gudui Spring. In the decreased factors of the certain spring flows, the reduction of precipitation is the main cause, and human activity is the secondary one, those including Chengtouhui Spring and Shentou Spring. However, in the decrease factors of the most spring flows, human activity becomes the number one factor, and the reduction of precipitation is the secondary factor, such as Jinci Spring, Lancun Spring, Niangziguan Spring, Shuishentang Spring, Liulin Spring, Guozhuang Spring, Hongshan Spring, Huoquan Spring, Longzici Spring, Xin'an Spring, Sangu Spring, Yanhe Spring, and Gudui Spring. It can be seen that the intensive development of karst water, mine drainage, engineering construction and other activities are mainly responsible for the decrease in karst spring flows. To turn around the situation, it is suggested that realistic measures be urgently taken to mitigate the ongoing spring flow reductions.

Spring flow prediction

Over the years, most of spring flows in Shanxi have a trend of continued decrease. For sustainable development and utilization of karst water in the spring catchments, it is necessary to be able to predict the spring flows in the future. Spring flow prediction has become a hotspot in recent years in China. Gray model (GM (1, 1)), Gray prediction-amending model (Guo et al. 2002), GM (1, 1) cycle correction model (Hao et al. 2003a), and gray prediction model of seasonal neural network (Li et al. 2008) were used to predict Shentou Spring flow. Gray system model (GM (1, 2)) and gray system decomposition model were used to predict Liulin Spring flow (Hao et al. 2006a, 2007). Zero flow risk model was applied to predict Jinci Spring flow (Shu and Zhu 2000). Fuzzy relation equation was used to predict the changes of Jinci Spring flow after the completion of Wanjiazhai Yellow River Diversion Project (Sun et al. 2001). Exponential smoothing method (Guo 2004), assembled extreme value statistical model (Fan et al. 2013), and artificial neural network model (Hu et al. 2008) were used to predict Niangziguan Spring flow. Mixed autoregressive model was used to predict Guozhuang Spring flow (Zhu 2008). Gray model (GM (1, 2)) and GM (1, 2) residual error correction model were used to predict Hongshan Spring flow (Lei 2014). Stochastic prediction model and real-time prediction model were used to predict Huoquan Spring flow (Zheng et al. 1999). Multiple regression model, stochastic-cycle-trend model, threshold autoregressive model, gray system model (Guo et al. 2004), and time series analysis method (Chen et al. 2012) were used to predict Xin'an Spring flow. Numerical simulation method was used to predict Yanhe Spring flow (Ren et al. 1998). Support vector machine forecast model was used to predict Pingshang Spring flow (Hou 2010). Artificial neural network was used to predict Jinci Spring flow (Yin et al. 2011).

Thus, it can be seen that many methods were used to predict the karst spring flows in Shanxi by investigators. These can be grouped into two major categories: deterministic and stochastic models. Although the chosen models have made some achievements in spring flow prediction, whether it is the deterministic model or the stochastic model, all of them were unable to reflect the specific impact of human activities and climate change on spring flow from the perspective of the karst hydrogeological conditions. For instance, in the prediction of Xin'an Spring flow, the use of multiple regression model reflected that the spring flow was related to precipitation and karst water abstraction, this is just a simple quantitative relationship, and the use of gray system model only reflected that the spring flow was changed with time, the two were unable to reflect the characteristics of karst water system. With the constant change of the external and internal environment of spring catchments, karst spring flows of Shanxi will also change in varying degrees. Therefore, it should be considered by researchers to carry out the research on spring flow prediction from the perspective of karst hydrogeological conditions.

Precipitation recharge and time-lag

Recharge estimation

Precipitation is one of the main recharge sources for karst groundwater within Shanxi spring catchments, which has great influence on karst spring flow and water level dynamics. Many investigators are concerned with the process of precipitation infiltration and percolation in spring catchments. By making use of a simple infiltration coefficient method, Han et al. (1993) determined the recharge estimates of the 18 karst springs in Shanxi except Leimingsi Spring catchment. This was followed by the determination of recharge estimates of another 11 catchments, namely Shentou Spring catchment, Guozhuang Spring catchment, Longzici Spring catchment, Huoquan Spring catchment, Gudui Spring catchment, Leimingsi Spring catchment, Sangu Spring catchment, Yanhe Spring catchment, Tianqiao Spring catchment, Liulin Spring catchment, and Hongshan Spring catchment (Yi 2001; Gao 2005; Cui and Cui 2007; Zhang and Zhang 2008; Xu and Zhang 2009; Wang and Lian 2009; Bai 2012; Liu et al. 2014).

It can be seen that the recharge due to rainfall infiltration in Shanxi Spring catchments was monologically calculated using the infiltration coefficient. Although these results are easily obtained, the infiltration coefficient method carries innate problems such as relying on use of the empirical value or expert opinions in the estimation, which renders the estimates with certain subjectivity in some cases. Therefore, it is necessary to consider a variety of methods to cross-check the recharge estimates.

Residence time of karst water

Due to the impact of the recharge mechanisms, the degree of karst development and the velocity of groundwater flow, there is a certain time-lag (or residence time) between precipitation event and resultant spring flow. In recent years, the time-lag has gradually gotten the attention of investigators. Total time lags for four spring catchments were determined as seen in Table 2. It is noticed that even within the same catchment the time lags may vary from 1 to 7 years due to various methods applied by different authors, as reflected in Linlin Spring in Table 2. By employing gray correlation analysis model, Hao et al. (2003b) obtained that there were some variations in the time-lag between precipitation input and Niangziguan Spring flow output in different areas. Using statistical regression model, Zang et al. (2013) concluded that the time-lag in Hongshan Spring is 7 years. Using the gray correlation method, Li et al. (2011) investigated the time-lag between precipitation and Jinci Spring flow, and pointed out that the average groundwater residence time of Jinci Spring is 7 years.

According to the above results, it can be seen that the previous works on the time-lag of precipitation recharge were

Table 2 Time Lag for Selected Karst Spring Catchments

No	Spring catchment	Time-lag (year)	Method	References
1	Liulin Spring	3, 4, 6	Gray correlation analysis model	Wang (2007)
2	Liulin Spring		Gray slope similar correlation degree analysis model	Fan et al. (2012)
3	Liulin Spring	1 (South), 7 (North)	Gray system theory	Hao et al. (2012)
4	Niangziguan Spring	Variation	Gray correlation analysis model	Hao et al. (2003b)
5	Hongshan Spring	7	Statistical regression model	Zang et al. (2013)
6	Jinci Spring	7	Gray correlation method	Li et al. (2011)

mainly concentrated in Liulin Spring catchment, Niangziguan Spring catchment, Hongshan Spring catchment, and Jinci Spring catchment, while little was done on the time-lag of precipitation recharge in the other 15 spring catchments, or at least it has not been reported in the literature. At present, the methods used in the assessment of the time-lag of precipitation recharge are mainly the gray correlation analysis, the gray slope similar correlation degree analysis and the statistical analysis. Among them the application of gray correlation analysis method is most popular. Although the application of these methods has been well established to deal with the time-lag issues, the residence time of spring flow is rather complex. In fact, there are many factors which can affect the time-lag of precipitation recharge, including degree of karstification, tortuosity of karst channels and fissures, alteration of hydrogeological conditions by mining activities, and the velocity of groundwater flow. The previous work as discussed makes consideration of only the impact of precipitation, without due consideration of the above-mentioned factors from the perspective of hydrogeological conditions. Therefore, it is necessary to consider the combined effects of the multiple factors on residence time of the spring flows.

Dynamics of karst groundwater level

The dynamics of karst groundwater level is one of the most direct signs of the change in aquifer storage. It is very necessary to assess groundwater level fluctuation, which may reveal useful hydrogeological information required for sustainable utilization of karst water resources. Karst groundwater levels in most of Shanxi Spring catchments have been declining overall (Han et al. 1993). Groundwater level of Shentou Spring catchment was in a state of continuous decline, the mean annual rate of decline in the recharge area was greater than that in the runoff area, and the rate in the runoff area was greater than that in the discharge area (Wang and Wang 1998). According to the difference of the location, the dynamics of groundwater level of Tianqiao Spring can be summarized into the turbulent type, the time-lag type and the consumable type (Cao et al. 2005). Under the condition of little change in karst water abstractions in the future, the decline trend of groundwater level of Lancun Spring catchment would become insignificant (Pang et al. 2014). Coal mining drainage in Jinci Spring catchment was the most sensitive anthropogenic factor, which had huge effect on groundwater level in the area (Li et al. 2012). Groundwater level of Liulin Spring catchment was in the state of decline for many consecutive years (Kang 2004). The mean annual decline rates of groundwater levels of Xin’an Spring catchment were different in various locations (Wang 2012a). Groundwater level in Yanhe Spring catchment had a significantly decline trend for many years according to a long-term water level series in the monitoring wells (Xu and Zhang 2008b).

At present, the study on the dynamics of karst groundwater levels in most spring catchments is still of concern. Focus on individual spring catchments such as Leimingsi Spring catchment is relatively small, which may be related to the fact that the karst groundwater monitoring wells were too few or the karst groundwater monitoring series were too short to obtain the dynamic change time series of karst groundwater levels in these spring catchments. Although the researchers have paid a certain attention to the spatial and temporal variations in the dynamics of the groundwater level changes, some considered the effect of a single factor such as precipitation or coal mining, while the other considered the effects of the combined factors. Since the area in most of Shanxi spring catchments is widely spread, the complexities of these combined factors collectively determine the behavior of the dynamics of karst groundwater levels. In fact, there are great differences in terms of water-level fluctuations in the recharge, runoff and discharge areas of each Shanxi spring catchment. For sustainable development of karst groundwater resources, it would require much needed attention to the dynamics of karst groundwater levels in each area of a spring catchment. For the spring catchment, water level fluctuations in recharge, runoff and discharge areas are individually conditioned by their own set of hydrogeological factors. Understanding of the karst water level behaviors can effectively guide the utilization and protection of karst aquifer integrity in each spring catchment. Therefore, further investigation on the dynamics of karst groundwater levels in the recharge, runoff and discharge areas of the spring catchment must be carried out.

Evaluation of karst water resources

The so-called karst water resource refers to the groundwater that is stored in the karst rock formation which can be made beneficial to legitimate users under current technical and economic conditions without negative impact on the environment in the catchment of concern. As shown in Fig. 3, the groundwater, the surface reservoir and the river form the water supply sources of Shanxi Province and account for 88, 8 and 4%, respectively. The groundwater is the main supply source for 77% of the population in Shanxi. Out of the 88% (groundwater), karst water, pore water and fissure water account for 44, 36 and 8%, respectively. Thus, it can be seen that the karst water resource is an important source of water supply in Shanxi. According to the purpose of karst water, the water consumption in industry, agriculture and drinking water account for 30, 60 and 10%, respectively (Fig. 4). For many years, the investigators have carried out the evaluation of karst water resources in Shanxi spring catchments from different perspectives. Fan (2005) carried out the systematic

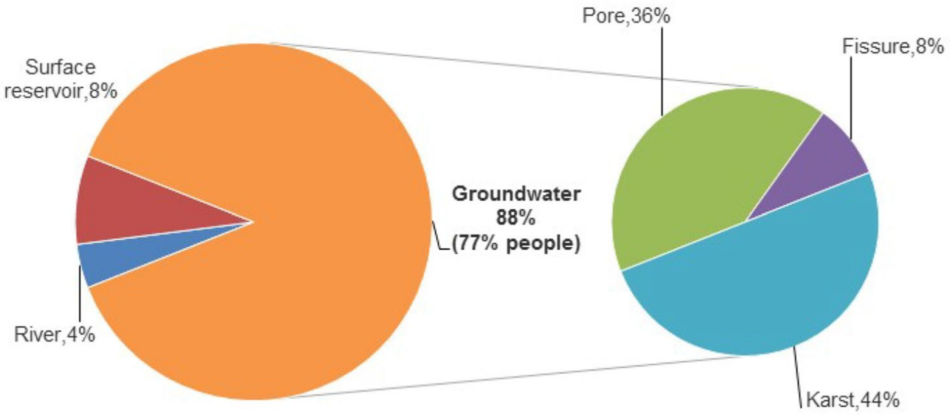

Fig. 3 Distribution of water supply sources

evaluation of karst water resources in 16 spring catchments including the Xin'an Spring, Tianqiao Spring, Niangziguan Spring, Guozhuang Spring, Shentou Spring, Liulin Spring, Pingshang Spring, Sangu Spring, Yanhe Spring, Lancun Spring, Longzici Spring, Jinci Spring, Huoquan Spring, Majuan Spring, Hongshan Spring, and Gudui Spring catchments. Fan (2005) discussed the natural and exploitable resources, which provide a basis for the development and protection of the karst water in Shanxi. The karst aquifer in question is an open system. Upon being polluted, it would be difficult to remedy. In the case of water for drinking purposes, whether or not the water quality meets prescribed standards, is a matter directly related to the safety and health of the urban and rural residents who are involved. Therefore, water quality cannot be over emphasized in the exploration and utilization of karst water in Shanxi to avoid water quality-induced water shortage caused by human activities in some spring catchments.

Groundwater quality evaluation

With the rapid economic development and population expansion in China, there is a shortage of water resources in many places. The pollution of drinking water sources in some cities are a serious problem, because drinking water safety is being threatened. Chinese Health Ministry and the Standardization Administration of China jointly issued the new mandatory national "Standards for Drinking Water Quality" (GB5749-2006) on July 1, 2007. The new standards carry the following three key messages: (1) the requirements of organic matter, microorganism, and water disinfection are strict, the drinking water quality indicators in new standards increased by 71 items from the original 35 items to 106 items; (2) unified the urban drinking water health standards with rural ones; and (3) drinking water standards achieved international standards. As can be seen in Fig. 5, the water quality standards in China are compatible with those of the WHO (World Health Organization) and the EU (European Union) in general. The selected key indicators include TDS, Nitrate, Fluoride, Mercury, Arsenic, E.coli and Total Coliform. Chinese alignment with international standards indicates that China attaches to its drinking water quality great importance. Moreover, China promulgated "Quality Standard for Ground Water" (GB/T14848-93) in 1994. According to the content published, the groundwater quality was divided into five Classes of I, II, III, IV and V, among them I, II and III are suitable for drinking water. Classes IV and V are not suitable for drinking water. Therefore, it is critical to fully realize the importance of meeting drinking water standards from the perspective of drinking water supply evaluation.

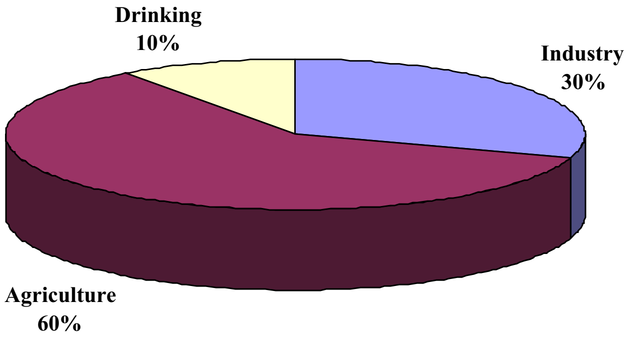

Fig. 4 The karst water consumption in industry, agriculture and drinking water

In recent years, some evaluations of the quality of karst springs in Shanxi spring catchments were made. Pingshang Spring was in line with Class III standards of "Quality Standard for Ground Water" (GB/T14848-93) and the groundwater quality was good in terms of the single index and comprehensive index (Wu 2014). The karst water quality of Lancun Spring was generally good in terms of the BP neural network model (Sun 2003). The total hardness, and sulfate in the upstream of Jinci Spring catchment, showed a gradual increasing trend (Gao 2012). The karst water of

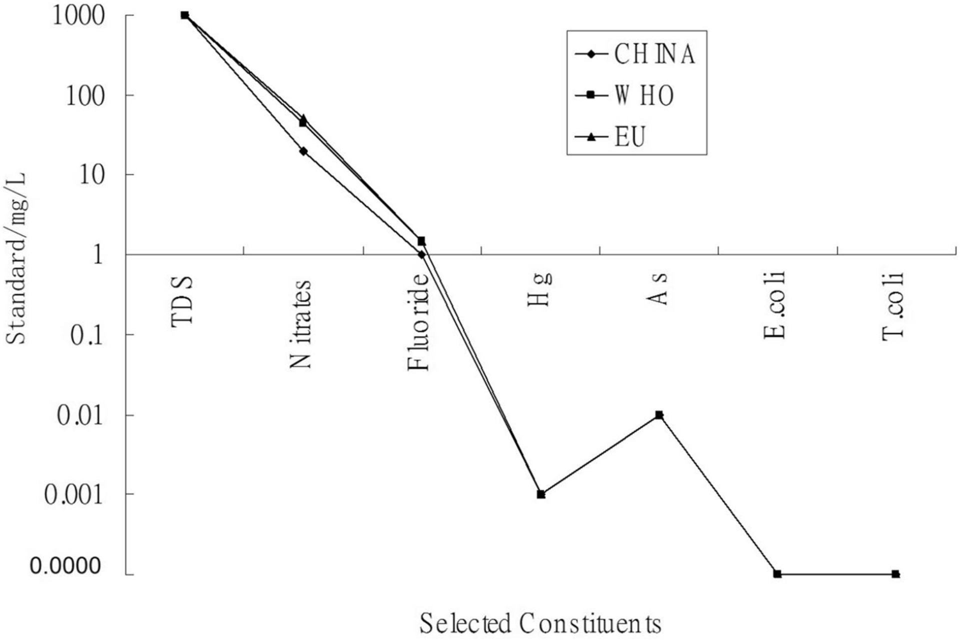

Fig. 5 The standards comparison of drinking water of China, EU and WHO

Niangziguan Spring was contaminated to varying degrees in terms of the single indicator and comprehensive indices (Yang et al. 2009). The water quality of Longzici Spring was deemed inferior to Class III "Quality Standard for Ground Water" (GB/T14848-93) in terms of the single indicator. But the water qualities of Huoquan Spring and Guozhuang Spring were in line with Class III "Quality Standard for Ground Water" (GB/T14848-93) (Jia 2009). The ArcGIS geostatistical results showed that the water quality of Xin'an Spring in temporal change followed a variation from good to poor and then back to good, and the pollution area in spatial distribution generally presented a trend of eastward diffusion (Zhang et al. 2013). The karst water of Sangu Spring was contaminated to varying degrees in terms of the single indicator (Xu et al. 2012). The karst water quality in most parts of Yanhe Spring catchment was acceptable, despite contamination being observed in isolated areas (Xu and Zhang 2008a).

To summarize the evaluation results of karst groundwater quality, it can be found that the karst water qualities in parts of Shanxi spring catchments were contaminated to varying degrees, and the protection of karst water for water supplies cannot be over-emphasized. In terms of the methods adopted for groundwater quality evaluation, the researchers made use of "Quality Standard for Ground Water" (GB/T14848-93) as the bench mark, including using the single indicator method and comprehensive indices method. It is noted that little use of national mandatory "Standards for Drinking Water Quality" (GB5749-2006) was made in the evaluation process. The reason behind this is that the researchers had not used the national mandatory standards for drinking water quality evaluation, and had not related the cost of testing 106 indices as required, to being more expensive than what can be afforded in practice in most cases. At present in China, if a groundwater sample is tested in accordance with the required 106 indices as prescribed by the standards for drinking water quality, the cost would be about US$5000. The area size of each spring catchment in Shanxi is large. Suppose that 10 karst water samples for each spring catchment are taken for analysis, accordingly the cost would amount up to US$50,000. According to the author's experience, projects are often limited by funds, which makes the required testing of 106 indices unaffordable, such as in the karst groundwater quality evaluation of Niangziguan Spring catchment, Longzici Spring catchment, Huoquan Spring catchment, Guozhuang Spring catchment, and Yanhe Spring catchment (Yang et al. 2009; Jia 2009; Xu et al. 2012; Xu and Zhang 2008a). The projects in many cases did not observe the national standards for drinking water quality. As a result, they often resorted to a limited number of sample analyses for drinking water assessment, which rendered the national mandatory standards unwanted. To secure the drinking water safety of all residents in Shanxi spring catchments, it is necessary to test and evaluate water samples according to "Standards for Drinking Water Quality" (GB5749-2006).

Evaluation of natural resources

Natural resources for a given aquifer system are the groundwater resources consisting of the components of natural recharge, interaquifer flow, surface water leakage, irrigation return flow, and snowmelt, which indicates the renewable quantity of groundwater resources within the aquifer over a certain period of time at the macro scale. According to Fan (2005), the mean annual total water resources in Shanxi is 123.8×10^8 m^3, among which the groundwater resources is 84.04×10^8 m^3, the surface water resources is 86.77×10^8 m^3, the river base flow (the repeated water) is 47.01×10^8 m^3. Hence the groundwater accounts for 67.88% of the total precipitation, while the surface water accounts for 70.09% of the total precipitation. The mean annual water resources of karst springs in Shanxi is 29.85×10^8 m^3, it accounts for 24.11% of the total water resources in Shanxi, and accounts for 35.52% of the groundwater resources. The quantification of individual spring catchments can be examined based on realistic methods under the principle of water balance. Using the discharge method and the recharge method, Han et al. (1993) claimed that they made the first attempt to evaluate the natural resources in 18 spring catchments of Shanxi, except for Leimingsi Spring catchment. Fan (2005) updated the natural resources in 16 spring catchments of Shanxi, short of Chengtouhui Spring catchment, Shuishentang Spring catchment, and Leimingsi Spring catchment, using the discharge method and the recharge method. There were individual efforts made for resources evaluation over the past years. For instance, Yi (2001) calculated the natural resources of Shentou Spring catchment using both recharge method and discharge method. Gao (2005) evaluated the natural resources of Guozhuang Spring, Longzici Spring, and Huoquan Spring using the discharge method, and calculated the natural resources of Gudui Spring using the recharge method. Cui and Cui (2007) calculated the natural resources of Leimingsi Spring using the recharge method. Xu (2008) calculated the natural resources of Xin'an Spring using discharge method. Zhang and Zhang (2008), together with Xu and Zhang (2009) evaluated the natural resources of Yanhe Spring and that of Sangu Spring using the discharge method, which was verified using the recharge method. Yang (2009) calculated the natural resources of Majuan Spring using the discharge method. Wang and Lian (2009) estimated the natural resources of Tianqiao Spring by the use of the recharge method. Du (2010) asserted the natural resources of Lancun Spring and Jinci Spring by the use of the discharge method. Bai (2012) determined the natural resources of Liulin Spring by the use of the recharge method and the discharge method. Wu (2014) assessed the natural resources of Pingshang Spring using the discharge method. Liu et al. (2014) calculated the natural resources of Hongshan Spring using the recharge method and the discharge method, and did verification through the water balance check.

It can be seen that nearly 95% of the 19 major spring catchments are evaluated to account for the natural resources. However, the degree of the evaluation varies from one catchment to another. At present, either recharge method or discharge method was used in most spring catchments, and both methods were jointly used only in limited spring catchments. The recharge method and the discharge method are based on the annual average flux of recharge and discharge, with the assumption that the fluxes are stationary, which ignores the fact that the natural fluxes can vary widely within the time periods considered. Due to the uneven temporal and spatial distribution of precipitation over the Shanxi spring catchments, the natural resources differ from dry season to wet season. If one heavily relies on only two methods for the evaluation, it is bound to cause either over-exploitation of karst water during dry season or under-exploitation during wet season. Although this approach seems to balance out within a hydrological year, it was observed that groundwater levels in the aquifer showed continuous decline for the long run in most spring catchments of interest. The limitations of the recharge method and discharge method for use in the evaluation of natural karst water resources will be discussed later in this paper.

Evaluation of exploitable resources

Exploitable resource is the maximum karst water quantity allowed to be abstracted from a karst aquifer under the condition of economic and technical feasibility without causing negative impacts geologically, environmentally and ecologically. Examples of such impacts are: the continuous decline of karst groundwater level, deterioration of water quality, and karst collapse. As can be seen from Fig. 6, the confined karst aquifer in a spring catchment, if the piezometric surface of karst groundwater is higher than the rational piezometric surface, it can ensure sustainable abstraction of the exploitable resource. If the piezometric surface is between the rational piezometric surface and the top of aquifer, it implies that the confined aquifer is in the state of excessive exploitation. If the piezometric surface in a confined aquifer runs below the confining layer, there would be two restrictive water levels in the aquifer, one for maintaining the spring, and the other for characterizing the water supply. If the groundwater level is lower than the water level restriction for early warning for the spring, the spring would cease to flow. If the groundwater level is lower than water level restriction for water supply, it would do great harm to the karst water resources of the spring catchment, such as the current water level found in Jinci Spring, which is well below the ground surface. Accurate determination of the exploitable resources of karst water is critical for sustainable utilization of karst water in Shanxi. Using frequency analysis method, attenuation coefficient method, and the correlation analysis method, Han et al. (1993) evaluated the exploitable resources in 18 spring catchments of Shanxi, except those of the Leimingsi Spring catchment. Fan (2005) investigated the exploitable resources in 16 spring catchments of Shanxi, except those of the Chengtouhui Spring catchment, the Shuishentang Spring catchment, and the Leimingsi Spring catchment, by

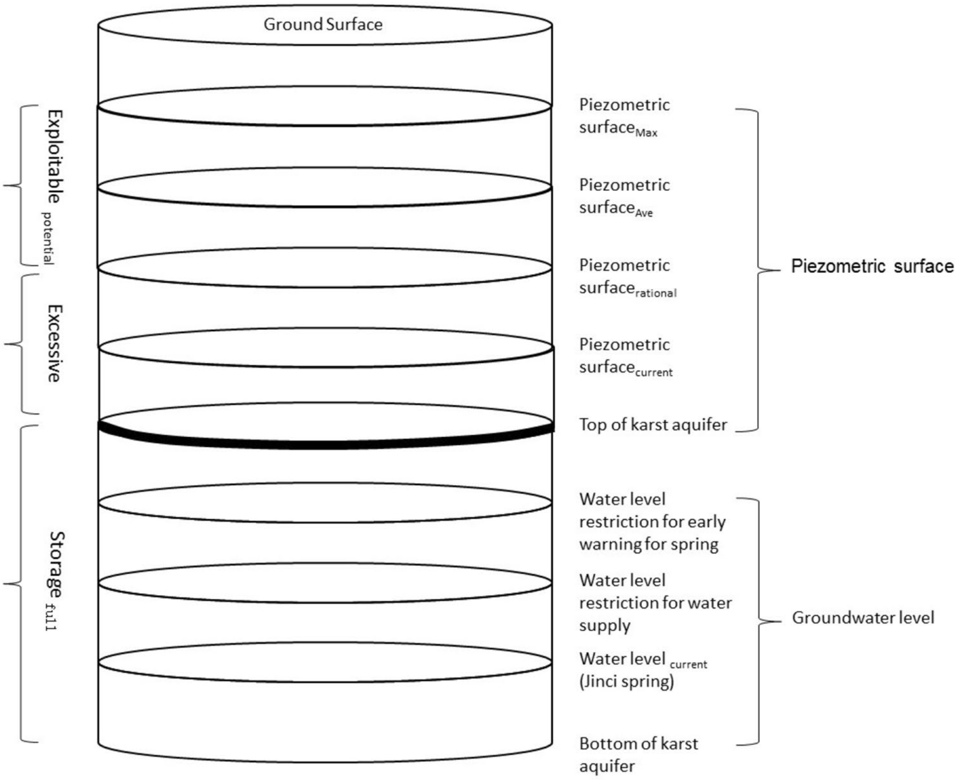

Fig. 6 Conceptualized exploitable water resources in karst aquifer system

the use of Theoretical Frequency Method and Attenuation Coefficient Method. By the use of the Boussinesq Equation, Wang and Yan (1998) calculated the exploitable karst water resources of the Shentou Spring catchment. Using an optimized evaluation management model, Liang and Han (2006) calculated the exploitable karst water resources of the Niangziguan Spring catchment. Using the frequency analysis method, Yang (2009) calculated the exploitable karst water resources of the Majuan Spring catchment. By the use of the recharge method, Wang and Lian (2009) calculated the exploitable karst water resources of the Tianqiao Spring catchment. Using a numerical method, Han et al. (1994b) calculated the exploitable karst water resources of the Sangu Spring catchment. By the use of a numerical method, Zhang (2009), Liu and Zhang (2009), calculated the exploitable karst water resources of the Yanhe Spring catchment and the Sangu Spring catchment. Using the theoretical frequency method, Wang and Zhang (2010) calculated the exploitable karst water resources of the Longzici Spring catchment. By the use of the theoretical frequency method, Yao et al. (2011) calculated the exploitable karst water resources of the Guozhuang Spring catchment. Using the frequency analysis method, Wang (2015) assessed the exploitable karst water resources of the Chengtouhui Spring catchment.

According to the above-listed cases, 18 out of 19 spring catchments were evaluated for exploitable karst water resources in the region. This is about 95% completed for all 19 catchments, which indicates that much attention has been paid to the evaluation of exploitable resources. At present, the frequency analysis method, the attenuation coefficient method, the correlation analysis method, the optimal management method, and the numerical simulation method are often used in the determination of the exploitable karst water resources. Although some results were obtained with the change of spring catchment conditions, the effort still needs to be carried out to fully ensure the sustainable utilization of karst water in all spring catchments. As pointed out by Seward et al. (2006), the exploitable karst water resource depends on the increased recharge and the decreased discharge under the conditions of pumping. If the evaluated quantity, which was determined by the methods mentioned above, is greater than the exploitable karst water resources within a spring catchment, the water resources development agencies or departments would accept a developmental plan as if everything was done properly. However, many cases indicated this approach led to an unsustainable utilization of karst water. For instance, the cessation of Jinci Spring flow was due to unreasonable evaluation of the exploitable karst water resources, which led to excessive exploitation. Therefore, it is very necessary to have a closer examination of the current methods which are used to evaluate the exploitable karst water resources of the spring catchments.

Water chemistry and environmental isotopes with purposing assession

Water chemistry

The chemical characteristics of groundwater in Shanxi spring catchments was in a status of constant variation, which attracted much attention. Tang et al. (1991) analyzed the water chemical composition and water chemistry type of Shanxi karst springs. Han et al. (1993) discussed the water chemical characteristics of 18 spring catchments in Shanxi except the Leimingsi Spring catchment. A three liner graph of karst water chemistry of the Tianqiao Spring catchment was plotted (Cao et al. 2005). Zheng (2004) pointed out that the characteristics and types of water chemistry of the Lancun Spring catchment are variable. Using the hydrogeochemical method in combination with multivariate statistical theory and computer simulation technology, Zang et al. (2015b) made an assessment of the dominate hydrogeochemical processes in the Liulin karst groundwater system. According to Li et al. (1998), the high concentration of SO_4^{2-}, Ca^{2+} and Mg^{2+} in the Niangziguan Spring catchment was mainly caused by gypsum dissolving, and sulfide oxidation in the aquifer bed. Karst water pollution was related to the natural environmental conditions, including the impact of human activities and the change of water cycle conditions (Huo 2015). Coal was a main contributor of polycyclic aromatic hydrocarbons to the karst water system of Guozhuang Spring (Shao 2014). Karst water hazards of concern within Guozhuang Spring were mainly the total hardness, fluoride, volatile phenol, sulfate, high TDS, iron, NO_2, COD, Cl and Mn (Wang et al. 2008). Water pollution in Longzici Spring catchment was mainly due to the discharge of industrial wastewater and domestic sewage (Zhao 2006). Guo et al. (2003) studied the major ion geochemistry of groundwater in the Shentou Spring catchment, and pointed out that the variation pattern of TDS, HCO_3^-, SO_4^{2-}, Ca^{2+}, Mg^{2+} contents of karst water samples can be explained by the karst water flow directions. Qin and Li (2008) analyzed the functional relationship between the content of erosive CO_2, mineral saturation index in karst water, and the top elevation of Ordovician limestone in the Yanhe Spring catchment. When the pollution sources were located in the recharge and runoff areas of the spring catchment, the pollution in the recharge and runoff areas was serious, as opposed to that in the runoff and discharge areas of the spring catchment; when the recharge, runoff and discharge areas of the spring catchment suffered from large pollution sources, the pollution became a serious concerned (Wang 2005).

It can be seen that some work has been done in understanding karst water chemistry of the Shanxi spring catchments, which provide essential references for the pollution prevention and protection management of the karst water. But less attention has been paid to account for both the AMD caused by coal mining and the effect of organic pollutants produced by human activities on karst water chemistry in spring catchments, which would undoubtedly need further effort for karst water protection in Shanxi spring catchments.

Environmental isotopes with purposing assession

Environmental isotopes can play a role in marking and dating of groundwater as their traces can provide important information for understanding the relationship between groundwater and the host rock media (Xu 2001). Up to now, some research projects were carried out in Shanxi spring catchments by the use of isotopes. According to the data of radioactive isotopes, Shi et al. (1988) estimated the ages of karst groundwater of Jinci Spring and Lancun Spring in the Taiyuan region as 318 years and 6117 years, respectively. Using the signal of the environmental tritium isotope in the northern hemisphere, Lian et al. (1988) calculated that the average residence time of karst water in the Guozhuang Spring catchment is 125 years. Using the environmental isotope method, Gong and Fu (1994) calculated the age, storage, precipitation infiltration coefficient, river leakage, and gypsum denudation rate of the karst groundwater in the Xin'an Spring catchment. Li and Wang (2003) studied that the temporal-spatial variation of ^{34}S in the Niangziguan Spring catchment and concluded that the higher sulfate concentrations were caused either by dissolved gypsum in the aquifer or by pyrite oxidation in coal-bearing formations, or both. The strontium isotope characterization of the Shentou Spring catchment was investigated by Wang et al. (2006), which suggested that the average values of the ratios of $^{87}Sr/^{86}Sr$ in the karst water decreased from the recharge area (0.7107) to the discharge area (0.7102). Zang et al. (2015a) analyzed the characteristics of the karst groundwater flow system in the Liulin Spring catchment through isotopic tracing (delta H-2, delta O-18, delta C-13 and H-3) and dating approaches (C-14), which confirmed that the primary source of recharge to the karst groundwater was from precipitation.

By comparison, the use of the isotopic analyses for understanding of the karst water in Shanxi spring catchments is still in its infancy. At present, there are six spring catchments, such as Jinci Spring catchment, Lancun Spring catchment, Niangziguan Spring catchment, Guozhuang Spring catchment, Shentou Spring catchment, and Liulin Spring catchment, where isotopic studies were carried out. This is about 32% coverage out of 19 spring catchments. The weak coverage may be related to the less of demand for the isotopic data and information required for the development and utilization of karst water by the relevant official departments. To effectively obtain the hydrogeological information of karst spring catchments in Shanxi, the use of the environmental isotopic analyses could be strengthened for providing better scientific information.

Aquifer integrity

Vulnerability

At present, many countries and regions in the world are facing water shortage problems. Due to the impact of irrational human activities, the reduction of water resources compounded by water pollution has severely affected the sustainable utilization of regional water resources. At the same time, climate change is changing the spatio-temporal status of water resources. These factors have exacerbated the vulnerability of water resources. To ensure the safety of water resources, especially in arid and semiarid regions, it is very necessary to assess the vulnerability of water resources in Shanxi where the mean annual precipitation is under 500 mm. Through the vulnerability assessment of water resources, on the one hand it can play an early warning role for the protection and development of water resources, on the other hand it can provide guidance to water resources management departments. In recent years, more attention was paid to karst water vulnerability of karst aquifer systems in Shanxi spring catchments. Using the COP method, Jin et al. (2014) obtained that the vulnerability of the karst aquifer of Shentou Spring catchment is low overall, and that it is not easy to be polluted. In the areas where limestone is exposed, and in the spring source area, the vulnerability is relatively high. Hao (2015) constructed the TURSLI vulnerability assessment model of water quality and the LMt vulnerability assessment model of water quantity for the Shentou Spring catchment, and obtained the vulnerability zoning maps of water quantity and water quality of the karst aquifer by the use of GIS platform. Using the Numerical Simulation Method, Wang (2012b) carried out the quantitative assessment of water quantity vulnerability of the karst aquifer in Niangziguan Spring catchment. By the use of the Fuzzy Comprehensive Evaluation method under the framework of the European Vulnerability Assessment method, Zhao et al. (2013) identified that the easily polluted areas of the Niangziguan Spring catchment are mainly distributed in the exposed area of spring groups and that the extremely difficult polluted areas are mainly distributed in the west regions of Yu County, Yangquan, Pingding, Xiyang, and Heshun. Groundwater vulnerability of a coal mine in the Guozhuang Spring catchment has an increasing trend from the middle to both sides of the mine area under conditions of coal mining (Pang 2015). Using the modified PI model, Zhang et al. (2016) assessed the vulnerability of karst water in the Jinci Spring catchment, and pointed out that the most vulnerable area is in the exposed limestone area seepage section of the Fenhe River, and the coal seam pressure mining area. By applying the modified RISKE model, Yang et al. (2016) evaluated karst groundwater vulnerability of the Xin'an Spring catchment, and concluded that the vulnerability of the spring source area and the river leakage section are the highest.

The coverage of vulnerability assessment of Shanxi spring catchments was about 26%, which is very limited, as they were mainly in the Shentou Spring catchment, the Niangziguan Spring catchment, the Guozhuang Spring catchment, the Jinci Spring catchment, and the Xin'an Spring catchment. It is noticed that the choice of index system, evaluation index, weight, scoring criteria, and evaluation methods selected by the researchers seemed subjective. Some took consideration of either the water quality vulnerability or water quantity vulnerability, and others took consideration of both aspects of the quality and quantity aspects. Despite these results providing useful references for the management of karst water in the spring catchments, the reasons for the low level of vulnerability research in Shanxi spring catchments would be that the karst water vulnerability has not served as a management tool for decision makers. Further, there may be a lack of common principles for karst water vulnerability assessment, as Shanxi has been a region of water scarcity, heavy coal mining, rapid urbanization, and sewage drainage. It is a matter of urgency to strengthen the vulnerability assessment in all spring catchments.

Impacts of coal mining and engineering activities on karst groundwater

At present, the impacts of human activities on groundwater mainly lie in (1) water depletion caused by excessive exploitation of groundwater; (2) groundwater pollution caused by the emission of industrial wastewater, waste gas, solid waste and sewage, which were not up to standards; (3) the decrease of groundwater quantity and deterioration of water quality caused by mining activities; (4) groundwater pollution caused by the heavy application of pesticide and fertilizer; and (5) groundwater pollution caused by engineering construction activities. For Shanxi spring catchments, there exists a lot of coal mining and engineering construction activities within environmentally fragile karst regions, which have had, and will still have serious impact on karst water in the spring catchments in questions. Therefore, special attention must be paid to the impact of coal mining and engineering construction. Zhang (2011) assessed the impact of coal mining on the water environment of the Shentou Spring catchment from four aspects, such as surface water, groundwater, water for rural residents, and solid waste. Hao (2008) thought that coal mining may cause the depletion and serious water-quality degradation of Leimingsi

Spring. Zhang (2014a) concluded that the open cast coal mining in non-key protected areas of the Tianqiao Spring catchment does not affect the recharge, runoff and drainage conditions, which has little effect on water quantity. Wang and Zhang (2014) indicated that the construction project of Taiyuan Steel General Hospital had little effect on the water environment of the Lancun Spring catchment after taking the treatment measures. Piao and Zhou (1998) pointed out that the coal mining with certain pressurized aquifer conditions, like in Xiyu coal mine, would have no effect on Jinci Spring. Using a numerical method, Shen and Zhang (2015) concluded that the dewatering of pressurized karst water in Ermugou coal mine had a big impact on the karst water of the Hongshan Spring catchment. He et al. (1999) pointed out that the construction of Wujiazhuang Reservoir may slightly increase the recharge in the Xin'an Spring catchment and that it will not cause deterioration of karst water quality. Tian (2012) thought that coal mining and dewatering would gradually pollute the karst water of the Xin'an Spring catchment. Chang (2010) analyzed the influence of the new Taixing Railway on the water environment of the Liulin Spring catchment. Wang (2011) researched the impacts of coal mining on the water environment of the Guozhuang Spring catchment. Tian (2016) analyzed the effect of the nano-material project on the water environment of the Sangu Spring catchment. Zhang (2016) studied the impact of a gas pipeline project on the water environment of the Chengtouhui Spring catchment.

In general, coal mining has impacted the karst water of Shanxi spring catchments in different ways and extents. It is suggested that prevention and protection measures be put in place to mitigate any karst water reduction and pollution. But, the impact of other engineering constructions on karst water cannot be ignored. At present, there is an insufficient research focused on the impact of coal mining and engineering construction on karst water, which has occurred mainly in 11 spring catchments, such as Shentou Spring catchment, Lancun Spring catchment, Jinci Spring catchment, Leimingsi Spring catchment, Tianqiao Spring catchment, Hongshan Spring catchment, Xin'an Spring catchment, Liulin Spring catchment, Guozhuang Spring catchment, Sangu Spring catchment, and Chengtouhui Spring catchment. For the remaining eight spring catchments little has been done, or has not been reported in literature. The current coverage of 58% of the 19 catchments is only concerned with the situation of the water reduction and pollution. There seems a lack of in-depth research on the mechanism of water inrush from coal mining floors and contaminant transport. Therefore, research on the impact of coal mining and engineering construction on karst water must be further strengthened.

Delineation of spring catchment sub-systems

To analyze the direction and flux of groundwater flow, which can be sub-divided into strong and weak runoff zones accordingly, and finally to delineate the karst water system, it is necessary to demarcate spring catchment sub-systems. Wang et al. (2003) commented that a traditional delineation of a karst water system is based on the observation of groundwater level, together with the regional hydrogeological conditions, and to plot a water level contour map of the spring catchment. For the karst water system of Shanxi spring catchments, there are often several sub-systems within any of the 19 catchments due to the different conditions of the individual catchments. The realistic delineation of sub-systems is very helpful for the rational development and adequate protection of karst water in the spring catchments. Based on the analysis of geological structure and the conditions of recharge, runoff and discharge, Han et al. (1994a) delineated the Sangu Spring catchment into four sub-systems. According to the relationship between c(Sr)/c(Ca) and the concentration of total dissolved solids, Guo and Wang (2006) delineated the Shentou Spring catchment into three sub-systems. Based on the hostrock settings of groundwater storage, the hydrodynamic relationship of recharge and discharge, water chemistry and environmental isotopes, Cheng (2003) delineated the Pingshang Spring catchment into three sub-systems. Based on the structural geology and hydrogeological settings, Taiyuan's karst groundwater system was divided into three sub-systems, such as Xishan, Dongshan and Beishan (Zhao and Cai 1990; He et al. 1997). Using a geographic information system technique, Han et al. (2006) concluded that the karst water system of the eastern and western mountain areas in Taiyuan can be delineated into three sub-systems, and Jinci Spring and Lancun Spring belong to the same regional flow system rather than to two separate groundwater system as is generally postulated. By the use of the international program MODFLOW of groundwater numerical simulation based on systematic analysis of the uncertainty of conceptual model, Xia (2011) established a distributed model of the karst groundwater system of the Taiyuan area claiming that there is no so-called variable boundary between Jinci karst water system and Lancun karst water system; this is consistent with Han et al. (2006), but contrary to Zhao and Cai (1990) and He et al. (1997). Using multiple isotopes and water chemistry methods, Sun et al. (2016) confirmed the reasonableness of dividing the Taiyuan karst groundwater system into three sub-systems. According to the results of isotope hydrogeology, Gong et al. (1994) delineated the Xin'an Spring catchment into three sub-systems. Based on the values of c(Sr)/c(Mg), c(Sr)/c(Ca), Wang et al. (2003) delineated the Yanhe Spring catchment into three sub-systems.

In a short, only 26% of 19 catchments have been subdivided in Shanxi. In one of the studies, Jinci and Lancun springs are suggested to share the same catchment (Han et al. 2006). The sub-divisions are related to the complex geologic settings of the karst water system in each spring catchment involved. At present, the methods used in the delineation of the spring catchment sub-systems mainly include the water chemical method, GIS (geographic information system) technique, isotope method, numerical simulation method and integrated method. Except for the integrated method, the other methods are relatively simple, which are not convincing upon their own. Therefore, it is necessary to explore a realistic methodology to delineate the sub-systems of karst spring catchments in Shanxi.

Protection and management measures

Delineation of protection zones

Over the past three decades, karst spring catchments in Shanxi have suffered from karst environmental hydrogeological problems such as reduced spring flow, declining groundwater levels, water contamination and pollution. To prevent these problems from getting aggravated, it is very necessary to implement protection measures in all important spring catchments. At present, delineation of protection zones is deemed as one of the most effective measures for karst water protection. Implementation of the delineated protection zones not only can protect water quality and water quantity of the karst aquifers, but it also can conserve water resources in the spring outcrop areas and in its tourism functions. The key protected areas in 19 karst spring catchments were delineated, which is mainly to protect the spring source and the river leakage section (Water Resources Management Committee Office of Shanxi Province 1998). Based on the self-purification capacity of the regional ecological environment, sewage separation capacity of the covering layer, and environmental capacity of karst aquifer, Ning et al. (1999) delineated the Shentou Spring catchment into three zones away from the spring issuing point. Hao et al. (2006b) delineated the Niangziguan Spring catchment into three zones away from the spring issuing point, among them, the confluence of the 11 spring systems and the discharge areas were defined as level-I protection zone, the recharge basin was level-II protection zone, and the slack water area where there is little surface recharge was the level-III protection zone. On the basis of dynamics principle, bacteriological die-off principle, and protection principle of the aquifer impermeable layer, Wang et al. (2008) delineated the Hongshan Spring catchment into the key protected zone and the general protected zone. According to the objectives and principles of protection, Liang et al. (2008) delineated the 19 karst spring catchments into spring source protection zone, water-quality protection zone, water-quantity protection zone and coal mine-pressurized protection zone. Guozhuang Spring catchment, Longzici Spring catchment, Xin’an Spring catchment, and Yanhe Spring catchment were also delineated into spring source key protection zone, water-quantity protection zone, water-quality key protection zone and coal mine pressure protection zone (Jia 2009; Li 2013; Zhang et al. 2011). Based on vulnerability assessment, Zhao et al. (2013) delineated separate protection zones for water quality and water quantity as well in the Niangziguan Spring catchment. In the cases of Jinci and Lancun spring catchments, Qiao et al. (2015) analyzed the influence of heterogeneity on groundwater flow simulation and wellhead-protected area delineation, which showed that stochastic methods could be used to generate a series of possible head distributions and to delineate a series of capture zones when compared with homogeneous methods.

In general, previous works have made efforts in the delineation of karst water protection zones in Shanxi spring catchments, which has laid a certain basis for consideration of protection. For the conventional delineation, namely the key protection zone or three-level protection zones, the main objective was to protect for water quality of the both degradable and persistent, which took little consideration of the characteristics of aquifer. For instance, Hao et al. (2006a) only considered the pollution sources, without consideration of other conditions. For the current delineation of spring source key protection zone, water-quantity protection zone, water-quality key protection zone and coal mine-pressurized protection zone, the main objective was to protect not only for water quality but also for the other parameters of resource quality such as water quantity, spring water level and its natural landscapes, which is deemed for resource quality objectives. Whether or not it is the conventional delineation of protection zones or the current delineation of protection zones, it would not be sufficient in the delineation of the scope of water-quality protection zones unless due consideration is given to the heterogeneity and anisotropy of the karst aquifer in the spring catchments. There is often a turbulent flow phenomena deduced in some cavities within some spring catchments, if the water quality protection zone is delineated according to Darcy’s law, the delineation of the scope of water quality protection zone would be unrealistic or too small, which may eventually lead to improper management decision making. Therefore, how to realistically delineate karst water protection zones can still be improved.

Management measures

Effective protection and management, the sustainable development and utilization of karst water can only be ensured through implementation of protection zoning with efficient management measures in place, which aims to avoid serious karst environmental problems. “Water Resources Protection Regulations of Spring Catchments in Shanxi Province” was issued in 1997 after cessation of Jinci Spring in 1994. This regulation provides some guidance for the protection and management of karst water in the region. In the past two decades, many workers took into account the reality of the resources of Shanxi spring catchments and put forward the protection and control measures for the spring catchments, which included water resources management, rational planning of water resources, water resources optimal allocation, control of groundwater development, curbing of pollution sources, prevention and control of water pollution, groundwater dynamic monitoring, strict implementation of the approval of coal mines and other projects. These measures can provide a step by step process for water resources management departments to carry out the protection and management measures for karst water (Han et al. 1993; Liu 2005; Jian 2007; Zhang et al. 2012; Zhao 2014; Chen 2006b; Bai 2010; Yang 2013; Li 2005; Zhang 2007; Song 2001; Cheng 2014; Ji 2006).

Although the protection and management of karst water in Shanxi spring catchments have been much talked about, the current proposed measures are not yet efficiently implemented as they are merely referred to as guidelines at levels of macro policy and qualitative standards, which lack actual measurable specifications to be implemented for the protection and management of karst water. The water resources system of a karst spring catchment is a complex one, as the causes of environmental problems are of multiple origins. Therefore, to truly protect and manage the karst water in the spring catchments, greater efforts need to be made in the framework of integrated water resources management.

Problems and difficulties

Based on the above discussion, it is clear that karst water occupies a very important position in the development and utilization of water resources in Shanxi Province. But exploitable resources are constrained by many factors and water quality is also being contaminated and polluted to various degrees in some parts of Shanxi spring catchments. It is reasonable to state that the impacts of human activity on karst springs in Shanxi are a factor of primary concern, whereas climate change is the secondary impact factor. The impacts of human activity on Shanxi karst springs were mainly manifested in the form of the wide distribution of wells within the spring catchments, dewatering of coal mines, and other engineering activities for infrastructures. The impact of climate change on Shanxi karst springs was mainly manifested in the form of reduced precipitation. Although much effort has been made on the characteristics of the spring catchments and the attempts to protect and manage the scarce water resources in Shanxi from different perspectives, due to the impact of geological and hydrogeological conditions, and the limitation of project coordination, it will still require improvement in the following aspects.

Issues of head water

Little attention has been paid to Leimingsi Spring and Tianqiao Spring, which feed Fenhe River and Yellow River, respectively. Leimingsi Spring is a head water of Fenhe River (Fig. 1), the largest tributary in Shanxi Province. The Fenhe River used to run through karst terrains in Shanxi, where it was one of the main recharge sources to Jinci Spring, Lancun Spring, and Guozhuang Spring (Du 2010; Gao 2002). This traditional role has changed due to construction of the Fehhe Reservoir upstream of the river reach where leakage took place for Jinci Spring and Lancun Spring. The investigation of such an impact of the reservoir on Leimingsi Spring head water could be re-examined. The artesian flow of Tianqiao Spring contributes to the Yellow River through its riverbed (Cao et al. 2005). Due to this factor, there is no actual measured data of the spring flow that exist. Despite this, an attempt was made to estimate its flow maginitude, if successful this is still unlikely to add much in account for evaluation of natural and exploitable karst water resources for the Tianqiao Spring catchment. Therefore, alternative methods need to be devised to improve accuracy of the karst water resources evaluation for both Leimingsi Spring and Tianqiao Spring. Some investigations placed focus on spring flow forecast, but it is also a lack of effective means to test and verify the forecast results of the model employed. The karst water systems in Shanxi are evolving dynamic systems. As the spring flow or discharge is an important indicator to reflect the status of the karst water environment in the spring catchment, there needs to be a set of systematic criteria for the assessment. At present, the methods used to predict spring flow mainly rely on statistical methods rather than hydrogeological principles or both combined. The statistical method cannot specifically incorporate the hydrogeological conditions of the spring catchment involved, or the degree of human disturbance into the evaluation. Therefore, research of spring flow based on the combined approach is recommended.

Infiltration recharge and residence time estimates

Since the infiltration coefficient method used in the study of precipitation infiltration recharge of karst water is relatively simple and infiltrate rates are difficult to measure, this renders recharge estimates difficult to be verified, which would affect the accuracy of natural resource estimates. The methods used in the estimation of the time-lag of precipitation recharge were mainly based on gray theory (Wang 2007;

Fan et al. 2012; Hao et al. 2012; Li et al. 2011) and statistical regression method (Zang et al. 2013), which were used to determine the cross-correlation between precipitation time series and spring flow time series. Of course, the cross-correlation is indeed an effective method to be used to determine the time-lag between the two time series. If the time-lag is only determined by the maximum correlation degree or the maximum correlation coefficient of the two time series or by even very effective cross-correlation analysis, the time-lag thus so obtained may not represent the real-time-lag of the precipitation recharge without a comprehensive consideration of the influence of recharge mechanisms, the degree of karstification, groundwater flow velocity, and the distance from recharge area to discharge area (Bai 2012). If the model cannot be calibrated with hydrogeological settings, the model would not forecast spring flows meaningfully. It is noticed that attention was paid to the temporal and spatial variations of karst groundwater level (Wang and Wang 1998; Cao et al. 2005; Pang et al. 2014; Kang 2004; Wang 2012b) and its influencing factors (Xu and Zhang 2008b), but effort on the delineation of uniform units of karst groundwater levels is still required.

Integrity of resources evaluation

The groundwater quality was mainly evaluated from the perspective of drinking water supply. Although "Quality Standard for Ground Water" (GB/T14848-93) was consulted to carry the evaluation. The evaluation method was relatively simple, most of the assessors made use of the single indicator method and multiple indices method (Wu 2014; Yang et al. 2009; Xu et al. 2012). Some investigators used BP network model (Sun 2003) or ARCGIS geological statistical model (Zhang et al. 2013), which could be combined with others to offer an integrated methodology to ensure that the evaluation results would be accurate and realistic. At the same time, due to the funding and other unforeseen reasons, the results of the evaluation of drinking water quality as set by the national mandatory "Standards for Drinking Water Quality" (GB5749-2006) are still unavailable, which led to the situation that the status of karst water quality cannot be fully understood. The conventional recharge method or discharge method are mainly used in the evaluation of natural resources (Yi 2001; Wang and Lian 2009; Gao 2005; Xu and Zhang 2009; Zhang and Zhang 2008). Having regarded the natural resource as a fixed value, they did not consider that the natural resource would be changing with the seasons, this would inevitably affect the sustainable utilization of karst water in the dry period. In the evaluation of exploitable resources, most of the methods were not based on the groundwater balance (Eljkovi and Kadi 2015). Some investigators did not seem fully value the fact that the exploitable resources are determined by the capture principle (Seward et al. 2006). For the Shanxi spring catchments, few investigators paid attention to the establishment of the rational piezometric surface of a confined aquifer for early warning purposes. Equally, few investigators paid enough attention to the water level restriction for early warning for maintaining spring flow and water level restriction for water supply if a confined aquifer, after being over-exploited, turns into the unconfined condition. As a result, the findings cannot be effectively used to guide the sustainable development and utilization of karst water in the future. However, the exploitable resources highlight the ecological and environmental factors and emphasize the renewable capability and sustainability of the sustainable exploitable resources (Sophocleous 2000). Once the abstracted water quantity exceeds more than the recharge that would be captured, it may cause problems such as the river drying up, the decline of groundwater level, deterioration of water quality, and degradation of aquatic ecosystem. Once the abstracted water quantity remains less than the recharge that would be captured, the exploitable resources may not be fully used for community growth and economic development within the spring catchments of concern. Therefore, further work on the evaluation of drinking water quality, natural resources and exploitable resources needs to be stressed.

Problems of AMD

In the face of the situation of coexistence of coal and water in Shanxi spring catchments where karst aquifers lie beneath the coal seems, there is still much needed work to be done in understanding and management of karst water pollution caused by AMD (Geldenhuis and Bell 1998; Paikaray 2015). For example, AMD of a coal mine in the region of Shandi Village in the suburb of Yangquan City decanted from the ground shafts to the surface, which flowed about 1 km downstream, and seeped into the exposed area of the lower Ordovician limestone. If AMD is not treated properly, it will cause severe environmental pollution. The problems of karst water pollution caused by AMD are detrimental and persistent. If the pollution is widespread, the treatment would be very difficult; especially after the mine is closed and abandoned, and with the rise of water level and the increase of water quantity of AMD in the gob. The potential threat to the underlying karst water would be high risk, but these problems have not been given much attention by the local government management departments, coal mining enterprises, and investigators. The efforts on the mechanisms of karst water pollution caused by AMD and its treatment in Shanxi spring catchments are still required, although some workers treated AMD in Shanxi coal mines by the use of loess, artificial wetlands, and microorganisms (Zhao et al. 2007; Zhang et al. 2007; Zhao et al. 2012). Due to the differences and complexity of geological, hydrogeological conditions of Shanxi spring catchments, these methods are not easy to be applied and promoted. As the treatment of AMD is a worldwide problem, solving AMD in Shanxi spring catchments would contribute towards ongoing global discussion on the matter.

Aspect of water chemistry

In the understanding of water chemistry, investigators carried out research projects to delineate hydrochemical characteristics (Cao et al. 2005; Tang et al. 1991; Zheng 2004), hydrogeochemical processes (Zang et al. 2015b), and the reasons of groundwater pollution (Huo 2015; Shao 2014; Zhao 2006). But, the shortcomings seemed that most works were mainly aimed at the evaluation of the status of karst water chemistry, which did not address the examination of the water chemical evolution and prediction of its future trend. In addition, due to excessive coal burning and oil spillage within Shanxi spring catchments, a lot of organic pollutants were produced and eventually introduced into the karst water, which will bring potential risks to the water supply in all the spring catchments involved. But at present, there is not enough attention being paid to the persistent organic pollutants (Shao 2014) in Shanxi spring catchments. Few indicators for the organic pollutants were considered in the evaluation of groundwater quality, which leads to data on organic pollutants being very slim, or the information is incomplete, and adds difficulty to the control and prevention of organic pollutants in many cases. In the research of the environmental isotopes, the tritium isotope (Lian et al. 1988), ^{34}S (Li and Wang 2003), strontium isotope (Wang et al. 2006), isotopic tracing and dating approaches (Zang et al. 2015a) were used to aid with the estimation of the residence time of karst groundwater and the storage capacity, the origin of sulfate, and the origin of groundwater. But the isotopes have not been widely used to investigate the karst water in the spring catchments, which led to a shortage of isotopic data and information in the spring catchment, and brought the time-lag to the follow-up research.

Methods of vulnerability assessment

In the vulnerability assessment of spring catchments, there was no consensus method for use in the indicator tally, as the researchers made use of various methods in terms of the calculation method, the grading standards and the classification standards (Hao 2015; Zhao et al. 2013; Pang 2015). This inconsistency already led to the situation that comparison of the calculation results cannot be made. For instance, when assigning an assessment weight of the indicator, the subjectivity of individual authors may be biased, leading to the inaccurate ranking of vulnerability of an aquifer of interest. As the area sizes of 19 spring catchments range from 377 to 10,950 km^2 (Water Resources Management Committee Office of Shanxi Province 1998), the issue of scale must be considered in the vulnerability assessment, such as how to choose an appropriate scale. A damage threshold as suggested by Seward (2010) can be adopted in karst water system in the spring catchment, but the threshold is theoretically a range. In many cases, the vulnerability classes were grouped in the lowest, low, moderate, higher and highest vulnerability (Jin et al. 2014). A similar classification includes extremely difficult to pollution, more difficult to pollution, a little difficult to pollution, easier to pollution and extremely easy to pollution (Zhao et al. 2013), which are almost identical to the former classes. However, either classification is relative in nature and fails to identify a range where the vulnerability can be accepted for sustainability according to the threshold principle.

Impact of mining activities

In the understanding of the impacts of coal mining and engineering construction on the karst water in Shanxi spring catchments, there are also some shortcomings. On the one hand, rich coal resources occur within the spring catchments, and many mining areas belong to the area under high pressure of karst groundwater. Once the karst water inrush from coal seam floor occurs (Pan et al. 1999; Lu and wang 2015; Zhang et al. 2015), it would cause great damage to the spring catchments involved. But according to previous works (Zhang 2011; Hao 2008; Shen and Zhang 2015; Tian 2012), little research was carried out on the aspects of the evolution, distribution law, penetration ability of the karst medium and water conducting channel, as well as, the development law, and mechanical characteristics of the fracture and collapse column. This gave rise to a situation of poor guidance for the prediction and control of water inrush from the floor in the process of coal mining. On the other hand, there is a lot of engineering construction taking place in Shanxi spring catchments, which have generated a large amount of sewage and waste water. In the exposed karst area or the covered karst area, the contaminants can easily find their way into the karst aquifers, which would cause karst water pollution. At present, there is insufficient research being carried out on the prediction of migration and dispersion of these pollutants in the karst aquifer, which renders difficulty to guide the prevention and control of karst water pollution.

Criteria of delineation of sub-systems

In pursuing the delineation of spring catchment sub-systems, there is not yet a relatively uniform principle for use in the delineation so far. Using different research methods, investigators delineated the spring catchments into sub-systems (Guo and Wang 2006; Cheng 2003; Gong et al. 1994; Wang et al. 2003). But the sub-systems could not yet be cross-referenced by other methods to confirm each other. The investigators often made the delineation according to the features of water chemistry or isotopic data. In fact, the features of either water chemistry or isotopes are a necessary condition for such delineation of sub-systems, but it is not a sufficient condition. The different features of chemistry and isotopes do not necessarily mean that the catchments are the different sub-systems per se. Conversely, the identical chemistry or isotopes do not necessarily mean that the catchments are the same sub-system. A variety of methods are needed to verify the likeliness or differences in sub-systems. By the convergence of multi-model simulation optimization, Xia (2011) concluded that there is a relationship between Jinci Spring catchment and Lancun Spring catchment, implying that the two spring catchments are not independent groundwater systems. This hypothesis based on numerical simulation was insufficient to certify the delineation of spring catchment sub-systems. The use of numerical simulation method is only an auxiliary means as the good fitting results between the simulated values and the observed values are a necessary condition for the relationship of shared spring catchment. The good fitting results between the simulated values and the observed values cannot be used as a sufficient condition to judge that the two spring catchments belong to a single spring catchment. In fact, the spring catchment sub-systems are often conditioned by their own boundary conditions. As long as the boundary conditions for a catchment are identified, the sub-systems can usually be determined. In addition, the delineation of sub-systems of karst spring in Shanxi has not taken consideration of the height of spring and the base level of discharge. For some spring catchments at present, due to the complexity of geology, geomorphology and hydrogeological conditions, there is also a certain degree of uncertainty for one to determine the boundaries of the sub-systems.

Zoning approach

In the delineation of protection zones, the classification method of protection zone initially used was relatively simple only to protect water quality (Water Resources Management Committee Office of Shanxi Province 1998; Ning et al. 1999; Hao et al. 2006a; Wang et al. 2008). For the delineation of protection zones for multi-objectives, later stage methods involved were comprehensive (Liang et al. 2008; Jia 2009; Li 2013; Zhang et al. 2011). However, the reliability of the delineation of water quality protection zones is subject to debate. Since the complexity of hydrogeological conditions, the heterogeneity and anisotropy of karst aquifers within spring catchment, especially in the cases of non-Darcian flow in cavities; these methods would lead to the inaccuracy of the delineation of water-quality protection zones and increase the difficulty of the management (Wang 1992). But it can be considered first to establish whether there is the problem of such non-Darcian flow based on the other methods including borehole television, electrical conductivity, and tracer test, prior to considering the comprehensive indices of the groundwater flow direction, the velocity of groundwater flow, and the hydraulic gradient. In the benefit of the protection and management of karst water, many investigators proposed some policies at a macro level, and qualitative measures for protection and management (Zhang et al. 2012; Zhao 2014; Yang 2013; Zhang 2007). There is a certain gap between local and international investigators regarding the methods used. For instance, on the basis of summarizing the situation of groundwater management in South Africa, Seward et al. (2015) proposed a simple method of influence radius to be added to the water balance approach to carry out groundwater protection, which is aimed to supplement the existing practice of groundwater management, and to ensure the sustainability of groundwater, but further work is needed for the protection and management of karst water in Shanxi spring catchments.

Way forward

According to the economic development of Shanxi Province guided through the national policy framework and the shortcomings of the current research on karst springs in Shanxi, it can be predicted that the perspective of the research on karst springs in Shanxi would be in the following aspects:

1. Climate change and human activities strongly conditioned the status and characteristic of karst springs in Shanxi spring catchments. These impacts also brought many environmental problems of karst water resources to the economic development of Shanxi. Over three decades, Shanxi spring flows were decreased with the decrease of precipitation and the increase of rapid exploitation (Ma et al. 2004; Hao et al. 2009b, c). Coal mining caused a great deal of negative impacts on karst water environment in Shanxi (Han et al. 1994b; Zhao 2010). The annual mean precipitation for many years (1958–2013) in Shanxi showed a downward trend with the decline rate significantly more than that of the national level (Li et al. 2015). Since the 1980s, the temperature of the Yellow River Basin has significantly increased with the annual mean precipitation showing an unconspicuous downward trend. In addition, the extreme hydrological phenomena such as the heavy rain, floods and droughts were more prominent (Zhao et al. 2015). At present, the prediction of future climate change in Shanxi by the use of GCM (global climate model) is rarely reported, which undoubtedly increases

the difficulty of understanding spring flow fluctuation. Moreover, the methods used to predict spring flow are not based on karst hydrogeological conditions, which cannot reflect the specific impact of various factors on spring flow. Therefore, research of Shanxi spring flows under the changing environment, based on karst hydrogeological conditions, is still worth investigation.

2. For the severe water shortage in semi-arid Shanxi karst area, accurate evaluation of the precipitation recharge of karst groundwater is a prerequisite for the rational planning and sustainable utilization of karst water resources in general. Infiltration recharge of karst groundwater in a spring catchment is affected by many factors including climate, geomorphology, lithology, vegetation, land use, and groundwater level. As this process is very complex, and with the uncertainty of the temporal and spatial karst groundwater recharge, the accurate evaluation of the precipitation recharge is very difficult. At present, the calculation method of precipitation recharge in Shanxi karst spring catchments remains monological per the use of the infiltration coefficient method. Thus, its reliability needs to be verified. It is suggested that multiple methods be incorporated into the existing approach. For instance, chloride mass balance method can be applied with due consideration of the dry deposition of chloride to carry out a comprehensive evaluation of precipitation recharge in Shanxi spring catchments.
3. If the water resources departments or researchers only pay attention to the limited water-quality indicators, and once the karst water does not conform to the national standard of drinking water quality, the potential will exist to have a negative impact on the health of the local residents. The natural resource of karst groundwater changes with the seasons, but the use of recharge method or discharge method has ignored such facts. The two methods of taking the natural resource as a fixed value cannot reflect the dynamic change process of the natural resource. If the piezometric surface of spring catchment is lower than the rational piezometric surface, the exploitation of karst groundwater should be reduced, otherwise, if the confined aquifer turns into the unconfined, the spring water will face the risk of cessation. To avoid the cessation or decrease of spring flow, groundwater levels should be restored to water-level restriction for early warning for spring use or the rational piezometric surface. Therefore, the realistic approach to investigation of the water quality, natural resources, and the exploitable resources of the karst groundwater should be established.
4. There are about 562 coal mines in Shanxi spring catchments. On the one hand, many coal mines operate under artesian conditions as it is very easy to cause floor water inrush. On the other hand, coal mining results in an increase of AMD. If AMD is not treated or managed properly, it would inevitably exert a negative impact on the karst water environment, and it is likely to lead to serious economic problems and health risks. Therefore, research on the mechanism of karst water inrush from the mine floor induced by coal mining, and the mechanism of karst water pollution induced by AMD and its treatment, should be taken seriously.
5. Karst water and coal seams coexist within Shanxi spring catchments. As there are a lot of human activities such as coal mining and engineering constructions, the water ecological environment is fragile. Once the domestic sewage, industrial waste water and persistent organic pollutants enter the karst aquifers, it would cause water contamination and pollution, and would directly threaten the water supply safety of the karst drinking water in the spring catchment. Therefore, vulnerability assessment of karst water still remains an area of great interest in Shanxi spring catchments.
6. Comparison with karst systems in Southern China is very complex, karst in Northern China has its own uniqueness in terms of heterogeneity and anisotropy within the water-bearing media (Wang 1992). The geological structure is mostly manifested in the forms of fault, and collapse column, and therefore formed different sub-systems. The delineation of spring catchment sub-systems is mainly determined by the boundary conditions, which need to be considered in terms of geology, geomorphology and hydrogeological conditions. In addition, the delineation of sub-systems of Shanxi spring catchments may also be related to the elevation of the spring or the base level of the discharge. Therefore, the delineation of sub-systems according to the boundary conditions, the height of spring, and the base level of the discharge would still need to be considered.
7. Future research trends may require applying advanced theories, methods and appropriate technologies available locally and internationally, such as RS, GIS, and GPS technology, for the investigation of karst springs, data statistics, analysis, and processing.
8. With the development of the economy in Shanxi spring catchments and the improvement of the people's consciousness of environmental protection, research on the analysis of karst spring protection, sustainable management of karst water, and water ecological environment of coal mine areas in spring catchments are also problems to be strengthened in the future (Seward et al. 2006, 2015).
9. Jinci Spring, Lancun Spring and Gudui Spring have ceased to flow for many years, the lack of karst water quantity has seriously affected the sustainable devel-

opment of the local economy and the society. As an important water supply source, if the karst groundwater cannot obtain effective recharge, the spring can no longer flow effectively, this will affect the development of local water ecological environments and tourism resources. Therefore, focus on the reflow of Jinci Spring, Lancun Spring, and Gudui Spring is a key point in the study of Shanxi karst springs.

10. Among 19 karst springs in Shanxi, Niangziguan Spring is the largest spring not only in Shanxi but also in Northern China. Along with the decrease of spring flow, karst groundwater levels in the spring catchments have been slowly declining. As a typical karst groundwater system in Northern China, the coal measure strata in the spring catchments are distributed in the upper reaches of the system, but the carbonate rocks are distributed in the downstream or lower reaches of the system. Therefore, coal mining and other human activities have an impact on the quality and quantity of karst water. At present, the problems of karst water quality pollution and the AMD from coal mines have threatened the sustainable development of the spring catchment's economy. Therefore, research on the karst water of the spring catchments needs to be further strengthened.

Conclusions and recommendations

This paper provides an overview of the karst springs in Shanxi Province of China. It critically reviews the research results of the karst springs in the region from the perspective of spring flow trend, precipitation recharge and time-lag, evaluation of karst water resources, water chemistry and environmental isotopes with purposing assession. The paper further evaluates the integrity of the aquifer system including the vulnerability, impacts of coal mining and engineering activities on karst groundwater, delineation of spring catchment sub-systems, and protection and management measures. It is concluded that human activities and climate change are the primary and secondary factors affecting karst springs, respectively. The impacts of human activities on karst springs are mainly in the abstraction of karst water, coal mining drainage, engineering construction and other activities. Karst water quality in parts of Shanxi spring catchments has been polluted in many places to various extents, which warrants necessity of protection zoning. The research results of the karst springs are quite encouraging, but there are still some problems, which lie mainly in (1) research of Shanxi spring flow under the changing environment, based on the karst hydrogeological conditions, is basically still required; (2) the method for study of precipitation recharge needs to be cross-checked, and research on the time-lag of precipitation in recharge events needs to incorporate the impacts of the recharge processes, the degree of karst development, the velocity of groundwater flow and the distance from recharge area to discharge area; (3) full attention needs to be paid to the fact that the exploitable karst water resources depends on the increase of recharge and the decrease of discharge under pumping conditions; (4) research on the mechanism of karst water pollution caused by AMD in coal mine areas and the treatment of AMD cannot over emphasized; (5) research on the impact of persistent organic pollutants on karst water is in its infancy; (6) vulnerability assessment of karst water has no commonly acceptable principles of how to use the indicators, thus the assessment results cannot indicate the damage threshold where karst aquifers are no longer acceptable; (7) in the delineation of spring catchment sub-systems, full consideration was not given to the boundary conditions which are determined by geology, geomorphology and hydrogeological conditions. Neither the elevation of the karst springs nor the base levels of their discharge are considered; and (8) there is still a certain gap in the protection and management with international best management practices.

To guarantee the economic development of Shanxi spring catchments guided through the national policy framework and the shortcomings of the current research on karst springs in Shanxi, the way forward of the research on karst springs in Shanxi should be in the following aspects (1) research of Shanxi spring flows under the changing environment, based on the karst hydrogeological conditions, is still worth investigation; (2) study on the precipitation infiltration recharge in spring catchments using various methods needs to be strengthened; (3) realistic approach to the investigation of the water quality, natural resources, and the exploitable resources of the karst groundwater should be established; (4) research on the mechanism of karst water inrush from the mine floor induced by coal mining, and the mechanism of karst water pollution induced by AMD and its treatment should be taken seriously; (5) vulnerability assessment of karst water still remains an area of great interest in Shanxi spring catchments; (6) the delineation of sub-systems according to the boundary conditions, the elevation of the spring, and the base level of the discharge would still need to be considered; (7) research on karst springs by the use of advanced theories, methods and technologies should be strengthened; (8) research on scenario analyses of karst spring protection, sustainable development of karst water in spring catchments, sustainable management of karst water and water ecological environment of coal mine areas in spring catchments needs to be strengthened; (9) focus on the reflow of Jinci Spring, Lancun Spring and Gudui Spring needs to be considered; and (10) study on karst water of Niangziguan Spring catchment should be strengthened systematically.

As coal seams coexist with karst water in Shanxi spring catchments, coal seams in many coal mines operate under artesian groundwater conditions. Coal mining in almost every spring catchment exerts impact on the karst water. With AMD problems induced by coal mining and the closed pit, therefore, the water ecological environment of Shanxi spring catchments is fragile. In recent years, under the impact of climate change and human activities, karst environmental hydrogeological problems of the decrease of spring flow, decline of karst groundwater level, karst water pollution, etc. are becoming more and more serious, it is an indisputable fact that the karst water in Shanxi has been negatively affected, which must be brought to the attention of government departments at all levels in Shanxi, coal mining enterprises, and the scientific community. In the development and utilization of karst water in Shanxi, it must be to take comprehensive consideration of the possible impacts on karst water, and make efforts to reduce these impacts to the extent that the karst water and ecological environment can be accepted, and at the same time, to strengthen the effective management and protection of karst water, thus to ensure the sustainable development and utilization of karst water resources in Shanxi spring catchments.

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