PROTECTION OF KARST SPRING IN SHANXI REGION, CHINA: A CASE STUDY FROM JINCI SPRING CATCHMENT

Dissertation submitted to the University of the Western Cape in the fulfilment of the degree of Doctor of Philosophy

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DECLARATION

I declare that **PROTECTION OF KARST SPRING IN SHANXI REGION, CHINA: A CASE STUDY FROM JINCI SPRING CATCHMENT** is my own work, and that has not been submitted for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledged by complete references.

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Signed Zhixiang Zhang

ABSTRACT

Protection of Karst Spring in Shanxi Region, China:

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Keywords: karst spring, karst water, Shanxi, spring catchment, water resources, Jinci Spring, drying up, capture principle, sustainable yield, karst groundwater, numerical modeling, re-outflow protection, ecological criteria, artificial recharge

Groundwater is an important part of water resources and plays a significant role in the water supply in most parts of the world. It is also an important ecological environmental factor, and its variations often affect the natural balance of the ecosystems. 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. Jinci Spring is one of the famous karst springs in Northern China, which possesses a significant historical and cultural value. Since Jinci Spring dried up on 30 April 1994, it still has not completely gained its re-outflow. This has not only lowered the tourism resource value of the Jinci Temple, but also caused the contradiction between supply and demand of water resources and the

degradation of the aquatic ecological environment in the downstream of the spring. Therefore, it is of great significance to review the research findings on karst springs in Shanxi, and it is necessary to further strengthen the investigation on the causes of the drying up of Jinci Spring and its protection for ecological re-outflow.

The goal is to protect the precious karst water resources in Shanxi and to prevent or reduce the occurrence of karst water contamination and pollution, as well as, to provide scientific basis for decision makers to make correct decisions on the ecological re-outflow program of Jinci Spring. Through the retrieval and analysis of some 200 local and international publications, this thesis 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, 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. On the basis of the data of karst groundwater done over a long-term monitoring programme in Jinci Spring catchment, the thesis investigates the causes of the drying up of Jinci Spring by using the capture principle. The study has assessed the sustainable yield of karst groundwater, quantified the sustainability threshold of karst groundwater and determined the ecological water level restrictions for early warning and water supply in Jinci Spring catchment. In addition, a simple 2D numerical model of karst groundwater in Jinci Spring catchment is used to design three different re-outflow protection scenarios, to forecast the dynamics of karst groundwater level, and to optimize the re-outflow protection scheme that meets the ecological criteria for Jinci Spring. The main results of the thesis are presented as follows.

1. 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; the impact of climate change on Shanxi karst springs are mainly manifested in the form of reduced precipitation. 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.

2. The research results of Shanxi 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 acid mine drainage (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.
3. 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 by using various methods needs to be strengthened; (3) realistic approach to the investigation of the water quality, the 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 re-outflow 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.

4. The drying up of Jinci Spring is the biggest water ecological environmental problem in Jinci Spring catchment. It is also a typical case of governance failure of karst groundwater in Shanxi and China. Climate change and the long-term consumption of karst aquifer storage are the key causative factors of the drying up of Jinci Spring.
5. The sustainable yield of karst groundwater in Jinci Spring catchment is determined by the leakage recharge of the overlying fissure aquifers and the reduced spring flow induced by groundwater exploitation, rather than natural recharge. The sustainable yield under ecological constraints has a series of permissible values that range from 0.622 to 2.35 m^3/s.
6. The sustainability threshold of Jinci Spring catchment is a limited range of the total exploitation of karst groundwater for industrial, agricultural and domestic water uses. The sustainability threshold of karst groundwater in Jinci Spring catchment is [12.35×10^8 m^3, 13.91×10^8 m^3].
7. The basic ecological spring flow in Jinci Spring catchment in dry season and other periods are 0.393 and 0.32 m^3/s, respectively. The ecological water level restriction for early warning and the ecological water level restriction for water supply are 803.35 and 803.21 m asl, respectively.
8. The numerical modeling results show that the artificial recharge of the Fenhe River leads to the rise of karst groundwater level, while groundwater abstraction results in

the decline of karst groundwater level. Compared with scenario 2 and scenario 3, scenario 1 (artificial recharge of the Fenhe River of 0.9 m^3/s and groundwater abstraction of 0.42 m^3/s) is optimal, and it is the re-outflow protection scheme that meets the ecological criteria for Jinci Spring.

9. In the implementation of the artificial recharge of the Fenhe River, neither can the pumping wells be completely closed nor can the groundwater abstraction be too large; otherwise, water resources will be wasted due to the higher karst groundwater level or the re-outflow time of Jinci Spring will be lagged and the ecological criteria will not be met.
10. The thesis will contribute towards the establishment of sustainable development and utilization of karst water in Shanxi and even in Northern China. The results of the investigation on Jinci Spring of the present study can provide an important basis for the implementation of the ecological re-outflow program of Jinci Spring, and also highlight the importance of the capture principle and numerical modeling in the study of the management and protection of karst groundwater resources.

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Chapter 1

Introduction

1.1 Background

Groundwater is an important part of water resources and plays a significant role in the water supply in most parts of the world. It is also an important ecological environmental factor, and its variations often affect the natural balance of the ecosystems (China Groundwater Science Strategy Research Group 2009). In many regions, the intensification of human activities has had negative impacts on groundwater, including the lowering of water level, a decrease in aquifer recharge, water contamination and pollution, which in turn affects the ecological functioning of groundwater.

China is one of a few countries in the world where karst is intensively developed. 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, equalling 9.5% of the total land area (Han 2015). The karst water resource is estimated at 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). 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 Zou 1996).

In the arid and semi-arid regions of Northern China, such as Shanxi, Shandong, and Hebei, there are large areas of carbonate rock formations. The karst groundwater resources are very abundant, and outflow occurring from the concentrated discharge area often becomes recharge to a river in the form of spring. Among them there are the famous karst springs including Jinci Spring and Niangziguan Spring of Shanxi Region, Baotu Spring and Heihu Spring of Shandong Region. Due to its deep burial, large reserves and good water quality, karst groundwater has become a major source for local industrial, agricultural, domestic and ecological water uses, playing a vital role in supporting economic and social development and maintaining ecological balance. According to statistics, there are more than 50 karst springs and each of their original flow is greater than 1 m^3/s in Northern China (Ma et al. 2004). These springs occur in their own unique landscapes, especially Jinci Spring, which is located in the Jinci Temple (the earliest extant imperial garden in China), and has become a famous scenic spot and tourist attraction.

With the dramatic increase in social water demand, the shortage of water resources has become very acute. By 2025, it is predicted that more than one-third of the population in the world will not have enough fresh water (Gleick 2001). Over the years, due to the burgeoning population, the acceleration of urbanization and industrialization, and the lack of coordinated protection and scientific management, overexploitation (Custodio 2002) of karst groundwater in Northern China has emerged, exceeding the carrying capacity of regional water resources (Duan et al. 2010), and resulting in the continuous decline of karst groundwater levels and the significant decrease of spring flows. Some springs have even ceased to flow, such as Jinci Spring, Gudui Spring and Lancun Spring in Shanxi, Heilongdong Spring in Hebei. Coupled with the drainage of industrial and domestic sewage, the karst groundwater resources quality (including water quality and quantity) is gradually getting deteriorated, which has become an important constraint to the sustainable development for regional economic community. It can be seen that under the impacts of anthropogenic activities, the ecological environment of karst groundwater in Northern China is threatened and enough attention should be paid for its protection.

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 (Figure 1-1). 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), Honasan 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 eco-scape in Shanxi.

Since the 1950s, due to the impact of natural and man-made factors, many problems in most parts of Shanxi spring catchments occurred, including the decrease in spring flow rates, and the decline of groundwater level, etc. (Hao et al. 2006a). 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 re-outflow 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.

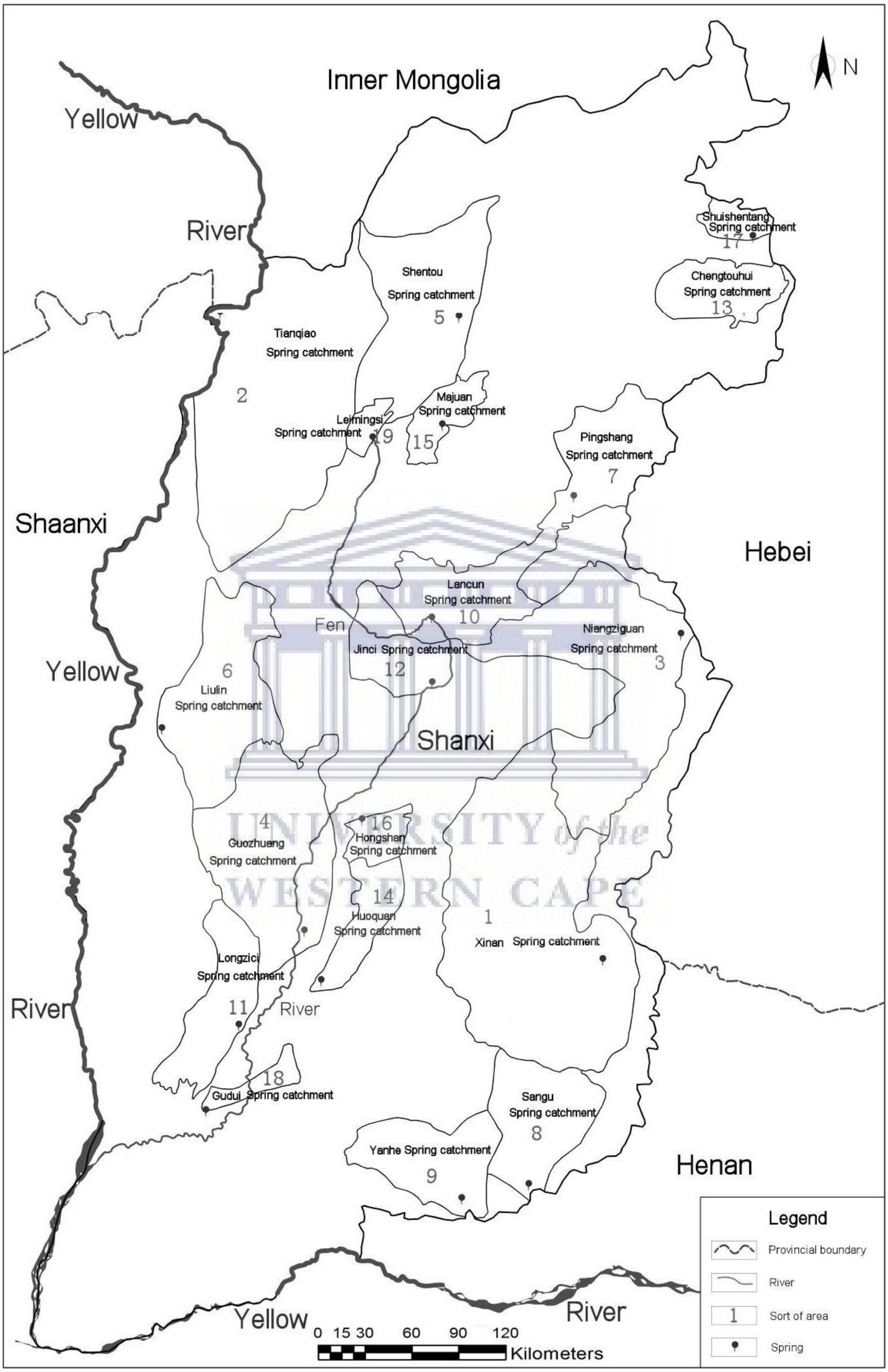


Figure 1-1 Nineteen big karst springs in Shanxi Province, China

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 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, 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 (adjacent provinces such as Hebei and Henan), 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. "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. 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.

Jinci Spring is one of the famous karst springs in Northern China, which possesses a significant historical and cultural value. It is also one of the important water supply sources for Taiyuan, Shanxi. Since Jinci Spring dried up (the groundwater level at the mouth of spring is lower than 802.59 m asl) on 30 April 1994, it still has not completely gained its re-outflow. This has not only lowered the tourism resource value of the Jinci Temple (the temple is famous for the spring and has a history of more than 3000 years, it not only has important historical, artistic, scientific and appreciative values, but also a precious heritage in the ancient Chinese culture and treasure house of human architectural art), but also caused the contradiction between supply and demand of water resources and the degradation of the aquatic ecological environment in the downstream of the spring. It can be seen that the drying up of Jinci Spring is the biggest water ecological environmental problem in Jinci Spring catchment, and it is also a typical case of governance failure of karst groundwater in Shanxi and China (Turton et al. 2007). This is like the water crisis in Cape Town, South Africa from 2015 to 2017 (Olivier and Xu 2018), which gives us profound lessons. Whether or not the re-outflow of Jinci Spring and when it will re-outflow have drawn considerable public attention. Since 2008, with the continuous implementation of the artificial recharge of the Fenhe River, closure of some production wells, and reduction of groundwater exploitation, karst groundwater level in Jinci Spring catchment has been increasing year by year, and Jinci Spring is expected to achieve ecological re-outflow. On 1 August 2013, the Standing Committee of the People's Congress of Shanxi Region re-issued "Water Resources Protection Regulations of Jinci Spring Catchment in Taiyuan City", which provides strong legal support for the ecological re-outflow protection of Jinci Spring. Therefore, it is necessary to further strengthen the investigation on the causes of the drying up of Jinci Spring and its protection for ecological re-outflow, which has important scientific significance and practical application value.

Seward et al. (2006) applied the capture principle (Lohman et al. 1972; Alley et al. 1999) to groundwater management in pore aquifers of Dissels River and Wadrif in South Africa, and proved that the application of the method is feasible and suitable. The differences between Southern and Northern karst in China are attributed to the depositional environments and the climate differences caused by tectonic uplifts (Yuan 1997; Hao et al. 2012a). Karst fissures and karst channels are developed in the Southern karst; while karst fissures and cave fissures are developed in the Northern karst, which is very similar to the characteristics of the porous media. In addition, every karst spring catchment in Northern

China is an independent karst water system with clear watershed and hydraulic boundaries (Han et al. 1993). Therefore, the capture principle can be practically applied to the study of karst groundwater in Northern China, especially for Jinci Spring.

For Jinci Spring catchment, the numerical modeling results are still insufficient. Karst aquifer is the main water supply source in Jinci Spring catchment, and is also the source for Jinci Spring. With the implementation of the artificial recharge of the Fenhe River, the published studies cannot meet the needs of ecological re-outflow protection of Jinci Spring. Thus, it is necessary to construct a numerical model of karst groundwater. The karst aquifer media in Jinci Spring catchment is the dissolution pore, and the karst water flow is reliable. On a regional scale, karst aquifer in Jinci Spring catchment has a uniform groundwater table; the water flow follows Darcy's law. Therefore, the equivalent porous media model can be approximately used to simulate the groundwater in karst aquifer in Jinci Spring catchment (Scanlon et al. 2003; Qian et al. 2003; Kang et al. 2011).

Hence, before solving the faced problems in Shanxi karst springs, especially Jinci Spring, it would be wise to speed up the study on karst springs in Shanxi and the protection for ecological re-outflow of Jinci Spring, 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. The results of the study are easily accepted by decision makers of the ecological re-outflow protection of Jinci Spring. Moreover, it will be possible to set target for the groundwater level allowed in the karst aquifer in question after the ecological re-outflow of Jinci Spring.

1.2 Research Objects

The goal is to protect the precious karst water resources in Shanxi and to prevent or reduce the occurrence of karst water contamination and pollution, as well as, to provide scientific basis for decision makers to make correct decisions on the ecological re-outflow program of Jinci Spring. This thesis reviews the research results of karst water, karst springs in Shanxi, aquifer integrity, safe yield and sustainability, numerical modeling, and Jinci Spring, and investigates the causes of the drying up of Jinci Spring and its protection for ecological re-outflow. Hence, the research objects of the thesis are expected as follows,

1. Through the retrieval and analysis of some 200 local and international publications, this thesis aims to review the research findings of karst water, karst springs in Shanxi, aquifer integrity, safe yield and sustainability, numerical modeling, and Jinci Spring for the past decades, to analyze the problems and difficulties in the research of Shanxi karst springs, and to point out the way forward of the research on karst springs in Shanxi.
2. On the basis of analyzing the long-term monitoring data of karst groundwater level of spring, spring flow, rainfall, groundwater exploitation, Fenhe River leakage and lateral discharge from 1956 to 2014, this thesis investigates the causes of the drying up of Jinci Spring by using the capture principle; assesses the sustainable yield of karst groundwater in Jinci Spring catchment; quantifies the sustainability threshold of karst groundwater in Jinci Spring catchment; and determines the ecological water level restrictions of Jinci Spring catchment.
3. Based on the analysis of the geological and hydrogeological conditions, a simple 2D numerical model of karst groundwater in Jinci Spring catchment is used to design three different re-outflow protection scenarios, to forecast the dynamics of karst groundwater level, and to optimize the re-outflow protection scheme that meets the ecological criteria for Jinci Spring.

Chapter 2

Literature Review

The previous studies on karst water, karst springs in Shanxi, aquifer integrity, safe yield and sustainability, numerical modeling, and Jinci Spring of interest in the thesis are reviewed in the following.

2.1 Karst water

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. Many significant theoretical and applied studies have been conducted over the past several decades to research the karst water at home and abroad.

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 by using an artificial neural 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 by 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. Most importantly, all of these studies provide a significant theoretical basis for the study on Shanxi karst springs and its karst water.

2.2 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.

2.2.1 Spring flow trend

2.2.1.1 Dynamic record of spring flow

Over the years, the dynamics of karst spring flows in Shanxi have changed in various degrees (Table 2-1). According to the decreasing sizes of spring catchments, the 19 karst springs in Shanxi from No. 1 to No. 19 are numbered as seen in Figure 1-1. 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 (Cheng 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 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 2006a). 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 (Figure 2-1). 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 2-1 with the previous investigations, it is evident that the majority of spring flows in question have been decreasing in general. As shown in Figure 2-1, 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, 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 literature 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. 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.

Table 2-1 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

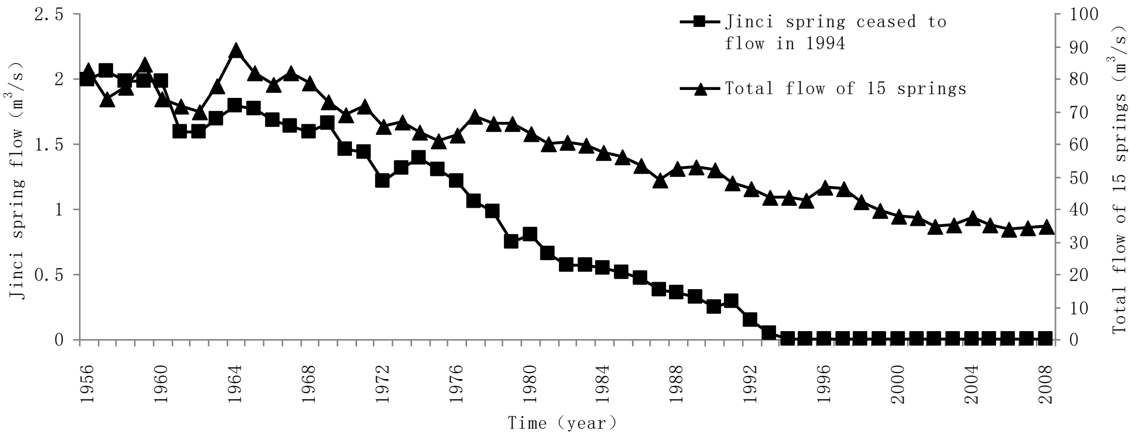


Figure 2-1 The annual flow of Jinci Spring and the total of 15 springs

2.2.1.2 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. 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). The reduction of precipitation was the main factor for the decrease of Lancun Spring flow before the 1970s, and the over-exploitation of karst water was the main cause for its decrease after the 1970s (Chen 2006a). 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. 2009c). 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. 2009b). 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. 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). In order 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. 1994a). 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 decrease 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.

2.2.1.3 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. Grey Model (GM (1, 1)), Grey Prediction-Amending Model (Guo et al. 2002), GM (1, 1) Cycle Correction Model (Hao et al. 2003a), and Grey Prediction Model of Seasonal Neural Network (Li et al. 2008) were used to predict Shentou Spring flow. Grey System Model (GM (1, 2)) and Grey System Decomposition Model were used to predict Liulin Spring flow (Hao et al. 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 2004a), Assembled Extreme Value Statistical Model (Fan et al. 2013) was used to predict Niangziguan Spring flow. Mixed Autoregressive Model was used to predict Guozhuang Spring flow (Zhu 2008). Grey 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, Grey 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 Grey System Model only reflected that the spring flow was changed with time, the two were unable to reflect the characteristics of karst water system. In addition, according to the previous literature, the prediction results of different models of the same spring such as Xin'an Spring are also different. The first reason is that there are differences in the use of models, and the second is that the influence factors of spring flow considered by different scholars are also different. 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.

2.2.2 Precipitation recharge and time-lag

2.2.2.1 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 by 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.

2.2.2.2 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 2-2. 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 2-2. By employing Grey 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.

Table 2-2 Time lag for selected karst spring catchments

No	Spring Catchment	Time-Lag (year)	Method	References
1	Liulin Spring	3, 4, 6	Grey Correlation Analysis Model	Wang (2007)
2	Liulin Spring		Grey Slope Similar Correlation Degree Analysis Model	Fan et al. (2012)
3	Liulin Spring	1(South), 7(North)	Grey System Theory	Hao et al. (2012b)
4	Niangziguan Spring	Variation	Grey 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)

According to the above results, it can be seen that the previous works on the time-lag of precipitation recharge were 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 Grey Correlation Analysis, the Grey Slope Similar Correlation Degree Analysis and the Statistical Analysis. Among them the application of Grey 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.

2.2.2.3 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. 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 (Xu and Zhang 2008a).

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.

2.2.3 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 Figure 2-2, 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 (Figure 2-3). 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 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, and 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.

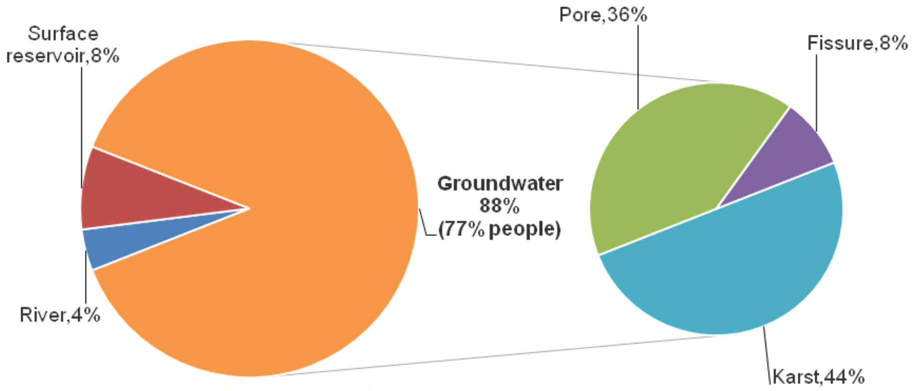


Figure 2-2 Distribution of water supply sources in Shanxi

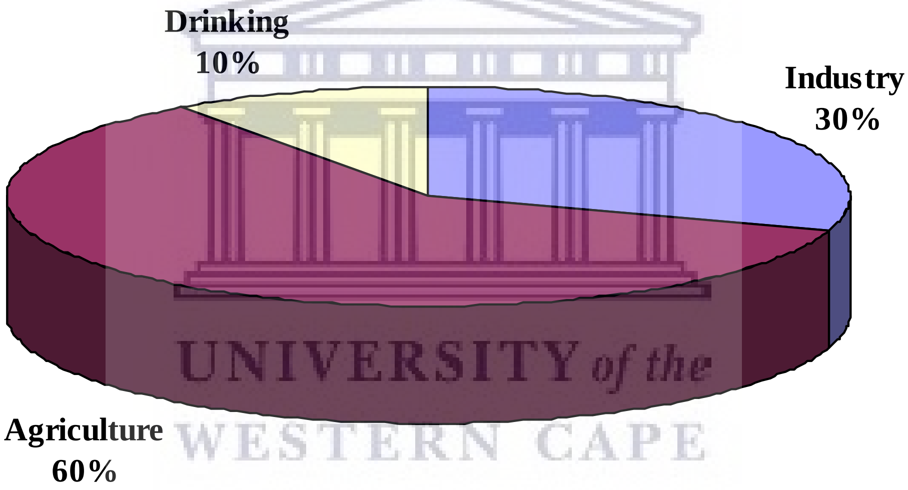


Figure 2-3 The karst water consumption in industry, agriculture and drinking water

2.2.3.1 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 Figure 2-4, 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 5 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.

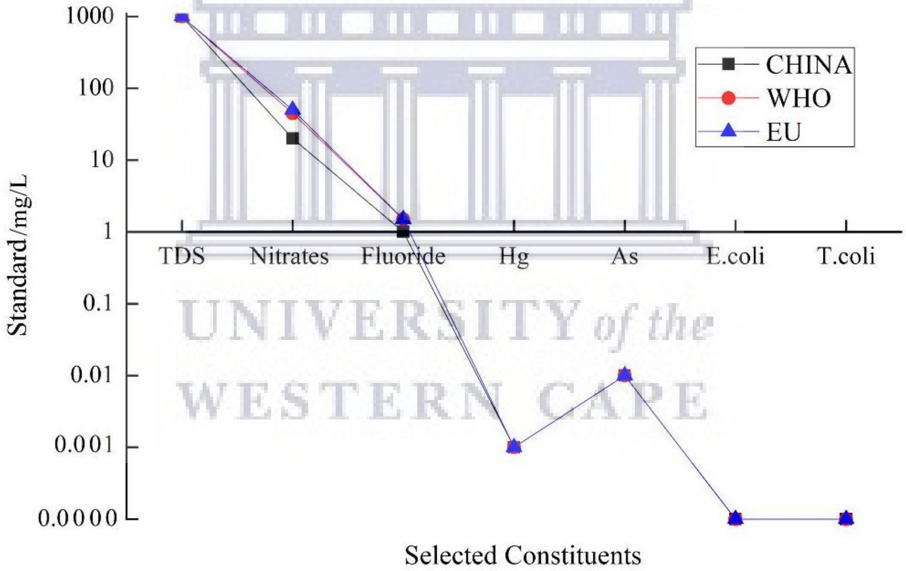


Figure 2-4 The standards comparison of drinking water of China, EU and WHO

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 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 of contamination being observed in isolated areas (Xu and Zhang 2008b).

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$5,000. 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. 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. In order 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).

2.2.3.2 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. By the use of 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 et al. (2005) updated the natural resources in 16 spring catchments of Shanxi, short of Chengtouhui Spring catchment, Shuishentang Spring catchment, and Leimingsi Spring catchment, by 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 by using both Recharge Method and Discharge Method. Gao (2005) evaluated the natural resources of Guozhuang Spring, Longzici Spring, and Huoquan Spring by using the Discharge Method, and calculated the natural resources of Gudui Spring by the use of the Recharge Method. Cui and Cui (2007) calculated the natural resources of Leimingsi Spring by the use of the Recharge Method. Xu (2008) calculated the natural resources of Xin'an Spring by 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 by the use of the Discharge Method, which was verified by using the Recharge Method. Yang (2009) calculated the natural resources of Majuan Spring by 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 by using the Discharge Method. Liu et al. (2014) calculated the natural resources of Hongshan Spring by 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 thesis.

2.2.3.3 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 Figure 2-5, 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, 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. By 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 et al. (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 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. By using an Optimized Evaluation Management Model, Liang and Han (2006) calculated the exploitable karst water resources of the Niangziguan Spring catchment. By 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. By using a Numerical Method, Han et al. (1994) 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. By 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. By using the Frequency Analysis Method, Wang (2015) assessed the exploitable karst water resources of the Chengtouhui Spring catchment.

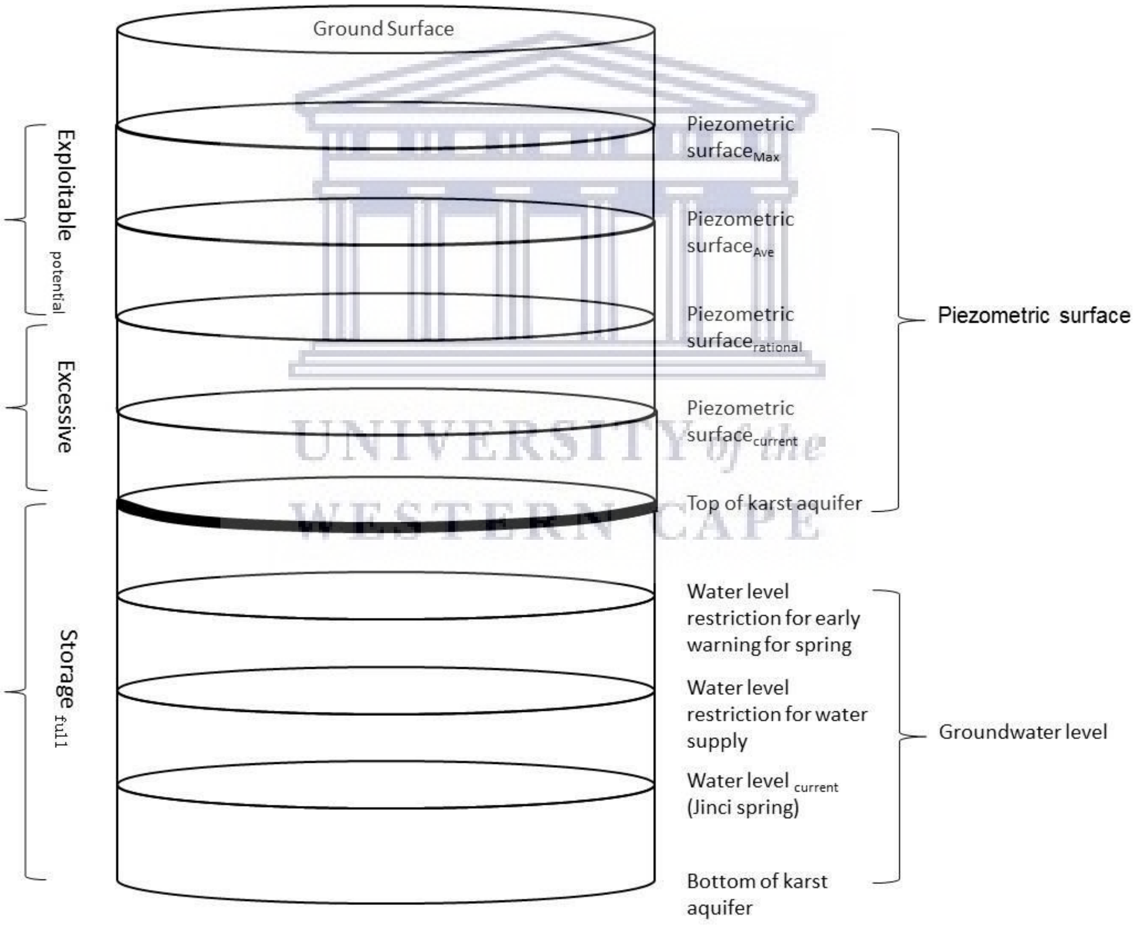


Figure 2-5 Conceptualized exploitable water resources in karst aquifer system

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.

2.2.4 Water chemistry and environmental isotopes

2.2.4.1 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. By using the hydrogeochemical method in combination with multivariate statistical theory and computer simulation technology, Zang et al. (2015a) made an assessment of the dominate hydrogeochemical processes in the Liulin karst groundwater system. According to Li et al. (1998a), 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.

2.2.4.2 Environmental isotopes

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. By 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. By 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. (2015b) 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 are still in its infancy. At present, there are 6 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. In order 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.

2.3 Aquifer integrity

2.3.1 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 have 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. In order 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. By 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. By 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). By 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.

2.3.2 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 exist 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 (2014b) 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. By 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 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 8 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.

2.3.3 Delineation of spring catchment sub-systems

To analyze the direction and flux of groundwater flow, which can be subdivided 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). By 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. 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 contrary to Zhao and Cai (1990) and He et al. (1997). By using multiple isotopes and water chemistry methods, Sun et al. (2016) confirmed the reasonableness of dividing the Taiyuan karst groundwater system into three subsystems. 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 sub-divided in Shanxi. 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.

2.3.4 Protection and management measures

2.3.4.1 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, and 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, 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. (2006b) 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.

2.3.4.2 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 (Liu 2005; Jian 2007; Zhang et al. 2012; Zhao 2014; Chen 2006b; Bai 2010; 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, in order 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.

2.4 Safe yield and sustainability

For many years, two concepts relevant to the development and utilization of groundwater are the safe yield and sustainability. Although the application of safe yield (Lee 1915; Theis 1940; Lohman 1972) is the earliest and longest, the concept has been widely criticized by scholars at home and abroad, mainly because many people mistakenly believe that it means a fixed groundwater supply (Todd 1959). In addition, due to the uncertainty of safe yield, some investigators suggested that the term should be abandoned (Thomas 1955; Kazmann 1956). Other researchers pointed out the shortage of safe yield, and believed that there is no single and fixed safe yield, but there is an optimal safe yield (Freeze and Cherry 1979).

In 1987, the Brundtland Commission gave a classical definition of sustainable development. Although the concept does not deal specifically with groundwater, it is the origin of the concept of sustainability. Since then, sustainability has gradually received much attention. Publications dealing with sustainability of groundwater are countless to cite. For example, Loucks (2000) argued that sustainable water resources are considered to meet the changing needs of present and future without system degradation. Sophocleous (2000) proposed that sustainability is originally comes from the groundwater storage, but ultimately comes from the induced recharge. Bredehoeft (2002) believed that groundwater sustainability is determined by the capture of natural discharge. Kalf and Woolley (2005) pointed out that sustainable development is the sustainability of aquifer system in a basin, and the sustainability can be deduced by using conservation of mass principles.

Although the concept of sustainability occurs late, its core is to limit the use of groundwater resources to a level that can be maintained for a long time (Alley and Leake 2004). Seward et al. (2006) reported that the sustainable use of groundwater depends on the increased recharge and/or reduced discharge, rather than natural or virgin recharge. According to Lohman et al. (1972) and Alley et al. (1999), the sum of the increased recharge and decreased discharge is called capture. At present, the concept of sustainability has been widely accepted by researchers. It can reflect the objective reality of groundwater resources more accurately and scientifically than safe yield, so it has the value of popularization and application. Most importantly, it provide a significant theoretical basis for the assessment of the sustainable yield and the sustainability threshold of karst groundwater in Shanxi spring catchments, especially for Jinci Spring catchment.

2.5 Numerical modeling

With regard to groundwater research, numerical modeling method has certain advantages in describing groundwater dynamics over other methods. It is the best tool for simulating the impacts of groundwater exploitation scenarios (Zhou 2009). Moreover, it is also an indispensable decision-making tool in groundwater management (Sophocleous 2000). Some investigators have constructed specific groundwater numerical models for relevant examples, and have achieved satisfactory results. For example, Qian et al. (2006) developed a 3D finite-element model to simulate karst groundwater level change in Jinan Spring catchment, the results suggested that the decrease of groundwater pumping is required to protect Jinan Spring flows. Xing et al. (2009) took groundwater level and spring flow as the threshold of groundwater environmental capacity, and used numerical modeling method to study the dynamic variability of karst water environmental capacity in

Jinan Spring. Zhang (2009) obtained the sustainable yield of Yanhe Spring catchment by using AQUA3D software based on Galerkin finite element method. Kang et al. (2011) constructed a regional 3D finite-difference numerical model to optimize the sustainable yields of the whole Jinan karst aquifer system. Sarma and Xu (2014) estimated the aquifer parameters of a study area in rural semi-arid Namibia based on the numerical modelling, and concluded that the aquifer system is sustained by the recharge and the gain in storage. Mengistu et al. (2014) developed a numerical groundwater flow model to assess the source of excess water of a pumping shaft in South Africa, the results show that the water intercepted at the shaft comes from the seepage of a mine tailings dam and the upper dolomite aquifer.

Thus, it can be seen that more and more scholars have focused on the research of groundwater numerical simulation. All of the above-mentioned studies provide a significant basis for local decision makers in regional groundwater management and protection. In addition, all the studies are beneficial to further research on the protection for Shanxi karst springs, especially the protection for ecological re-outflow of Jinci Spring.

2.6 Studies on Jinci Spring

Jinci Spring is the most famous karst spring in Shanxi Province, it ceased to flow on April 30, 1994 (Shu and Zhu 2000; Zhang et al. 2018). Over the years, a variety of causes were considered to be responsible for the decrease and/or the drying up of Shanxi karst spring flows, which include, in the order of significance, the increase of groundwater exploitation, the decrease of rainfall, the dewatering of karst groundwater in coal mines, and the decrease of river leakage (Liu 2004; Hao et al. 2009b). All of the previous studies provide a certain basis for the karst spring study in Shanxi. However, these did not provide a more in-depth explanation of the key causative factors of the decrease and/or the drying up of spring flows, particularly for Jinci Spring.

The drying up of Jinci Spring not only seriously affected the tourism resource value of the Jinci Temple, but also caused a shortage of water supply in Taiyuan City. Therefore, the research of Jinci Spring has become a hotspot for scholars in the past two decades. For example, Hao et al. (2009c) pointed out that the karst water abstraction was the main factor for the decrease of Jinci Spring. By using the Zero Flow Risk Model, Shu and Zhu (2000) predicted the Jinci Spring flow. Du (2010) calculated the natural resources of Jinci Spring catchment by using the Discharge Method. By the use of Artificial Neural Network, Yin et al. (2011) predicted the variation of Jinci Spring flow. Li et al. (2011) investigated the time-lag between Jinci Spring and rainfall. Li et al. (2012) described that coal mining drainage had lowered the karst groundwater level of Jinci Spring catchment. In addition, many investigators carried out a lot of studies on the protection for Jinci Spring (Li et al. 1998b; Sun et al. 2001; Jin et al. 2005; Gao 2012; Zhao 2014; Zhang et al. 2016), but most of the studies focused on spring flow dynamics, karst groundwater level, groundwater vulnerability, groundwater risk, water quality, and the recovery of spring. Besides, Jia et al. (2017a, b) analyzed the hydrogeochemical evolution of karst groundwater in Jinci Spring catchment. On the basis of reviewing the published studies of karst springs in Shanxi, China, Zhang et al. (2018) reported that the study on the re-outflow of Jinci Spring is one of the key areas in the future research of Shanxi karst springs. Ran et al. (2018) concluded that the groundwater overexploitation had affected the water balance of Jinci Spring catchment. Zhang et al. (2019) analyzed the changing trend of karst groundwater level in Jinci Spring catchment by using the Mann–Kendall trend test method, and concluded that there is a significant rising trend for karst groundwater level. Lv et al. (2019) investigated the variation of reservoir storage of Jinci Spring.

All the previous results provide reference for the re-outflow of Jinci Spring and karst groundwater protection. Nevertheless, special study on the causes of the drying up of Jinci Spring and its protection for ecological re-outflow is still lacking, especially the comprehensive application of the capture principle and numerical modeling in the study of Jinci Spring is still in the blank. This will not be useful in further advancing the knowledge of karst groundwater in Jinci Spring catchment.

As previously mentioned, research on numerical modeling of Jinci Spring is still insufficient. As one of the important water supply sources in Taiyuan, there are many factors affecting the karst groundwater in Jinci Spring catchment, such as the groundwater exploitation, rainfall, coal mining drainage, and Fenhe River leakage. The change of these factors have been affecting the change of groundwater level of Jinci Spring. The implementation of the artificial recharge of the Fenhe River is a good measure for the ecological re-outflow protection of Jinci Spring. Due to the equivalent porous media model can be approximately used to simulate the groundwater in karst aquifer in Northern China (Qian et al. 2003; Kang et al. 2011), this makes it possible to carry out numerical simulation of karst groundwater in Jinci Spring catchment. To understand the effects of various factors on karst groundwater, it is of great significance to construct a numerical model of karst groundwater in Jinci Spring catchment.

Therefore, the investigation on the cause of drying up of Jinci Spring and its protection for ecological re-outflow is needed. This is expected to further advance the knowledge and improve the karst water situation in Jinci Spring catchment.

2.7 Problems and difficulties

Based on the above discussion, it is clear that karst water has become an important area in hydrogeology. The concept of sustainability has been widely accepted by researchers. Numerical modeling has been used to simulate the impacts of groundwater exploitation scenarios. 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 is 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.

2.7.1 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 (Figure 1-1), the largest tributary in Shanxi Province. The Fenhe River used to runs through karst terrains in Shanxi, where it was one of the main recharge sources to Jinci Spring, Lancun Spring, and Guozhuang Spring. This traditional role has changed due to construction of the Fenhe 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. 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.

2.7.2 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 Grey Theory and Statistical Regression Method, 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. 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 (Pang 2014) and its influencing factors, but effort on the delineation of uniform units of karst groundwater levels is still required.

2.7.3 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. Some investigators used BP network model or ARCGIS geological statistical model, 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. 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 valued the fact that the exploitable resources is 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, which 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.

2.7.4 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 of Shanxi 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.

2.7.5 Aspect of water chemistry

In the understanding of water chemistry, investigators carried out research projects to delineate hydrochemical characteristics, hydrogeochemical processes, and the reasons of groundwater pollution. 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 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, ^{34}S, strontium isotope (Wang et al. 2006), isotopic tracing and dating approaches, 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.

2.7.6 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. 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 km^2 to 10,950 km^2, 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.

2.7.7 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, 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.

2.7.8 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. By using different research methods, investigators delineated the spring catchments into sub-systems. 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.

2.7.9 Zoning approach

In the delineation of protection zones, the classification method of protection zone initially used was relatively simple only to protect water quality. For the delineation of protection zones for multi-objectives, later stage methods involved were comprehensive. 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 firstly 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 (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.

2.8 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. 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. 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. 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. 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. 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. 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. 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.

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 development of the local economy and the society. Therefore, focus on the re-outflow 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. As a typical karst groundwater system, 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. 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.

2.9 Summary

This chapter provides an overview of the karst springs in Shanxi Province of China. 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. The impact of climate change on Shanxi karst springs was mainly manifested in the form of reduced precipitation. Karst water quality in parts of Shanxi spring catchments has been polluted in many places to various extents, which warrants necessity of protection zoning.

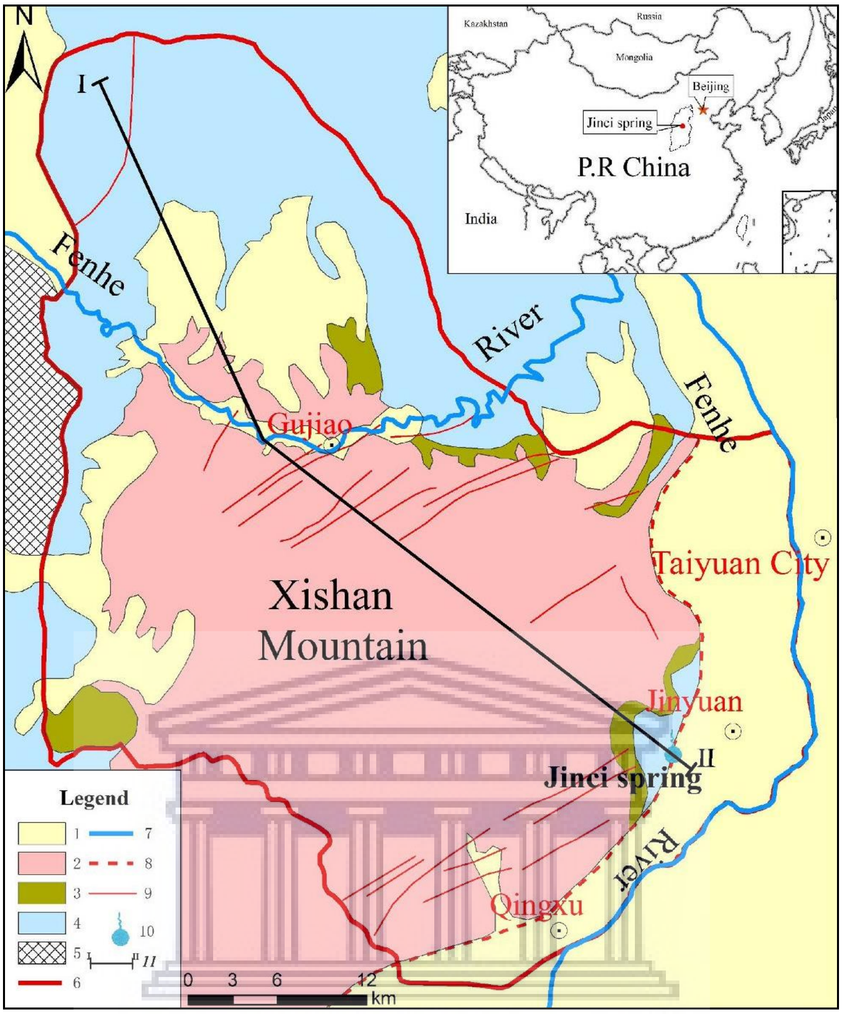
The problems of research results of the karst springs in Shanxi lie mainly in (1) research of Shanxi spring flow under the changing environment, based on the karst hydrogeological conditions, is basically still required; (2) the method for study of precipitation recharge needs to be cross-checked, and 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.

Chapter 3

Description of the Jinci Spring catchment

3.1 Jinci Spring and its Location

The famous Jinci Temple in Taiyuan (the capital city of Shanxi Province, China) is highly valued due to presence of Jinci Spring. Jinci Spring catchment (Figure 3-1) is located in Xishan Mountain of Taiyuan City, Shanxi Region, and its scope mainly includes Gujiao City, Wanbailin District, Jinyuan District, and a small part of Loufan County, Jiancaoping District and Qingxu County. It is a typical karst groundwater system with a total area of 2030 km^2 between latitude 37°32′-38°12′N and longitude 111°54′-112°38′E in Northern China. The exposed and semi-exposed areas of the north are 600 km^2, the central buried area is 1171 km^2, and the plain area in the southeast is 259 km^2. Jinci Spring occurring from limestone of Upper Majiagou formation of Middle Ordovician (O_2m_2) with the elevation of 802.59 m asl, which is an ascending spring of non-full discharge type. Jinci Spring water is one of the important water supply sources in Taiyuan. Figure 3-2 shows the annual spring flow from 1956 to 1994. Before 1960, Jinci Spring remained in its natural or virgin state, the maximum flow was 2.06 m^3/s in 1957, and the minimum flow was 1.90 m^3/s in 1960. After 1961, due to climate change and human activities, Jinci Spring was under increasing pressure, the flow gradually decreased and dried up on 30 April 1994, which directly affected the karst water balance in the spring catchment. Since 2008, the measure termed “clean water re-outflow” (i.e., artificial recharge of the Fenhe River) has been implemented by the water conservancy department, which supplemented 0.1~0.15 billion m^3 ecological water to the Fenhe River every year through the upstream reservoir, and some production wells in Jinci Spring catchment have been closed and karst groundwater exploitation has been discouraged. By the end of 2013, the karst groundwater level had risen to an elevation of 793.56 m asl, but it was still 9.03 m lower than the elevation at the mouth of spring (802.59 m asl). Up to now, Jinci Spring still has no re-outflow. Thus it can be seen that the ecological re-outflow protection of Jinci Spring is still facing severe challenges.



1 Quaternary unconsolidated sediments 2 Permian clastic rocks 3 Carboniferous clastic rocks
4 Ordovician carbonate rocks 5 Archean metamorphic rocks 6 Boundary of spring catchment
7 River 8 Peripheral fault 9 Buried fault 10 Spring 11 section line

Figure 3-1 Geological map of Jinci Spring catchment

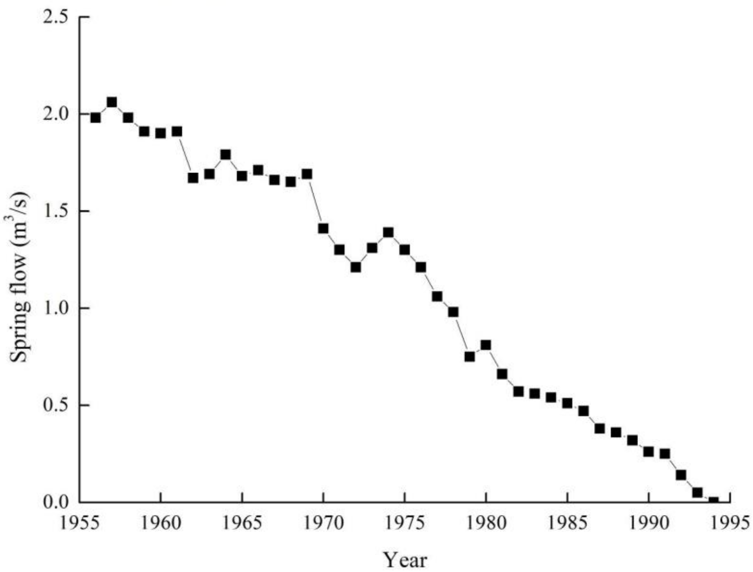


Figure 3-2 Annual spring flow of Jinci Spring catchment (1956-1994)

3.2 Landform and geomorphology

The Xishan Mountain area where Jinci Spring is located belongs to the Luliang Mountain System. The landform is generally high in the north and low in the south, and high in the west and low in the east. The mountainous area is a medium-low mountain formed by a denudation structure with an average elevation of 1300 m asl. The plain area is the Taiyuan fault basin, with an average elevation of 780 m asl. The mountainous area is in direct contact with the basin with a large relief, forming the basic pattern of the topography of the Jinci Spring catchment.

3.3 Climate

The Jinci Spring catchment has a semi-arid continental monsoon climate, and it is characterized by drought and wind, concentrated precipitation, strong evaporation and four distinct seasons. Figure 3-3 shows the annual rainfall from 1956 to 2014. The mean annual rainfall is 464.49 mm, and 60 percent of the annual rainfall is concentrated from June to September. The geographical distribution of rainfall is characterized by the mountainous area larger than the basin area, and the western area larger than the eastern area.

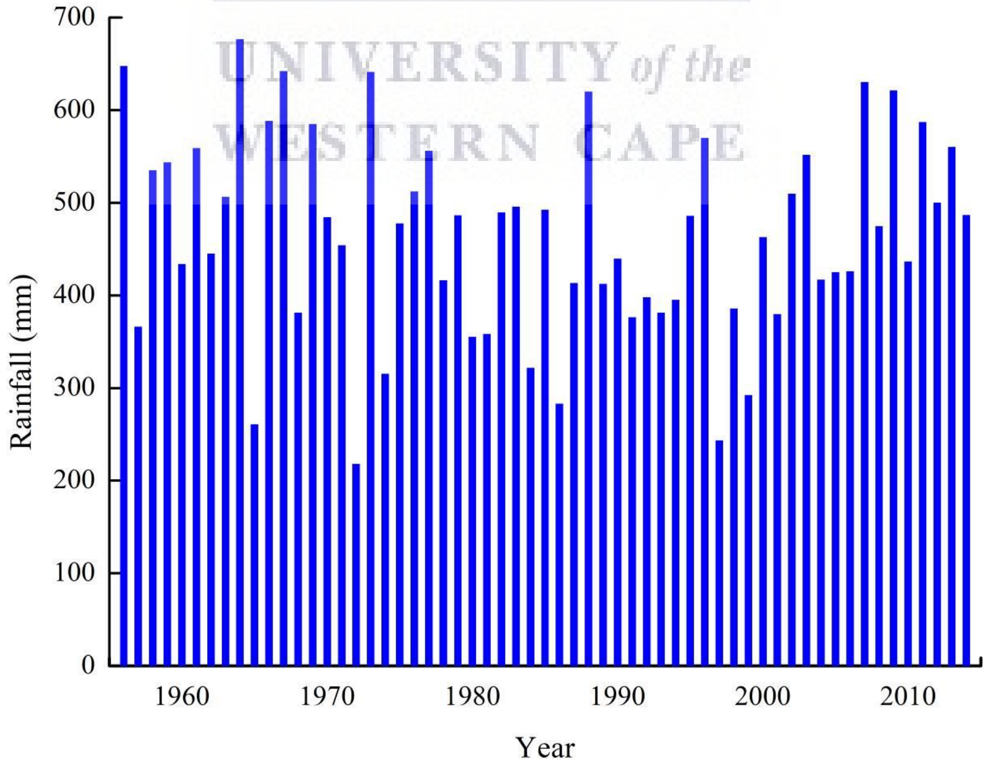


Figure 3-3 Annual rainfall of Jinci Spring catchment (1956-2014)

The average annual temperature is 8.1 °C, it is the highest in July and the lowest in January. The average annual evaporation is 1871.8 mm. The average relative humidity is 60%, the maximum frozen soil layer is 1.1 m thick, and the frost-free period is about 160 days. The dominant wind direction is the northwest wind in winter and spring, and the southeast wind in summer and autumn.

3.4 Hydrology

The river system of the Jinci Spring catchment is relatively developed, all belonging to the Yellow River system (Figure 1-1). The Fenhe River is the largest within the provincial region (Figure 3-1). It passes through the area from west to east, and then turning southward after flowing out of the Xishan Mountain.

The annual average measured runoff at the lower reaches of the reservoir is 13.02 m^3/s. The larger tributaries of the Fenhe River include Tianchi River, Shizi River, Tunlan River, Yuanping River, Dachuan River, Liulin River, etc., all of which are seasonal rivers. The Fenhe River runs for about 44 km across carbonate rocks in Jinci Spring catchment, the average leakage rate is 15%.

Figure 3-4 shows the annual Fenhe River leakage from 1956 to 2014 in Jinci Spring catchment.

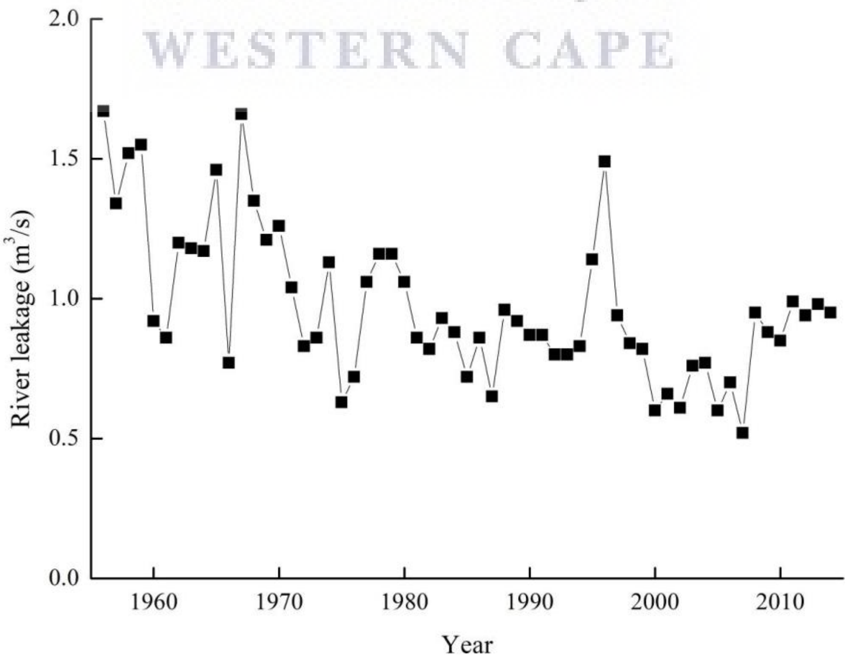


Figure 3-4 Annual Fenhe River leakage of Jinci Spring catchment (1956-2014)

3.5 Geology

In terms of the geology, the Xishan Mountain area within Jinci Spring catchment is composed by Archean (Ar) metamorphic rocks, Cambrian (€) carbonate rocks, Ordovician (O) carbonate rocks, Carboniferous (C) clastic rocks with coal-bearing strata, Permian (P) and Triassic (T) clastic rocks; part of the area along the Fenhe River is covered by Quaternary (Q) sediments as seen in Figure 3-1.

Taiyuan Fault basin area in the eastern of the catchment is covered by very thick Cenozoic strata. Under the action of multi-stage tectonic activities and different stress fields, multi-sequence tectonic traces had been formed, which controlled the karst development of the carbonate rocks in mountainous area of Jinci Spring catchment, indicating that the geological structure in the study area is relatively complex. In particular, the peripheral fault zones of Xishan Mountain in the southeastern parts of the study area provide a groundwater discharge zone for the karst aquifer in Middle Ordovician (O_2). The faults located at the margin of Xishan Mountain form the boundary between Xishan Mountain area and Taiyuan Basin area.

Figure 3-5 and Figure 3-6 show the geological cross-section and stratigraphy of the Jinci Spring catchment, respectively.

Detailed description of the geological conditions of Jinci Spring catchment is given by Zhao and Cai (1990).

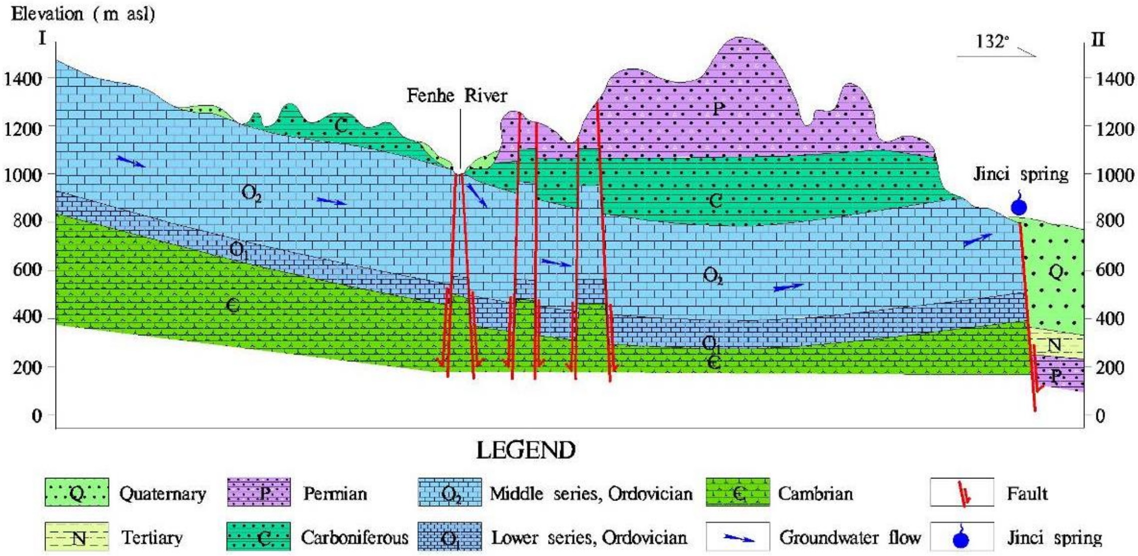


Figure 3-5 Geological cross-section of Jinci Spring catchment

System	Series	Column	Discription
Quaternary	Holocene		Most of the mountainous areas are river facies sediments, the lower part is gravel and the upper part is secondary loess
	Upper Pleistocene		The mountainous area is massive loess, and the basin is loess sub–clay and sub–clay
	Middle Pleistocene		Light red, yellow clay and sub–clay
	Lower Pleistocene		Lake–deposited clay, sandy clay with sand layer, with four to eight sedimentary rhythmic structures
Triassic	Lower Triassic		Fine–grained feldspar sandstone with shale and sandy mudstone, with an increase in argillaceous composition from bottom to top
Permian	Lower Permian		Grey–green coarse–medium–grained feldspar quartz sandstone with gray shale, yellow–green fine sandstone and variegated mudstone
			Sandstone, gray sandy shale, sandstone
Carboniferous	Upper Carboniferous		Sandstone, black shale, sandy shale, Maoergou limestone, carbonaceous shale, Dongdayao limestone
	Middle Carboniferous		Shanxi–type iron ore at the bottom, white bauxite, bauxite shale, grey sandstone and sandy shale
Ordovician	Middle Ordovician		Yellow breccia marl and marl, dark gray thick layered limestone, pure texture
			Gray–yellow breccia marl, limestone, gray medium–thick leopard–like limestone, dolomitic limestone
			Gravel–like marl, dark gray medium–thick layer dense limestone, light gray medium–thick layer dolomitic limestone
	Lower Ordovician		Light gray medium–thick layered mudstone dolomite, medium thick layered, thick layered dolomite containing vermiculite
			Gray–yellow thin layered argillaceous dolomite, bamboo–leaf limestone, gray–yellow muddy dolomite
Cambrian	Upper Cambrian		Medium–thick layered dolomite, dolomitic limestone with bamboo–leaf dolomite and a small amount of dolomitic marl
			Thin layered argillaceous limestone with yellow–green shale at the bottom, often with dolomitic limestone at the top
	Middle Cambrian		Medium–thick layered oolitic limestone, with a small amount of muddy strips and bamboo–leaf limestone
			Thin quartz gravel, purplish red siltstone, purplish red and gray–green shale
			Quartz sandstone, purplish red shale, sandy shale, dolomitic limestone
	Lower Cambrian		Quartz sandstone, purplish red shale, marl and dolomitic limestone, with gravel at the bottom
Archean			Mixed gneiss, mixed granite, mica schist, mica granulite, coarse–grained marble, dropsied quartz, amphibolite, etc.

Figure 3-6 Stratigraphy of Jinci Spring catchment

3.6 Hydrogeology

According to lithology and flow characteristics, the various types of aquifers in Jinci Spring catchment are fully developed. The bedrock fissure water is distributed in the western and northern areas. The carbonate karst fissure water and the clastic fissure water are widely enriched in the central area of Xishan Mountain. The unconsolidated pore water is widely distributed in Taiyuan Basin area, while in Xishan Mountain area it is mainly distributed in the mountain valley area.

Based on Zhao and Cai (1990), the Ordovician rocks are mainly composed of limestone, dolomite, and marl interbedded with gypsum, including two series of formations. The Lower Series is composed of the Yeli formation (O_1y) and the Liangjiashan formation (O_1l). The Middle Series consists of the Fengfeng formation (O_2f) and the Majiagou formation (O_2m), which is the predominant aquifer with regional water supply significance in Taiyuan region. The overlying Carboniferous, Permian and Triassic clastic rocks may partially be aquifers, but they are aquicludes in most areas, which constitute the upper confining bed of the carbonate aquifer. The Quaternary alluvium constitutes the main water supply aquifer in Taiyuan Basin area.

The Jinci karst aquifer system occurs in a synclinal structure. Rainfall is the main recharge source of groundwater in Jinci Spring catchment. The Fenhe River leakage is another important recharge source. The predominant discharge of karst groundwater has changed from the natural spring flow to well pumping; there are also the lowering of pressure and dewatering of karst groundwater in coal mines and the lateral outflow of groundwater to the Quaternary unconsolidated aquifer along the peripheral faults zone of Xishan Mountain. After receiving the rainfall recharge and the Fenhe River leaks in the limestone mountainous area of the north and the Fenhe River valley, respectively, karst groundwater flows from the northwest to the southeast and to the piedmont areas of Xishan Mountain. After entering the peripheral faults zone, due to the sudden change of the water-bearing medium to the Quaternary unconsolidated rocks with the relatively weak permeability, the karst groundwater is blocked and flows out as a spring.

According to the collected data, the average annual groundwater exploitation (including well pumping and coal mining drainage, the same below) is 1.54 m^3/s (1994–2014). Figure 3-7 shows the contour map of karst groundwater level of Jinci Spring catchment at the initial of 2014.

Figure 3-8 shows the quantitative changes in the six major ions (Na^+, Ca^{2+}, Mg^{2+}, HCO_3^-, SO_4^{2-} and Cl^-) and pH of Jinci Spring catchment during the period of 1994-2014. As can be seen from the Figure 3-8, the major ions and pH as a whole show an increasing trend (Zhang et al. 2019).

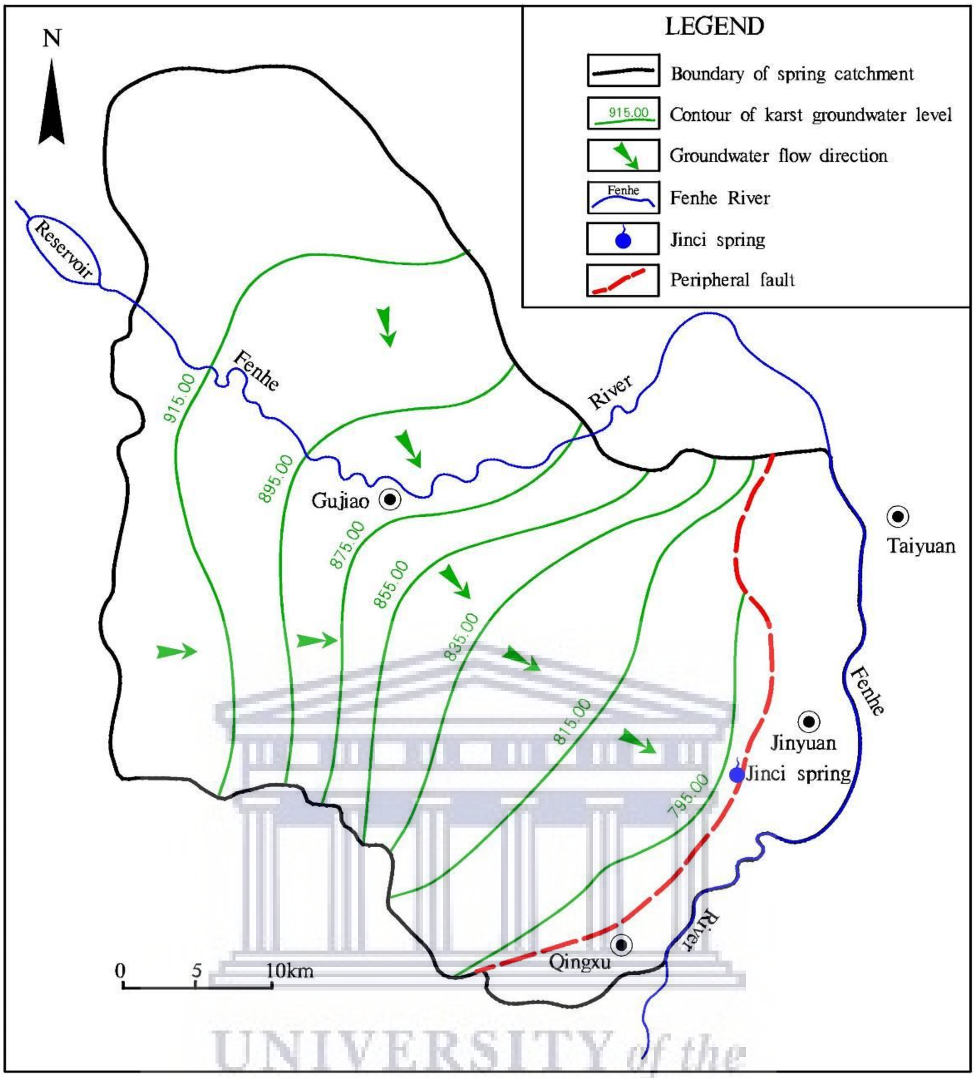


Figure 3-7 Contour map of karst groundwater level at the initial of 2014

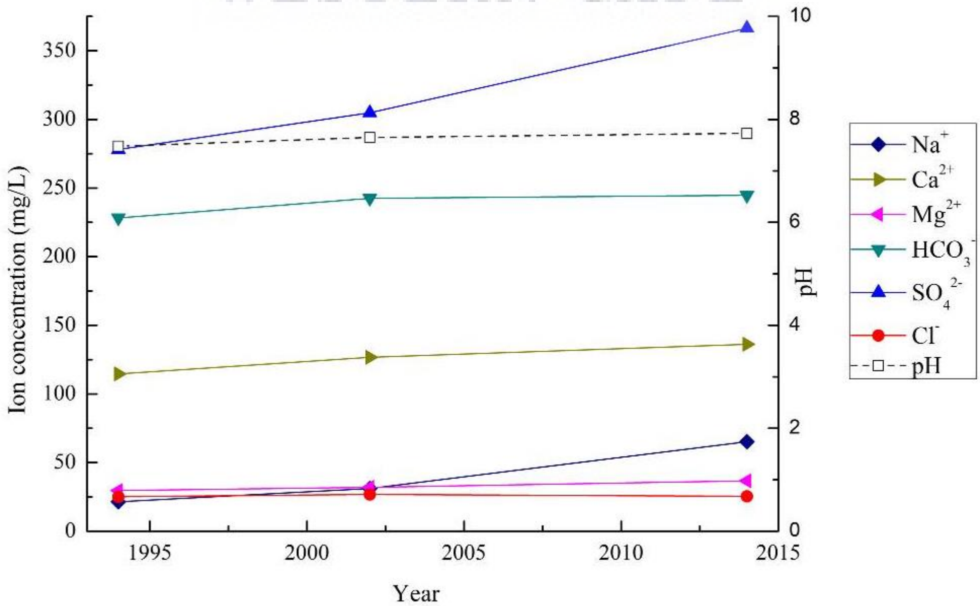


Figure 3-8 Changes in major ions and pH

Compared the major ions and pH of 1994 with that in 2014, the percentage increase is shown in Table 3-1.

Table 3-1 Percentage increase in the major ions, from 1994 to 2014

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

It can be seen from Table 3-1, Na^+ (203.96%) rose the most, followed by SO_4^{2-} (31.75%), Mg^{2+} (23.99%), Ca^{2+} (18.85%), HCO_3^- (7.23%) and Cl^- (1.19%). The average increase of the three cations was 82.27%, and the average increase of the three anions was 13.39%. Therefore, the average increase of all six ions was 47.83%.

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

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

3.7 Summary

The famous Jinci Temple in Taiyuan is highly valued due to presence of Jinci Spring. The Fenhe River is the largest within the provincial region. Jinci Spring is an ascending spring of non-full discharge type. The spring dried up on 30 April 1994. The Middle Series of the

Ordovician rocks consists of the Fengfeng formation and the Majiagou formation, which is the predominant aquifer with regional water supply significance in Taiyuan region. Groundwater recharge is dominated by the precipitation infiltration and leakage of the Fenhe River. Groundwater discharge includes spring, well pumping, lateral discharge to the Quaternary aquifer and dewatering of karst groundwater in coal mines. The major ions and pH as a whole show an increasing trend.

Chapter 4

Causes of the drying up of Jinci Spring and its sustainability

In this chapter, the author investigates the causes of the drying up of Jinci Spring; assesses the sustainable yield of karst groundwater in Jinci Spring catchment; quantifies the sustainability threshold of karst groundwater in Jinci Spring catchment; and determines the ecological water level restrictions of Jinci Spring catchment.

4.1 Data acquisition and methodology

4.1.1 Data acquisition

The data (1956-2014) used in this study mainly were collected from three different sources. The data of karst groundwater level of spring, spring flow, groundwater exploitation (including well pumping and coal mining drainage, the same below), Fenhe River leakage and lateral discharge were done over a long-term monitoring programme by the local water authority. Rainfall data were obtained from the local meteorological administration. Borehole and pumping test data were acquired from the local hydrogeological investigation department.

4.1.2 The capture principle

The capture principle means that if groundwater of an aquifer in a basin is abstracted, the supply of abstraction comes from three factors (Theis 1940): (1) reduction in aquifer storage; (2) more water enter into the aquifer system (increased recharge); (3) less water leave out of the aquifer system (decreased discharge), in which the sum of the increased recharge and decreased discharge is called capture, and the aquifer system can reach groundwater equilibrium when the abstraction is balanced by capture.

Thus, on the basis of analyzing the data of rainfall, spring flow, karst groundwater level of spring, groundwater exploitation and Fenhe River leakage in Jinci Spring catchment from 1956 to 2014, the variation trends are identified and quantified, and the causes of the drying up of Jinci Spring are investigated by using the capture principle. The comparison between the average annual recharge (not taking into account of the induced recharge) and the average annual discharge is used to make a further interpretation.

4.1.3 The methods for the sustainable yield assessment

4.1.3.1 The capture equation

The capture equation (Lohman 1972; Seward et al. 2006) is described as follows:

$$R + \Delta R = D + \Delta D + Q + S\Delta h/\Delta t \qquad (1)$$

where: R is virgin or natural recharge, ΔR is increased recharge induced by groundwater abstraction, D is virgin or natural discharge, ΔD is decreased discharge induced by groundwater abstraction, Q is rate of groundwater abstraction, and $S\Delta h/\Delta t$ is rate of change of aquifer storage.

For equation (1), in the long-term virgin or natural conditions, R equals D and $S\Delta h/\Delta t$ equals 0. Therefore, if the groundwater of an aquifer in a basin is abstracted, and if groundwater equilibrium conditions are achieved, then the equation (1) changes to equation (2):

$$Q = \Delta R - \Delta D \qquad (2)$$

Therefore, the equation (2) reveals that it is the increased recharge and decreased discharge that determine the sustainable yield of a groundwater system.

4.1.3.2 GAWDU method

Due to the complexity of river ecosystems, there are no universally accepted methods for calculating the basic ecological water demand of rivers. In fact, there are many calculation methods abroad, and the domestic methods are still in its infancy. Because of the lack of ecological data in China's rivers, the international methods are not necessarily suitable for the study area in China. "Guidelines for Assessment Water-Draw and Utilization in Construction Projects" (GAWDU method) issued by the Ministry of Water Resources of China in 2005 requires that the ecological base flow of the northern rivers should not be less than 20% of the average flow rate during the dry season, and not less than 10% of the average flow rate during other periods. The GAWDU method is suitable for maintaining the health of the northern river ecosystems at the present stage. Jinci Spring catchment is in the northern China. Therefore, the GAWDU method can be used to assess the basic ecological water demand of the downstream of the spring.

Thus, the equation (1) is used to derive the capture equation of karst groundwater in Jinci Spring catchment. Combining with the multi-year series of karst groundwater exploitation, GAWDU method is used to assess the sustainable yield of karst groundwater under ecological constraints.

4.1.4 The method for quantification of the sustainability threshold

For Jinci Spring catchment, karst groundwater development should not only consider the consumptive use (the industrial, agricultural and domestic water uses), but also consider the nonconsumptive use (the aquatic ecological demand of the downstream of the spring). That is to say, both consumptive use and nonconsumptive use must meet the sustainability (McCartney et al. 2000; Seward 2010). Rajkumar and Xu (2011) reported that the groundwater resources protection requires good planning and collaborative efforts. Thus, the basic goal of sustainability of Jinci Spring catchment is to set a clear objective for karst groundwater protection, that is, to achieve a certain balance between the consumptive use and the nonconsumptive use. This method can be used to quantify the sustainability threshold of karst groundwater in Jinci Spring catchment.

Therefore, based on the analysis of the total benefits of the consumptive use and nonconsumptive use of karst groundwater in Jinci Spring catchment, the sustainability threshold is quantified in terms of the ecological constraints of spring flow and the total exploitation of karst groundwater for many years.

4.1.5 The method for ecological water level restrictions

By using the fitted equation between spring flow and karst groundwater level of spring from 1956 to 1994, the ecological water level restriction for early warning and the ecological water level restriction for water supply are calculated by the basic ecological spring flow of dry season and the basic ecological spring flow of other periods, respectively.

4.2 Results and discussion

4.2.1 Causes of the drying up of Jinci Spring

What caused Jinci Spring flow to decrease and eventually dried up in a short period of 39 years (1956~1994)? Only by clarifying the causes can we provide warnings and references for its protection for ecological re-outflow and the sustainable use of karst groundwater. The study showed that groundwater levels in monitoring wells are the most basic indicator reflecting groundwater conditions (Taylor and Alley 2001) and are critical to assess the quality and quantity of groundwater and its interaction with surfacewater. Therefore, the long-term monitoring data of karst groundwater are used to analyze the impacts of groundwater exploitation in Jinci Spring catchment, and the causes of the drying up of Jinci Spring are investigated by using the capture principle.

Figure 4-1 illustrates the annual rainfall, karst groundwater level of spring, spring flow, groundwater exploitation and Fenhe River leakage of Jinci Spring catchment from 1956 to 2014.

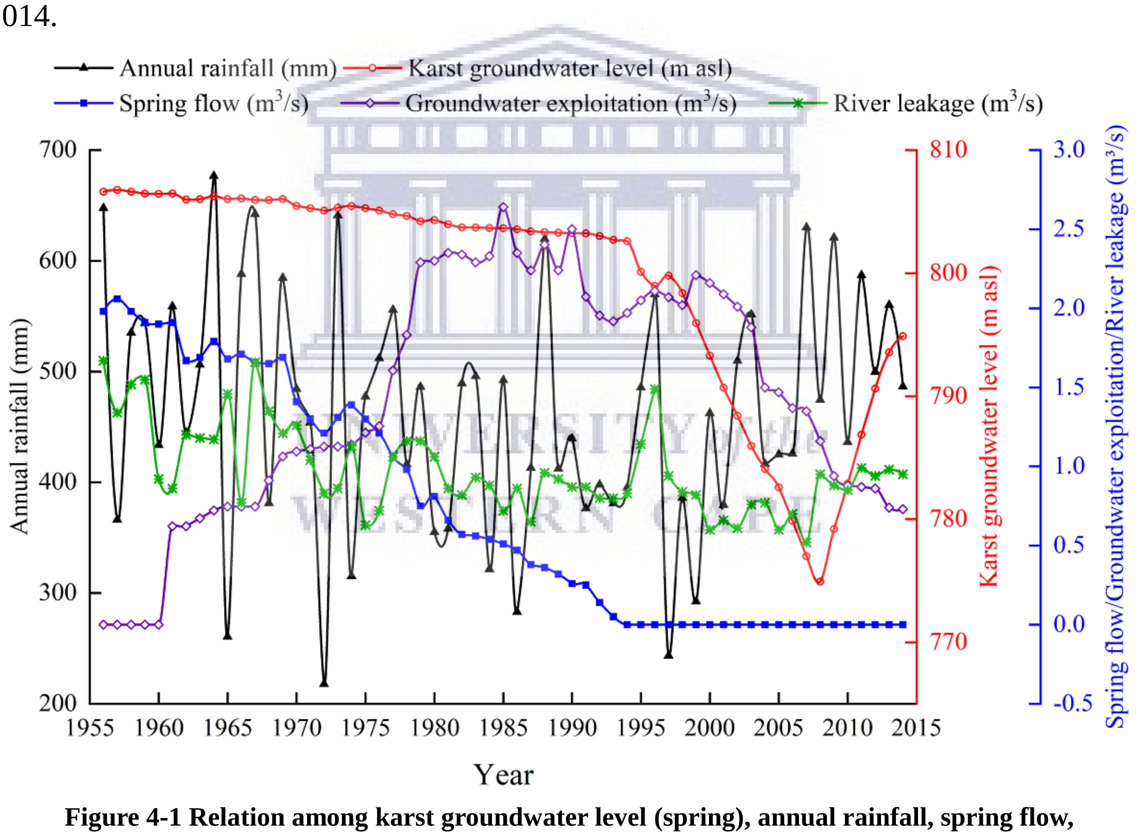


Figure 4-1 Relation among karst groundwater level (spring), annual rainfall, spring flow, groundwater exploitation, and river leakage, from 1956 to 2014

As shown in Figure 4-1, the annual rainfall had strong variations, with a significant decreasing trend in 1956-1994 and a significant increasing trend in 1995-2014. The spring flow showed an obvious downward trend from 1956 (1.98 m^3/s) to 1994 (0 m^3/s), indicating a 100% decrease over 39 years, with a decreasing trend of 0.05 (m^3/s)/year. The decrease of spring flow was accompanied by the change in rainfall during the period of

1956-1994, and there was a certain lag before 1980. Since 1980, however, this relation has become smaller and smaller, indicating that another factor plays an increasingly important role in the decrease of spring flow.

In order to identify the variation trend of karst groundwater level of spring, the study period was divided into three segments, 1956-1994, 1995-2007 and 2008-2014. In the first segment, the karst groundwater level had a slow decreasing trend of 10.3 cm/year. The groundwater exploitation showed an increasing trend and the Fenhe River leakage showed a decreasing trend, resulted in a decreasing trend of karst groundwater level. In the second segment, the karst groundwater level had a significant decreasing trend of 184.3 cm/year. Though the rainfall showed an increasing trend and the groundwater exploitation showed a decreasing trend, the decrease of Fenhe River leakage aggravated the decline of karst groundwater level. In the third segment, the karst groundwater level had a significant increasing trend of 284.8 cm/year. The rainfall and the Fenhe River leakage both showed an increasing trend, and the groundwater exploitation showed a decreasing trend. All of them played an active role in promoting the rise of karst groundwater level, but the rising amplitude decreased obviously in the latter stage.

It can be seen that under the influence of rainfall fluctuations, the increase of groundwater exploitation and the decrease of the Fenhe River leakage intensify the decline of karst groundwater level of spring, while the reduction of groundwater exploitation and the increase of the Fenhe River leakage result in the rise of karst groundwater level of spring.

Based on the data of karst groundwater level of spring, groundwater exploitation, and rainfall from 1956 to 1994, the present study established the correlation linear model between karst groundwater level of spring and groundwater exploitation, as well as rainfall, and calculated the correlation coefficient (Table 4-1).

It can be seen from Table 4-1 that the correlation coefficient of karst groundwater level of spring and groundwater exploitation is 0.8112, while the correlation coefficient of karst groundwater level of spring and rainfall is 0.0992. Thus, the impact of groundwater exploitation on karst groundwater level of spring is much greater than that of rainfall. In other words, the exploitation of karst groundwater is the dominant factor in the cessation of Jinci Spring.

Table 4-1 The correlation linear model between karst groundwater level of spring and groundwater exploitation, as well as rainfall

Relation	Correlation linear model	Correlation coefficient
Karst groundwater level of spring (H) and groundwater exploitation (Q)	$H = -1.7844Q + 807.03$	0.8112
Karst groundwater level of spring (H) and rainfall (R)	$H = 0.00404R + 803.002$	0.0992

Zhang et al. (2018) considered that the climate change and human activities have negative impacts on Shanxi spring flows. Based on the analysis of climate change of 1959-2008 in Shanxi Region, Fan and Wang (2011) concluded that the average annual temperature has increased by 1.20 °C and the average annual rainfall has decreased by 99.20 mm, and the central region of Shanxi has experienced a significant decrease in rainfall in the past 50 years. As can be seen from Figure 1-1, Jinci Spring catchment is located in the central region of Shanxi. During 1956-1994, the decrease of rainfall directly led to the decrease of recharge, which aggravated the decrease and cessation of Jinci Spring accordingly. Therefore, climate change is one of the key causative factors of the drying up of Jinci Spring.

Before 1961, the karst groundwater system of Jinci Spring catchment was in a long-term state of dynamic equilibrium, and the recharge equaled the discharge (Alley et al. 1999). Since 1961, the karst groundwater in Jinci Spring catchment has been in a state of exploitation. According to the capture principle, if the karst groundwater in Jinci Spring catchment was exploited, this exploitation must be provided by: more water flowing into the groundwater system (increased recharge), less water leaving the groundwater system (reduced discharge), and removing the stored water (Theis 1940). Figure 4-2 shows the relationship between the change in storage, increased recharge, and reduced discharge due to groundwater abstraction in Jinci Spring catchment (Leake 2001).

Under the condition of exploitation, the natural balance of karst groundwater is broken. The discharge mode of karst groundwater is increased, and the discharge of karst groundwater is also changed. Therefore, a new equilibrium must be found through the change of karst groundwater level in Jinci Spring catchment.

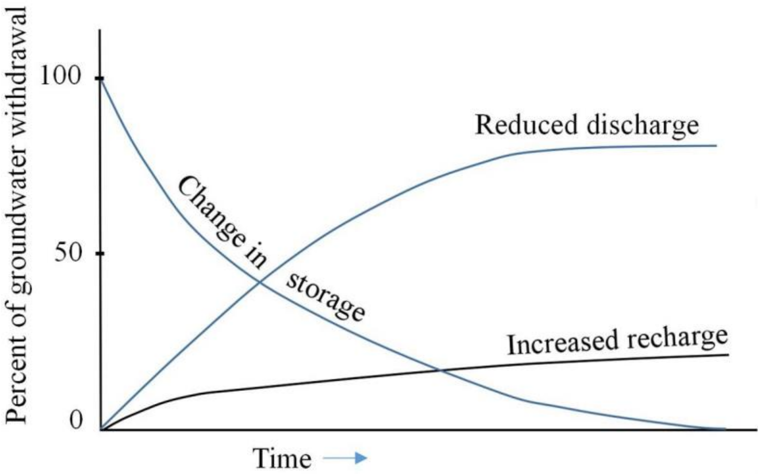


Figure 4-2 Impacts of pumping on increased recharge, reduced discharge and storage of karst aquifer in Jinci Spring catchment (adapted from Leake, 2001)

It can be seen from Figure 4-2, prior to the equilibrium of karst groundwater system in Jinci Spring catchment, due to the relative small volume of the increased recharge and reduced discharge, part of the groundwater must be removed from karst aquifer storage to meet the needs of abstraction rate. With the continuing groundwater withdrawal in Jinci Spring catchment, the change in storage gradually decreased. Equilibrium can only be achieved when karst groundwater exploitation is fully supplied by capture. By this time, the karst aquifer storage is no longer consumed. Although the equilibrium state was reached, it resulted in the consumption of original storage. This consumption is determined by the area under the curve of the change in storage, which is actually a volume. Thus, for certain exploitation within a certain period of time, the consumption of storage must be accompanied by the decline of karst groundwater level, and the decline in karst groundwater level inevitably led to the decrease in spring flow. It can be seen that under the impacts of karst groundwater withdrawal in the previous period, the effects of groundwater withdrawal in the latter period was superimposed, which repeatedly led to the consumption of storage and the decline of karst groundwater level. In this period, karst groundwater level was higher than the elevation at the mouth of spring (802.59 m asl) and the spring could still outflow, but the decrease of spring flow was increased.

With the further increase of karst groundwater exploitation in Jinci Spring catchment in the later stages, the karst groundwater eventually reached an unstable state. The interannual exploitation in the 1980s was greater than that in the 1990s. The average decrease rate of Jinci Spring flow was 0.04 (m^3/s)/year in the 1980s, while in the 1990s it was 0.063 (m^3/s)/year. All of these fully demonstrate that the karst groundwater withdrawal has reached an unstable state in the 1990s. The decrease of spring flow has further accelerated and the spring was dry in 1994. This is due to the fact that the sum of the increased recharge and reduced discharge cannot be infinitely increased, and the karst aquifer storage is continuously consumed because the groundwater exploitation cannot be balanced by capture. As the karst groundwater level runs below the elevation at the mouth of spring (802.59 m asl), the outflow conditions of the spring cannot be met. Therefore, the long-term consumption of karst aquifer storage is another key causative factor of the drying up of Jinci Spring.

Figure 4-3 shows the total average recharge and total average discharge of Jinci Spring catchment in different periods (1956-1994).

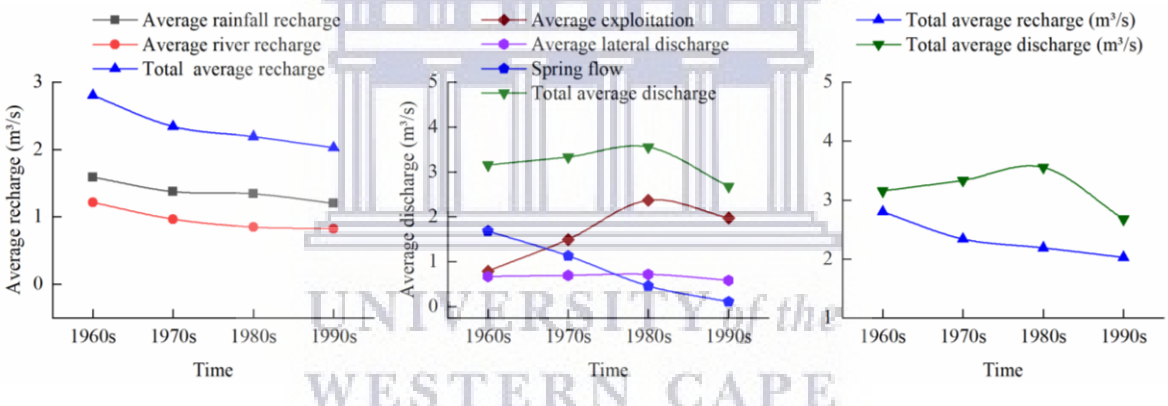


Figure 4-3 Total average recharge and total average discharge in different periods (1956-1994)

As can be seen from Figure 4-3, the total average recharge (the sum of the average rainfall recharge and average Fenhe River leakage) of Jinci Spring catchment in the 1960s, 1970s, 1980s, and 1990s (1991-1994) showed a decreasing trend. In the same period, the total average discharge (the sum of the average abstraction, average lateral discharge and average spring flow) changed from the increasing trend to the decreasing trend. However, the total average discharge was always greater than the total average recharge. Based on statistics, the average recharge of karst groundwater for many years (1961~1994) was 75.5×10^6 m^3/year, and the average discharge was 103×10^6 m^3/year. The difference was -27.5×10^6 m^3/year. Thus, the karst groundwater for many years (1961-1994) has been in a state of overexploitation, and the karst aquifer storage has been continuously consumed, resulted in the continuing decline of groundwater level and the drying up of Jinci Spring. Although this interpretation does not reflect the capture principle of groundwater, it supports the previous view from the perspective of groundwater balance, that is, the long-term consumption of karst aquifer storage is another key causative factor of the drying up of Jinci Spring.

In the light of the above facts and findings, it is concluded that climate change and the long-term consumption of karst aquifer storage are the key causative factors of the drying up of Jinci Spring.

4.2.2 Sustainable yield of karst groundwater

The exploitable resource of karst groundwater is the maximum amount of karst water that can be abstracted from an aquifer without causing geological, environmental and ecological adverse effects under economic and technical feasibility (Zhang et al. 2018). This is similar to the sustainable yield of groundwater described in the introduction of this thesis. It can be said that this concept is another description of the sustainability of karst groundwater.

From the perspective of Jinci Spring catchment, karst groundwater always maintains the equilibrium for a certain period of time, that is, groundwater balance. It's just that this balance reflects the capture of karst groundwater withdrawal. Therefore, the capture equation (1) can be used to assess the sustainable yield of karst groundwater in Jinci Spring catchment.

Before 1961, karst groundwater in Jinci Spring catchment was in an undeveloped state, and Jinci Spring maintained a natural or virgin flow. The natural equilibrium equation of its karst groundwater is as follows:

$$R_{rainfall} + R_{river} = D_{spring} + D_{lateral} \qquad (3)$$

where: $R_{rainfall}$ is rainfall recharge, R_{river} is Fenhe River leakage, D_{spring} is natural spring discharge, and $D_{lateral}$ is lateral discharge to Quaternary unconsolidated aquifer.

Jinci Spring catchment belongs to an independent karst groundwater system. It has a clear groundwater divide and hydraulic boundary with the Lancun Spring catchment mentioned earlier. Since 1961, there has been groundwater withdrawal in Jinci Spring catchment. Based on the capture equation (1), the groundwater equilibrium equation of Jinci Spring catchment under pumping conditions can be written as follows:

$$R_{rainfall} + R_{river} + \Delta R = D_{spring} + D_{lateral} + \Delta D + Q_{well\ pumping} + Q_{mine\ drainage} + S\Delta h/\Delta t \quad (4)$$

where: ΔR is increased recharge caused by karst groundwater withdrawal, ΔD is decreased discharge caused by karst groundwater withdrawal, $Q_{well\ pumping}$ is rate of well pumping, $Q_{mine\ drainage}$ is rate of mine drainage, and $S\Delta h/\Delta t$ is rate of change of karst aquifer storage.

Actually, for Jinci Spring catchment, under long-term natural or virgin conditions, SΔh/Δt equals to 0. When karst groundwater withdrawal reaches the equilibrium conditions, the following results can be obtained:

$$Q_{well\ pumping} + Q_{mine\ drainage} = \Delta R - \Delta D \quad (5)$$

Based on the long-term monitoring data in Jinci Spring catchment, the lateral flow from karst aquifer to Quaternary unconsolidated aquifer has been maintained at around 0.68 m^3/s. It can be regarded as a fixed value. Jinci Spring flow has changed greatly and decreased continuously. Therefore, for Jinci Spring catchment, the reduced discharge caused by groundwater withdrawal is approximately equals to the reduced spring flow, i.e. $\Delta D = \Delta D_{reduced\ spring\ flow}$. The leakage section of the Fenhe River is located in the northern part of the catchment, the difference between the river water level and karst groundwater level is over 120 m. The pumping wells are mainly located in the southern discharge area. The minimum distance from the leakage section of the Fenhe River to the pumping wells is 30 km. The interactions between groundwater and surfacewater are complex, which are determined by human activities and the geometries and positions of aquifers and surfacewater (Levy and Xu 2012). The capture in a balance sense is related to the radius of influence of the pumping well (Seward et al. 2015). In fact, this “capture” is quite different from the “capture” zone described in contaminant hydrogeology (Zhou 2011). According to the publications, the maximum well spacing can generally less than 6 km (Brozović et al. 2006), that is to say, the radius of influence is less than 3 km. For Jinci Spring catchment, the distances from the leakage section of the Fenhe River to the pumping wells are far greater than the radius of influence, there is no increased recharge of the Fenhe River leakage caused by groundwater exploitation. Therefore, the increased recharge induced by groundwater exploitation mainly comes from the leakage recharge of the overlying fissure aquifers, i.e. $\Delta R = \Delta R_{induced\ leakage\ recharge}$. Due to $Q_{exploitation} = Q_{well\ pumping} + Q_{mine\ drainage}$, it is obtained from equation (5):

$$Q_{exploitation} = \Delta R_{induced\ leakage\ recharge} - \Delta D_{reduced\ spring\ flow} \quad (6)$$

where: $Q_{exploitation}$ is rate of well pumping and mine drainage, $\Delta R_{induced\ leakage\ recharge}$ is induced leakage recharge of the overlying fissure aquifers caused by karst groundwater withdrawal, and $\Delta D_{reduced\ spring\ flow}$ is reduced spring flow caused by karst groundwater withdrawal.

From the perspective of groundwater exploitation, equation (6) is the capture equation of karst groundwater in Jinci Spring catchment. With regard to a groundwater system, sustainability is determined by the increased recharge and reduced discharge induced by groundwater withdrawal. Therefore, it is considered that the sustainable yield of karst groundwater in Jinci Spring catchment is determined by the induced leakage recharge and the reduced spring flow (Figure 4-4).

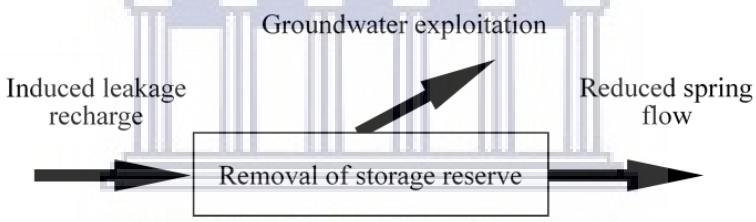


Figure 4-4 Water budget under groundwater exploitation in Jinci Spring catchment

The reduced spring flow caused by groundwater exploitation is easily determined, but due to the scarcity of leakage recharge of the overlying fissure aquifers induced by groundwater exploitation, it is impossible to directly assess the sustainable yield of karst groundwater by the capture equation (6). Nevertheless, the capture equation (6) is of great significance, which shows that the sustainable yield of karst groundwater in Jinci Spring catchment is not determined by the natural recharge.

The assessment of sustainable yield has technical and political problems (Seward et al. 2006). For a groundwater system, the technical problem is to arrange the pumping wells and choose the groundwater exploitation in order to grab as much groundwater losses as possible; the political problem is the amount that is allowed to reduce in the existing discharges. This view is consistent with the water governance proposed by Hoogester and Wester (2015). The common purpose of both is to avoid water problems. Therefore, under the premise of meeting technical and political problems, the sustainable yield of karst groundwater in Jinci Spring catchment is not a single and fixed value, but has a series of permissible values, that is, a series of sustainable yield of karst groundwater.

There are a series of data of karst groundwater exploitation in Jinci Spring catchment from 1961 to 1994, but this does not mean that all the data meet sustainable development. In fact, the data only meet technical problem, but do not meet the political problem (the allowable reduction in Jinci Spring flow). When considering the basic ecological water demand of the downstream of the spring, the spring flow cannot be reduced indefinitely. Sustainable development of groundwater must ensure that water resources are not threatened by overexploitation, and protect the natural environments that rely on water resources (Sophocleous 2005). In the development of karst groundwater in Jinci Spring catchment, the basic ecological water demand of the downstream of the spring was neglected for many years. The major role of groundwater on river flow is its contribution to the base flow (Levy and Xu 2012). According to basic ecological water demand, the ecological spring flow is the minimum flow that maintains and protects the most basic ecological functioning of the downstream of the spring. Thus, ensuring the basic ecological spring flow is of great significance.

Jinci Spring flows from 1956 to 1960 were in a natural or virgin state, with an average spring flow of 1.966 m^3/s. In the light of the GAWDU method, the two basic ecological spring flows are identified as 0.393 m^3/s (dry season) and 0.197 m^3/s (other periods). As previously mentioned, karst groundwater development in Jinci Spring catchment in the 1990s (1991-1994) was already unstable and unsustainable. The maximum spring flow is 0.25 m^3/s, which is greater than 0.197 m^3/s. The spring flow in 1990 was 0.26 m^3/s, which should not be regarded as the basic ecological spring flow (other periods) from the perspective of aquatic ecology. The spring flow in 1989 was 0.32 m^3/s, which is sustainable and meets the basic ecological water demand of the downstream of the spring. Therefore, the present study determined that the two basic ecological spring flows are 0.393 m^3/s (dry season) and 0.32 m^3/s (other periods) in Jinci Spring catchment.

According to the serial data of groundwater exploitation from 1961 to 1989, the minimum was 0.622 m^3/s in 1961, and the maximum was 2.64 m^3/s in 1985. The spring flows from 1961 to 1986 were greater than the basic ecological spring flow of 0.393 m^3/s (dry season). The spring flows from 1961 to 1989 were greater than or equal to the basic ecological spring flow of 0.32 m^3/s (other periods). For Jinci Spring catchment, only the sustainable yield under development condition is meaningful. To prevent groundwater from becoming unstable, the sustainable yield of groundwater should be less than the average annual recharge (excluding induced recharge). The average annual recharge of Jinci Spring catchment for many years (1956-1989) was 2.53 m^3/s. Thus, the exploitation of 2.64 m^3/s in 1985 was unsustainable. As mentioned earlier, the sustainable yield of karst groundwater in Jinci Spring catchment is not a single and fixed value, but has a series of permissible values. In addition, the exploitation were large from 1981 to 1989, with an average of 2.35 m^3/s, which is the same as that in 1981. However, the exploitation of 2.40 m^3/s in 1988 was greater than the average (2.35 m^3/s). To facilitate the protection of karst groundwater, the present study assessed the maximum sustainable yield as 2.35 m^3/s. Finally, it is concluded that the sustainable yield of karst groundwater under ecological constraints has a series of permissible values range from 0.622 to 2.35 m^3/s (Table 4-2).

Table 4-2 Sustainable yield of karst groundwater in Jinci Spring catchment

Year	Sustainable yield (m^3/s)	Note
1961	0.622	minimum
1981	2.350	maximum

4.2.3 Sustainability threshold of karst groundwater

According to McCartney et al. (2000), the present study clarifies two key concepts of the sustainability of karst groundwater in Jinci Spring catchment. The first concept is "optimization", that is, to exploit a certain amount of groundwater from the karst aquifer and leave a certain amount of groundwater to the aquatic ecosystems in the downstream of the Jinci Spring. The aim is to promote the integrity of karst groundwater and aquatic ecosystems. It can be seen from Figure 4-5 (McCartney et al. 2000; Seward 2010), in the initial stage, with the gradual increase of the consumptive use of karst groundwater in Jinci Spring catchment, the total benefits (the sum of the consumptive and nonconsumptive benefits) gradually increases and then reaches the optimal level. Afterwards, the total benefits begin to decrease when more groundwater is removed from the karst aquifer. The second concept is "threshold", that is, as the consumptive use of karst groundwater in Jinci Spring catchment continues to increase, it will eventually exceed a certain amount, threatening the integrity of the aquatic ecosystems that depend on karst groundwater in the downstream of the Jinci Spring. In Figure 4-5, the sustainability threshold of Jinci Spring catchment is shown as an interval. The interval is closely related to the two basic ecological spring flows of 0.393 m^3/s (dry season) and 0.32 m^3/s (other periods). To ensure the sustainability of karst groundwater and the aquatic ecosystems in the downstream of the Jinci Spring, the sustainability threshold is a limited range of the total exploitation of karst groundwater for industrial, agricultural and domestic water uses.

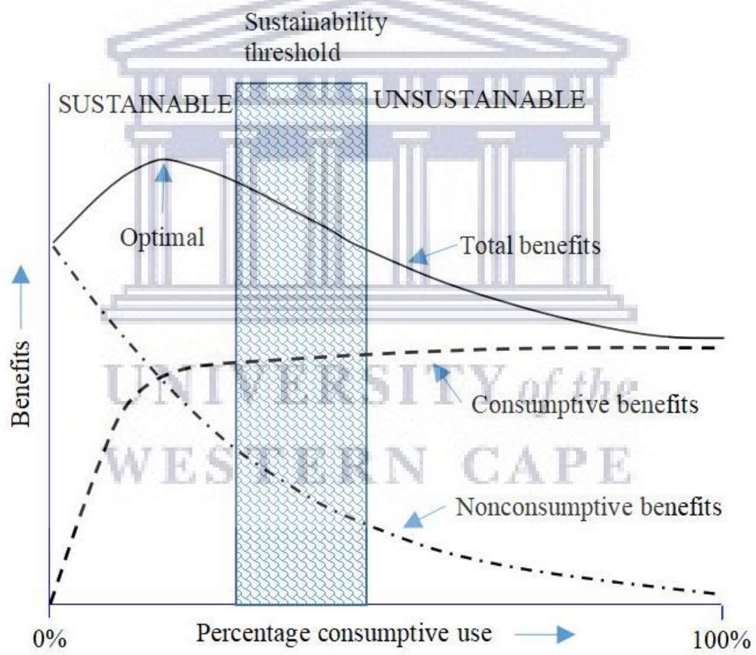


Figure 4-5 Total benefits vs. consumptive use percentage (adapted from McCartney et al. 2000 and Seward 2010)

The minimum flow of Jinci Spring from 1961 to 1986 was 0.47 m^3/s in 1986, which is greater than the basic ecological spring flow of 0.393 m^3/s in dry season. The maximum flow of Jinci Spring from 1987 to 1994 was 0.38 m^3/s in 1987, which is less than the basic ecological spring flow of 0.393 m^3/s in dry season. The total exploitation of karst groundwater from 1961 to 1986 was 11.74×10^8 m^3, and from 1961 to 1987 it was 12.45×10^8 m^3. Therefore, using the interpolation method, this research obtained that the total exploitation (Q_{total}) under the basic ecological spring flow of 0.393 m^3/s in dry season was 12.35×10^8 m^3. The calculated equation for Q_{total} is as follows:

$$(12.45\times10^8 - Q_{total}) / (0.393 - 0.38) = (Q_{total} - 11.74\times10^8) / (0.47 - 0.393) \qquad (7)$$

By solving equation (7), it obtained that the $Q_{total} = 12.35\times10^8$ m^3. This value meets the requirements of karst groundwater optimization. The minimum flow of Jinci Spring from 1961 to 1989 was 0.32 m^3/s in 1989, which is equal to the basic ecological spring flow of 0.32 m^3/s in other periods. The maximum flow of Jinci Spring from 1990 to 1994 was 0.26 m^3/s in 1990, which is less than the basic ecological spring flow of 0.32 m^3/s in other periods. The total exploitation of karst groundwater from 1961 to 1989 was 13.91×10^8 m^3. Thus, the total exploitation under the basic ecological spring flow of 0.32 m^3/s in other periods was 13.91×10^8 m^3, which also meets the requirements of karst groundwater optimization. Therefore, the sustainability threshold of karst groundwater in Jinci Spring catchment is quantified as [12.35×10^8 m^3, 13.91×10^8 m^3]. The threshold is the boundary between sustainability and unsustainability of karst groundwater.

Unfortunately, since 1990, the total exploitation of karst groundwater for many years in Jinci Spring catchment has crossed the sustainability threshold. It eventually led to the continuing decline of karst groundwater level and the drying up of Jinci Spring, and had serious impacts on the aquatic ecosystems in the downstream of the spring and the ecotourism value of the Jinci Temple. Hence one can see that the sustainability threshold has important implications.

4.2.4 The ecological water level restrictions

Karst groundwater level in Jinci Spring catchment is not only related to the resources of aquifer, but also to the aquatic ecosystems in the downstream of the spring and the ecotourism value of the Jinci Temple. Therefore, the sustainable development of karst groundwater should not only partially meet the demand for water supply, but also maintain the annual outflow of Jinci Spring and meet the aquatic ecological water demand in the downstream of the spring.

The author believe that the most basic indicator for sustainable development of karst groundwater in Jinci Spring catchment is the ecological water level restrictions, including the ecological water level restriction for early warning and the ecological water level restriction for water supply. The two terms are very similar to the water level restriction for early warning for spring and water level restriction for water supply described by Zhang et al. (2018). But in fact they have completely different meanings. The new terms consider aquatic ecological water use, while the old terms do not. The water level restriction for early warning for spring and water level restriction for water supply are equal to and lower than the elevation at the mouth of spring (Zhang et al. 2018), respectively. The ecological water level restriction for early warning and the ecological water level restriction for water supply must be higher than the elevation at the mouth of Jinci Spring.

Jinci Spring flow is restricted by the karst groundwater level at the mouth of the spring, which makes it more closely related to the karst groundwater level of spring. Based on the long-term monitoring data of the spring flow and karst groundwater level of spring from 1956 to 1994, the fitted equation of the spring flow and karst groundwater level is established: $Q_{spring} = 0.4992 H_{karst\ groundwater\ level} - 400.64$, the correlation coefficient R^2 = 0.9992 (Figure 4-6). Statistical analysis shows that there is a positive correlation between spring flow and karst groundwater level.

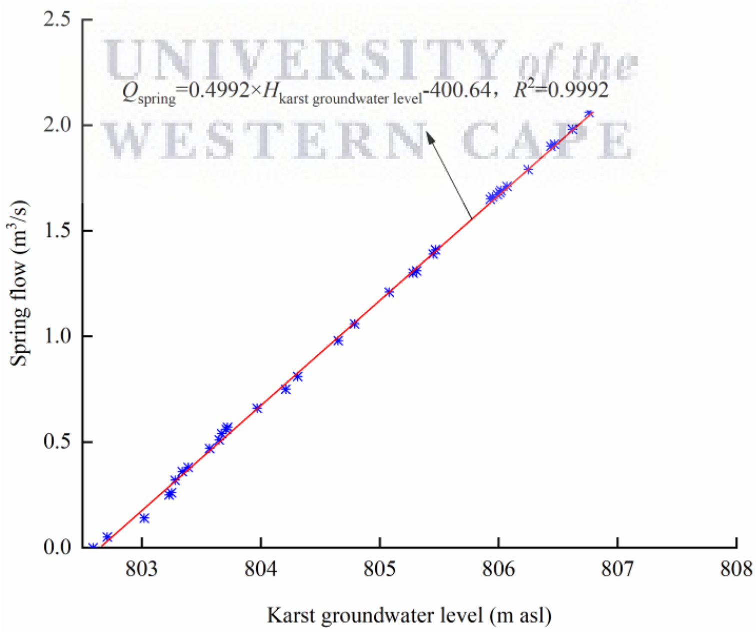


Figure 4-6 Correlation between Jinci Spring flow and karst groundwater level, from 1956 to 1994

The ecological constraints of the downstream of Jinci Spring are as follows: the basic ecological spring flow of 0.393 m^3/s in dry season and the basic ecological spring flow of

0.32 m^3/s in other periods. The karst groundwater level of spring corresponding to the two basic ecological spring flows are referred as the ecological water level restriction for early warning ($H_{early\ warning}$) and the ecological water level restriction for water supply ($H_{water\ supply}$).

The calculation results show that when Jinci Spring flow is 0.393 m^3/s, the ecological water level restriction for early warning ($H_{early\ warning}$) is 803.35 m asl (Figure 4-7); when Jinci Spring flow is 0.32 m^3/s, the ecological water level restriction for water supply ($H_{water\ supply}$) is 803.21 m asl (Figure 4-7). The two ecological water level restrictions can also be called the critical elevations of karst groundwater for the ecological re-outflow of Jinci Spring.

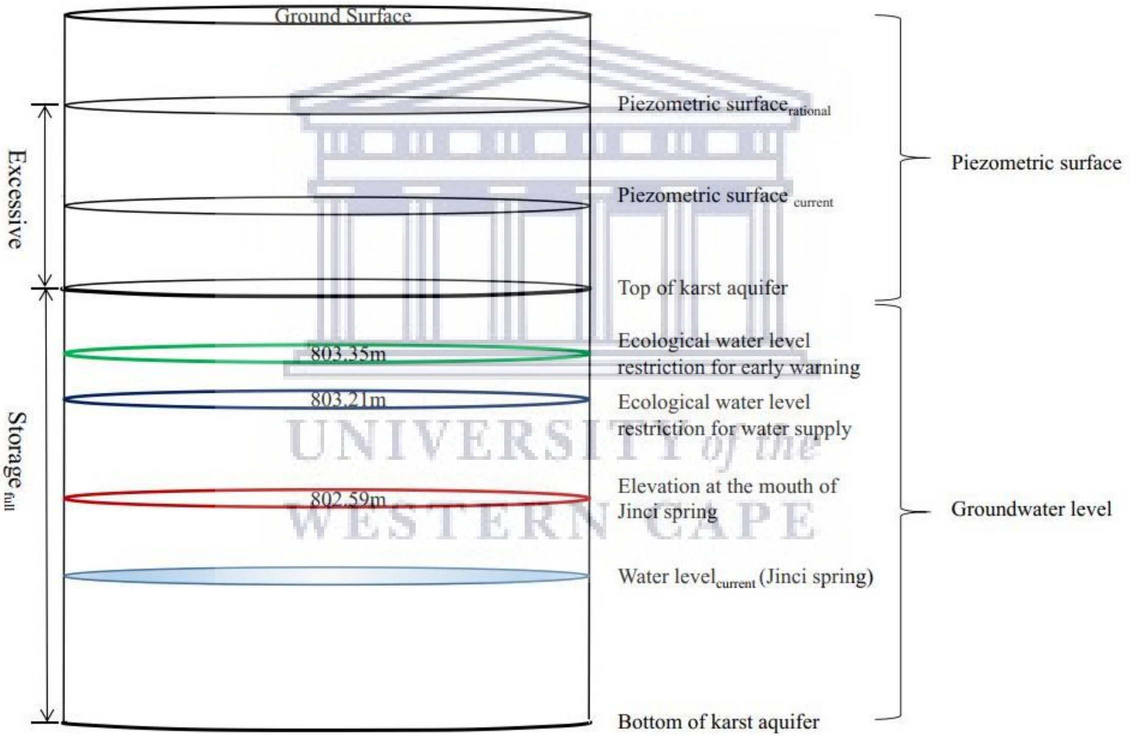


Figure 4-7 The ecological water level restrictions after the re-outflow of Jinci Spring

As the groundwater level at the mouth of Jinci Spring runs between 803.21 and 802.59 m asl, the spring still has a certain free flow, but the groundwater development is actually unsustainable. Therefore, the long-term monitoring of the karst groundwater level and Jinci Spring flow should be continuously strengthened after the ecological re-outflow of Jinci Spring. As the karst groundwater level and spring flow run below the ecological water level restriction for early warning of 803.35 m asl and the basic ecological spring flow of 0.393 m^3/s, respectively, the Water Resources Management Department must issue a warning in time. As the karst groundwater level and spring flow run below the ecological water level restriction for water supply of 803.21 m asl and the basic ecological spring flow of 0.32 m^3/s, respectively, the groundwater development department must stop the exploitation of groundwater to maintain the aquatic ecological water demand in the downstream of the spring.

4.3 Summary

The drying up of Jinci Spring is the biggest water ecological environmental problem in Jinci Spring catchment. It is also a typical case of governance failure of karst groundwater in Shanxi and China. The correlation coefficient of karst groundwater level of spring and groundwater exploitation is 0.8112, while the correlation coefficient of karst groundwater level of spring and rainfall is 0.0992. Climate change and the long-term consumption of karst aquifer storage are the key causative factors of the drying up of Jinci Spring. The sustainable yield of karst groundwater is determined by the leakage recharge of the overlying fissure aquifers and the reduced spring flow induced by groundwater exploitation, rather than natural recharge. The sustainable yield under ecological constraints is not a single and fixed value, but has a series of permissible values that range from 0.622 to 2.35 m^3/s. The sustainability threshold of karst groundwater in Jinci Spring catchment is [12.35×10^8 m^3, 13.91×10^8 m^3], which meets the requirements of groundwater optimization. The ecological water level restriction for early warning and the ecological water level restriction for water supply are 803.35 and 803.21 m asl, respectively. The long-term monitoring of the karst groundwater level and Jinci Spring flow should be continuously strengthened after the ecological re-outflow of Jinci Spring.

Chapter 5

Numerical modeling of re-outflow protection of Jinci Spring

In this chapter, to verify the influence of the groundwater abstraction and the recharge of the Fenhe River on karst groundwater level, the Jinci karst aquifer system is taken as the study area, and a simple 2D numerical model of karst groundwater in Jinci Spring catchment is used to design three different re-outflow protection scenarios, to forecast the dynamics of karst groundwater level, and to optimize the re-outflow protection scheme that meets the ecological criteria for Jinci Spring.

5.1 Method

In the light of the data of borehole, pumping test, source and sink, the finite difference algorithm of MODFLOW is used for numerical modeling of karst groundwater. Through the comparison of the simulation results of three different re-outflow protection scenarios, to optimize the re-outflow protection scheme that meets the ecological criteria for Jinci Spring. A fundamental premise of this numerical modeling is that the hydrogeological unit represented by model layer is composed of equivalent porous media. In simulating different scenarios, groundwater recharge is provided by rainfall and artificial recharge of the Fenhe River. Groundwater discharge occurs mainly through groundwater withdrawal, lateral discharge and spring discharge. The rainfall is distributed to the exposed limestone areas in the north by the average annual rainfall. The artificial recharge of the Fenhe River is uniformly assigned in the form of 30 injection wells in the limestone leakage section, and the lateral discharge of the peripheral faults zone is evenly assigned in the form of 25 pumping wells. Groundwater abstraction is assigned to the cells based on the location of pumping wells. The layer attribute of the model is specified as confined. The property of "spring" are implemented by the "drainage", which is a module in the software. When the spring water level is higher than 802.59 m asl, the spring flow will discharge through this "drainage" module automatically.

5.2 Boundary conditions

The northern boundary is adjacent to the metamorphic rock mountain area, which is an impermeable boundary. The western boundary is next to the metamorphic and igneous rocks mountain areas, which is a no-flow boundary. The southern boundary is the peripheral faults zone of the Xishan Mountain, which is a weakly permeable boundary. The northern of the eastern boundary is bounded by the watershed of the Liulin River and the Shizi River, which is a no-flow boundary; the southern of the eastern boundary is the peripheral faults zone, which is a discharge boundary of karst groundwater to the Taiyuan basin.

5.3 Hydrogeological conceptual model

For the groundwater numerical model, it simulates the idealized field scenario. If the majority of the assumptions are partially or completely satisfied, the most reliable result is obtained (Swanson and Bahir 2004; Voss 2011). In order to reduce the uncertainty of the model parameters and facilitate the calibration and verification of the model, it is necessary to generalize a reasonable hydrogeological conceptual model, which is the basis for the success of numerical modeling (Mengistu et al. 2014). In accordance with the hydrogeological conditions of Jinci Spring catchment, the proposed model covers Jinci karst aquifer system (Figure 5-1), with a total area of 1771 km^2 (excluding the Taiyuan basin area in Jinci Spring catchment). The objective aquifer is identified as the karst fissure aquifer of Ordovician carbonate, including limestone of the Majiagou Formation and the Fengfeng Formation in Middle Series. For the convenience of calculation, the study area is summarized as a one-layer confined aquifer system. The flow direction of karst aquifer is approximately horizontal in terms of space, and the groundwater flow shows 2D movement. Karst groundwater has the characteristics of the heterogeneity and isotropy. Therefore, the karst groundwater system in the study area can be generalized into a 2D heterogeneous, isotropic and transient confined water flow model.

5.4 Mathematical model

On the basis of hydrogeological conceptual model, a mathematical model describing karst groundwater level distribution in the study area was built. The mathematical model of the

Jinci karst groundwater system is as the following.

$$
\begin{cases}
\dfrac{\partial}{\partial x}\left(K\dfrac{\partial H}{\partial x}\right)+\dfrac{\partial}{\partial y}\left(K\dfrac{\partial H}{\partial y}\right)+W=S_s\dfrac{\partial H}{\partial t} & (x,y)\in D \\
H(x,y,t)\big|_{t=0}=H_0(x,y) & (x,y)\in D \\
H(x,y,t)\big|_{B_1}=H_t(x,y) & (x,y)\in D \\
K_n\dfrac{\partial H}{\partial \vec{n}}\big|B_2=q(x,y,t) & (x,y)\in D \quad t\geq 0 \\
K_n\dfrac{\partial H}{\partial \vec{n}}\big|B_2=0 & (x,y)\in D \quad t\geq 0
\end{cases}
$$

where K is the hydraulic conductivity of karst groundwater system along the x and y axes (m/d); H the groundwater level of karst groundwater system (m); H_0 the initial head (m); S_s the specific storativity (1/m); W the algebraic sum of source-sink of karst groundwater system (m/d); D the groundwater planar seepage zone (m^2); B_1 the first boundary of the seepage calculated area; B_2 the secondary boundary of the seepage calculated area; q the flow rate per unit area of secondary boundary of the seepage calculated area (m^3/d); K_n the hydraulic conductivity in the normal vector of secondary boundary (m/d); and $\vec{n}$ the outer normal vector of secondary boundary.

5.5 Model construction

According to the collected data of the field exploration and groundwater resources development in Jinci Spring catchment, such as geology, pumping test, rainfall recharge, Fenhe River leakage, groundwater exploitation, lateral discharge, and karst groundwater level, a simple 2D finite difference groundwater numerical model was constructed using the MODFLOW software. The model consists of one layer with 226 rows and 257 columns. In the light of the characteristics of hydrogeological conditions, and combined with the cross-section of the geological map of Jinci Spring (Figure 3-5), the study area was divided into four parameter zones (Figure 5-1). The parameters such as hydraulic conductivity and specific storativity obtained by the pumping test data were assigned to each parameter zone. For the model, the rainfall infiltration coefficient (α) of the recharge area is defined as 0.25. MODFLOW was used to simulate the ecological re-outflow of

Jinci Spring and to analyze the interaction between the artificial recharge of the Fenhe River, the groundwater abstraction and the karst groundwater.

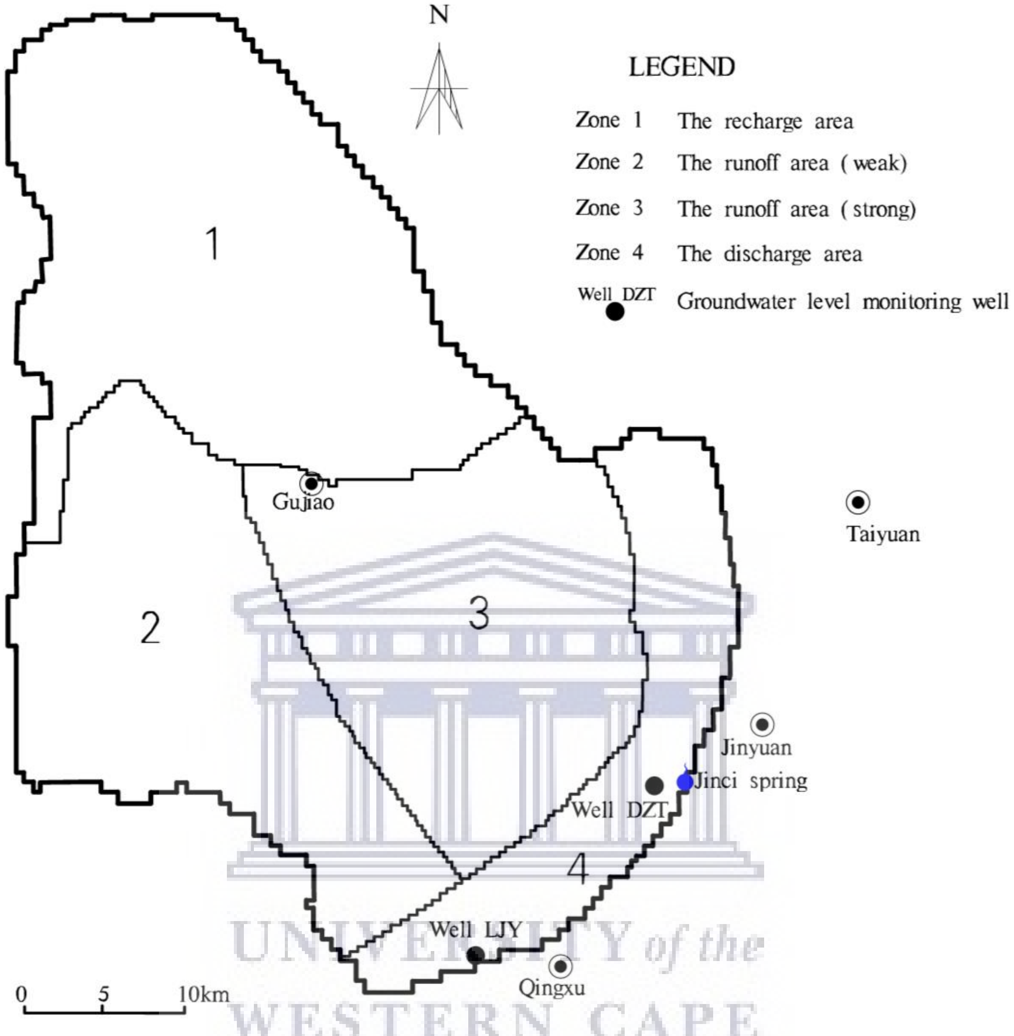


Figure 5-1 The hydraulic conductivity and specific storativity zones for the karst aquifer in Jinci Spring catchment (see Table 5-1)

5.6 Model calibration and verification

The calibration period is from 1 January 2014 to 31 December 2014, and the time step is calculated in 10 days. Through the running of the model, the hydraulic parameters of the karst aquifer were continuously adjusted until the error between the simulated water levels and the observed water levels of each observation well reach the minimum error, that is, the simulated water levels agree well with the measured values (Figure 5-2).

It can be considered that the calibration of the parameters of the model has been completed. The best fit hydraulic parameters were obtained from the optimization process, as shown in Table 5-1.

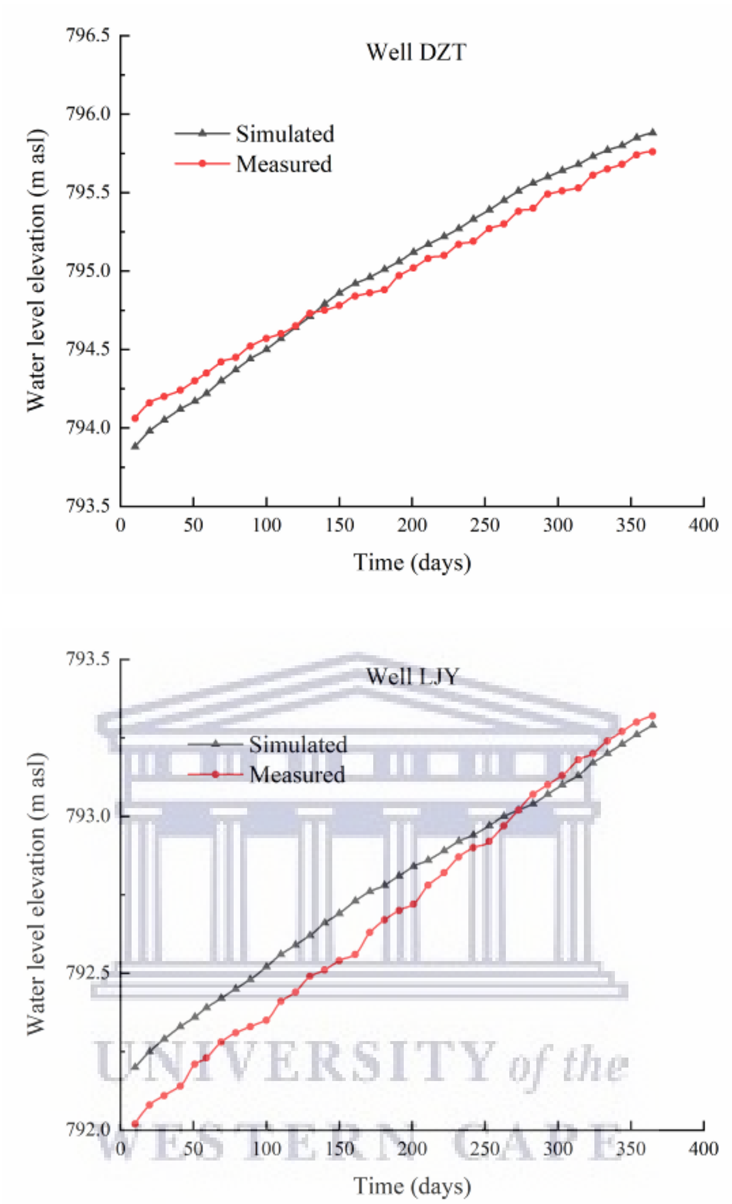


Figure 5-2 Comparison of calculated and measured groundwater level in observation wells in the calibration period

Table 5-1 Optimized hydraulic conductivity and specific storativity for the Jinci karst aquifer

Zone No.	Hydraulic conductivity (m/d)		Specific storativity (m^{-1})
	K_x	K_y	
1	6.83	6.83	$2.2e^{-5}$
2	0.58	0.58	$1.5e^{-5}$
3	5.95	5.95	$2.6e^{-5}$
4	10.26	10.26	$3.8e^{-5}$

In order to check the predictive ability of the calibrated model, it needs to be verified. The verification period is from 1 January 2015 to 31 December 2015, and the time step also is calculated in 10 days. Through the running of the model, the accuracy of the hydraulic parameters optimized during the calibration period was verified, and the consistency between the simulated water levels and the observed water levels of each observation well was tested (Figure 5-3).

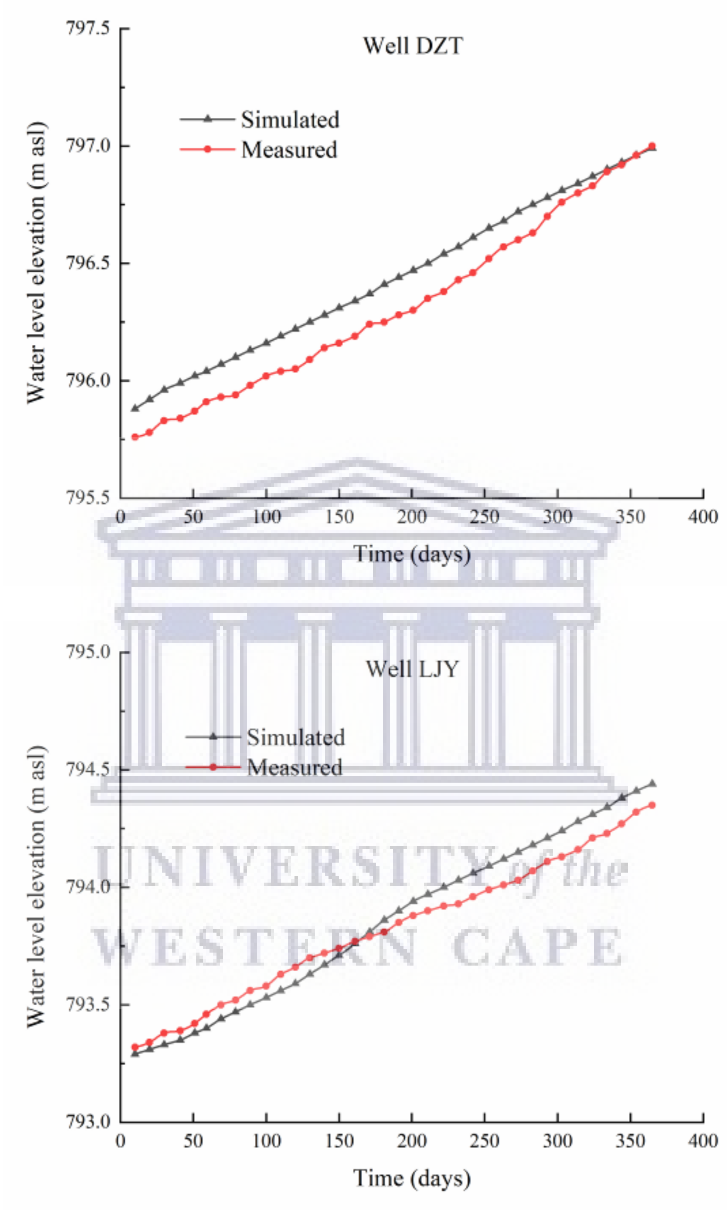


Figure 5-3 Comparison of calculated and measured groundwater level in observation wells in the verification period

It can be seen that the running of the model can basically reproduce the dynamics of karst groundwater in Jinci Spring catchment. In other words, the present study gain confidence in the ability of the model to simulate the actual situations. This further demonstrates that the groundwater level dynamics in Jinci Spring catchment can be forecasted by using the verified numerical model under different re-outflow protection scenarios.

5.7 Scenario design

To understand the response of groundwater level of karst aquifer and Jinci Spring to various re-outflow protection scenarios pertaining to the conditions of the artificial recharge of the Fenhe River and groundwater abstraction, using the verified numerical model, the average annual rainfall of 464.49 mm (1956-2014) and the lateral discharge of 0.68 m^3/s in Jinci Spring catchment were used to estimate the karst groundwater levels under the following three different re-outflow protection scenarios. It should be pointed out that the use of average annual rainfall in the scenario design is mainly due to the prediction of rainfall is actually a global problem. Although there are many rainfall prediction models in the world, the prediction values of the models are different. In addition, the rainfall predicted by the model does not necessarily occur in the future. Considering that the average annual rainfall is one of the important indicators of climate in a region, it can reflect the basic status of rainfall for the region, and it is representative and indicative, neither extreme drought nor extreme humid. Therefore, in order to better explore the ecological re-outflow of Jinci Spring, the average annual rainfall in Jinci Spring catchment is selected as the rainfall of the simulation model in the scenario design. Among the designed groundwater abstraction, only the pumping wells in discharge area are used to exploit karst groundwater, and there is no karst groundwater drainage in coal mines. According to the designed data of the artificial recharge of the Fenhe River and groundwater abstraction (Table 5-2), a transient model was executed on the basis of stress period of 10 years (2014-2023). Combined with the ecological criteria of the basic ecological flow of 0.393 m^3/s of Jinci Spring and the ecological water level restriction for early warning of 803.35 m asl, the re-outflow protection scheme that meets the ecological criteria was optimized.

It must be emphasized that the groundwater abstractions of the three scenarios 0.42, 0.84 and 0 m^3/s are designed based on the minimum planned demand for karst water in Taiyuan after 2014, the average karst water abstraction in 2009-2014, and no consideration of the exploitation of karst water resources, respectively. Under the conditions of the artificial recharge of the Fenhe River (0.9 m^3/s) and average annual rainfall (464.49 mm), and compared with the sustainable yield of karst groundwater obtained in chapter 4, these designed values do not exceed the sustainable yield of Jinci Spring catchment, but they cannot meet the requirements of sustainability threshold from the perspective of the spring water has not been re-outflowed. This is due to the fact that when the spring flow is less than 0.32 m^3/s, all groundwater abstractions (including 0) cross the sustainability threshold of Jinci Spring catchment. Nevertheless, the design of these values is of practical significance from the point of view of ecological re-outflow protection of spring water, as they can provide a comparison for the determination of the optimal scenario and provide a reference for the implementation of re-outflow program by the water resources management department of Shanxi.

Table 5-2 The designed re-outflow scenarios of numerical modeling in Jinci Spring catchment

Scenario	Duration (days)	No. of time steps	Artificial recharge of the Fenhe River (m^3/s)	Groundwater abstraction (m^3/s)
1	3,650 (10 years)	10	0.9	0.42
2	3,650 (10 years)	10	0.9	0.84
3	3,650 (10 years)	10	0.9	0

5.8 Results

5.8.1 Scenario 1

In scenario 1, the groundwater abstraction is 0.32 m^3/s less than that of 2013 (0.74 m^3/s). The karst groundwater levels of Jinci Spring catchment in 2014-2023 are forecasted.

According to the model results, after the 10-yr artificial recharge of the Fenhe River and well pumping, the regional karst groundwater level (Figure 5-4a) will rise significantly on the basis of the initial water level. This is due to the fact that the artificial recharge of the Fenhe River (0.9 m^3/s) is greater than groundwater abstraction (0.42 m^3/s). It is suggested that under the condition of the average annual rainfall of 464.49 mm, the measure of artificial recharge of the Fenhe River and reduction of the groundwater abstraction is effective for the recovery of karst groundwater levels in Jinci Spring catchment.

Figure 5-5a shows the predicted water level response of Jinci Spring. As can be seen from the Figure 5-5a, with the rise of the groundwater level at the mouth of spring, it will just run above 802.59 m asl on the 2328 day (18 May 2020), the re-outflow of the spring will be attained. But since then, the groundwater level variation curve will change gradually from steep to gentle, indicating that the spring flow will gradually increase with the re-outflow of the spring, which is equivalent to increasing the discharge of groundwater, and resulting in a gradual decrease in the annual increase of groundwater level after the re-outflow of the spring. By 31 December 2021, the karst groundwater level will run to 803.45 m asl, which is 10 cm higher than the ecological water level restriction for early warning (803.35 m asl). By this time, the spring flow will reach 0.442 m^3/s, which is also higher than that of the basic ecological spring flow (0.393 m^3/s). By the end of 2023, the groundwater level will run to 805.18 m asl. During the 10-yr simulation period, the groundwater level at the mouth of spring increased by 11.62 m.

5.8.2 Scenario 2

In scenario 2, the groundwater abstraction is 0.1 m^3/s more than that of 2013 (0.74 m^3/s). The karst groundwater levels of Jinci Spring catchment in 2014-2023 are forecasted.

According to the model results, after the 10-yr artificial recharge of the Fenhe River and well pumping, the regional karst groundwater level (Figure 5-4b) will also rise on the basis of the initial water level. However, the elevation of regional karst groundwater level is relatively lower compared with Figure 5-4a. This is because the groundwater abstraction is 0.42 m^3/s larger than that in scenario 1. It indicates that under the condition of the average annual rainfall of 464.49 mm, the same artificial recharge of the Fenhe River is adopted, but the large groundwater abstraction is not conducive to the recovery of karst groundwater level in Jinci Spring catchment.

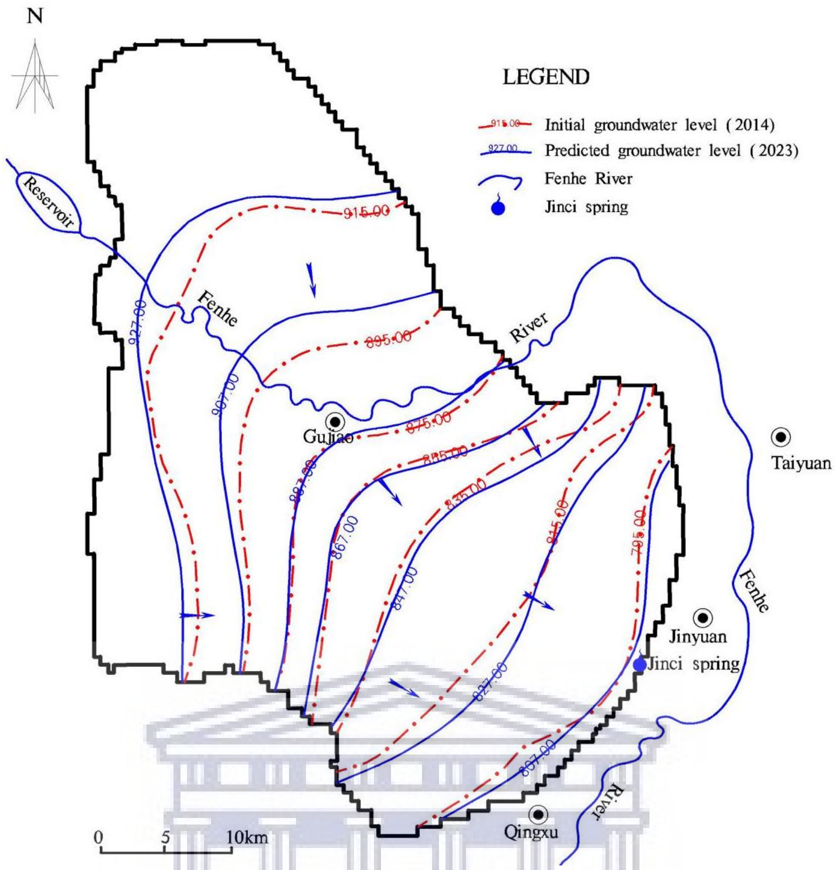
Figure 5-5b shows the predicted water level response of Jinci Spring. It can be seen from the Figure 5-5b, with the rise of the groundwater level at the mouth of spring, it will just run above 802.59 m asl on the 3453 day (17 June, 2023), and the re-outflow of the spring will also be attained. Since then, the groundwater level variation curve will change very small, indicating that the spring flow is small and has little effect on the rise of groundwater level. By 31 December 2023, the groundwater level will run to 803.08 m asl, which is still below the ecological water level restriction for early warning (803.35 m asl); and the spring flow will reach 0.257 m^3/s, which is lower than that of the basic ecological spring flow (0.393 m^3/s). During the 10-yr simulation period, the groundwater level at the mouth of spring increased by 9.52 m.

5.8.3 Scenario 3

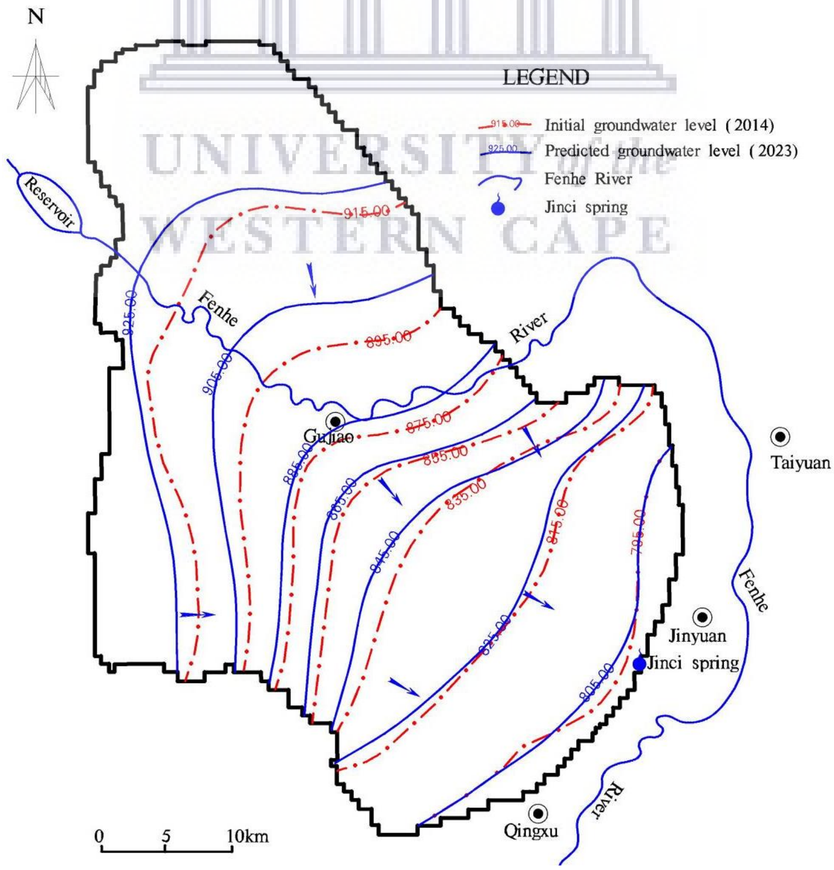
In scenario 3, all the pumping wells are closed (the groundwater abstraction is 0). The karst groundwater levels of Jinci Spring catchment in 2014-2023 are forecasted.

According to the model results, after the 10-yr artificial recharge of the Fenhe River, the regional karst groundwater level (Figure 5-4c) also will rise more significantly on the basis of the initial water level. However, the elevation of regional karst groundwater level is relatively higher compared with Figure 5-4a. This is due to the fact that there is only the artificial recharge of the Fenhe River. It shows that under the condition of the average annual rainfall of 464.49 mm, when the same artificial recharge of the Fenhe River and the complete closure of the pumping wells are implemented, the recovery of karst groundwater level in Jinci Spring catchment can be accelerated.

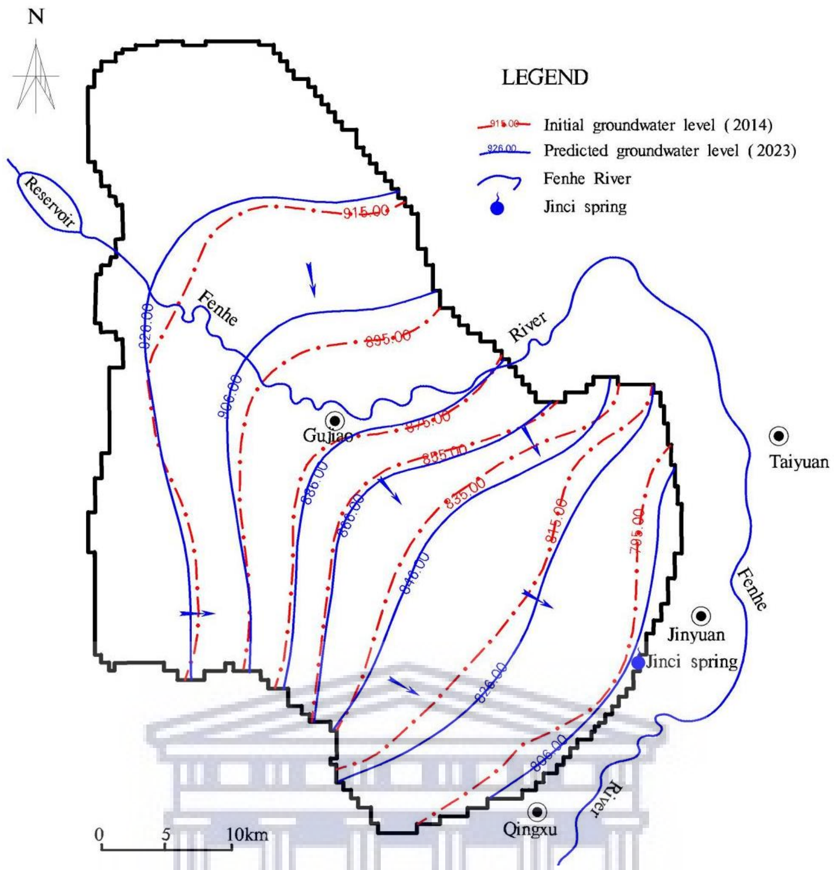
Figure 5-5c shows the predicted water level response of Jinci Spring. It can be seen from the Figure 5-5c, with the rise of the groundwater level at the mouth of spring, it will just run above 802.59 m asl on the 1745 day (12 October 2018), and the re-outflow of the spring will also be attained. Since then, the groundwater level variation curve will also change gradually from steep to gentle. It indicates that the spring flow increases gradually, which is equivalent to increasing the discharge of groundwater, and results in a gradual decrease in the annual increase of groundwater level. By 31 December 2019, the karst groundwater level will run to 803.70 m asl, which is 35 cm higher than the ecological water level restriction for early warning (803.35 m asl). By this time, the spring flow will reach 0.567 m^3/s, which is much larger than the basic ecological spring flow (0.393 m^3/s). By the end of 2022, the groundwater level will run to 806.04 m asl. In 2023, the groundwater level remains at 806.04 m asl, it means that the groundwater level is in dynamic equilibrium. During the 10-yr simulation period, the groundwater level at the mouth of spring increased by 12.48 m.



a scenario 1

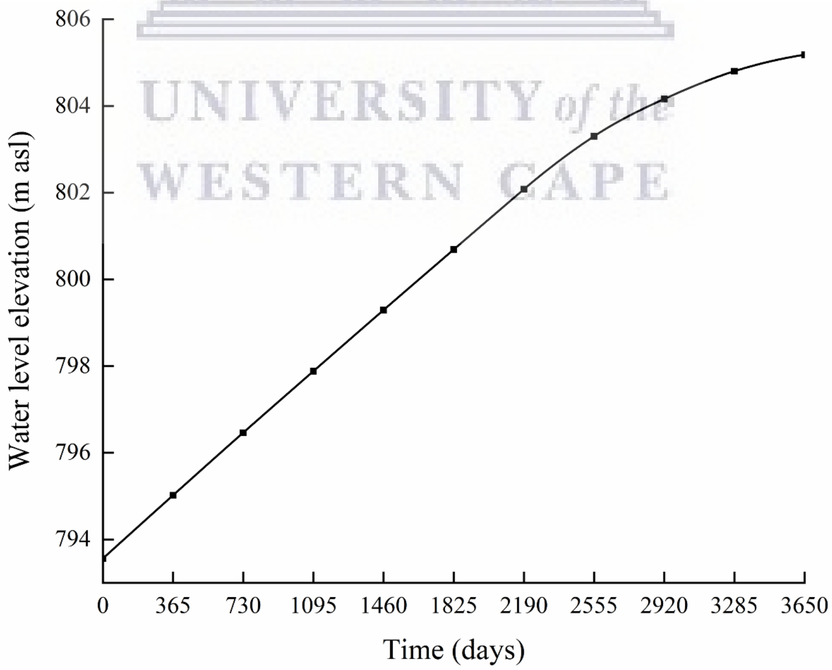


b scenario 2

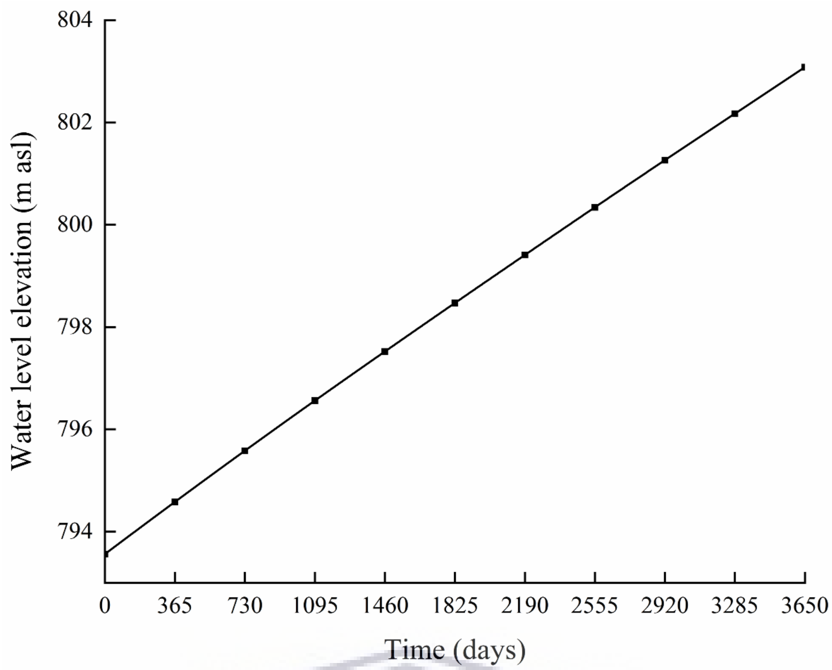


c scenario 3

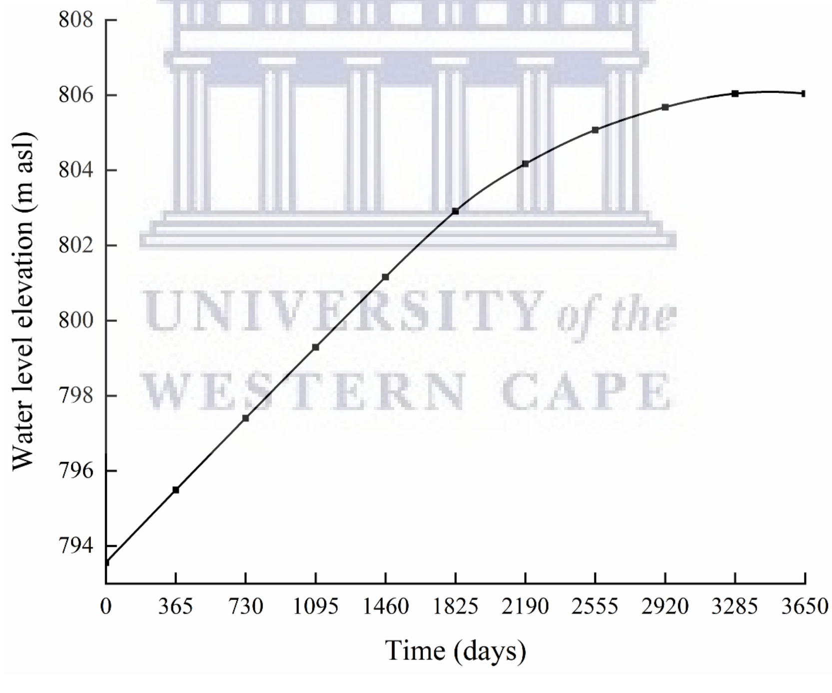
Figure 5-4 Model running results. Groundwater levels are displayed in m asl



a scenario 1



b scenario 2



c scenario 3

Figure 5-5 Predicted water level at the mouth of Jinci Spring

5.9 Discussion

In view of the numerical modeling results of three re-outflow protection scenarios, it is concluded that the artificial recharge of the Fenhe River leads to the rise of karst groundwater level, while the groundwater abstraction results in the decline of karst groundwater level. Both of them play important roles in re-outflow protection of Jinci Spring. This verifies that the groundwater abstraction and the artificial recharge of the Fenhe River have significant impacts on the karst groundwater level. According to the comparison of the forecast results of three different scenarios, it can be seen that the rise of karst groundwater level is the lowest and the re-outflow time of Jinci Spring is the latest (2023) in scenario 2; the rise of karst groundwater level is middle and the re-outflow time of Jinci Spring is the second (2020) in scenario 1; the rise of karst groundwater level is the highest and the re-outflow time of Jinci Spring is the earliest (2018) in scenario 3.

Compared with scenario 1, under the same artificial recharge of the Fenhe River, the large groundwater abstraction in scenario 2 hinders the rise of karst groundwater level. The rise of groundwater level is slower and the re-outflow time of Jinci Spring is lagged for 3 years. At the end of the simulation, it will not run to the ecological water level restriction for early warning (803.35 m asl) and/or the basic ecological spring flow (0.393 m^3/s). Therefore, scenario 2 cannot effectively meet the ecological criteria for the re-outflow protection.

Compared with scenario 1, under the same artificial recharge of the Fenhe River, the closure of all pumping wells in scenario 3 cannot hinder the rise of the karst groundwater level. The rise of groundwater level is faster and the re-outflow time of Jinci Spring is 1.6 years ahead. But with the rising groundwater level in the later period, the spring flow is greater than the basic ecological spring flow (0.393 m^3/s). It shows that scenario 3 can achieve the purpose of re-outflow, but there is a large waste of groundwater resources. In addition, according to the current demand for groundwater in Taiyuan, karst groundwater must be exploited. Therefore, it is unrealistic to close the pumping wells completely.

Thus, it can be seen that scenario 1 not only can meet the ecological re-outflow of Jinci Spring, but also will not cause large waste of groundwater resources. It shows that scenario 1 is optimal among the above three scenarios, and can achieve the ecological re-outflow protection of Jinci Spring. In comparison, it can be concluded that scenario 1 is the re-outflow protection scheme that meets the ecological criteria for Jinci Spring.

From the above numerical simulation results, it can be seen that for each of the three designed scenarios, karst groundwater levels in Jinci Spring catchment are rising. After running for different periods of time, Jinci Spring can achieve its re-outflow accordingly. From the perspective of spring re-outflow, the three scenarios are all effective. Under the conditions of closing all coal mines and the same artificial recharge of the Fenhe River as well as average annual rainfall, different abstractions can ultimately ensure the rise of karst groundwater level and the re-outflow of Jinci spring. The rise of karst groundwater level means that the total recharge is greater than the total discharge in Jinci Spring catchment, and the groundwater is in a positive equilibrium, which is the guarantee and prerequisite for the re-outflow of Jinci Spring. This shows that the measures of the artificial recharge of the Fenhe River, reduction of karst groundwater exploitation and closure of all coal mines are completely correct. According to the previous literature (Li et al. 1998b; Shu and Zhu 2000; Yin et al. 2011), the designed exploitation (including coal mining drainage) in Jinci Spring catchment is greater than 1 m^3/s, while the maximum exploitation in the three designed scenarios of the present study is 0.84 m^3/s. Compared with the three designed scenarios of the present study, under the condition of smaller Fenhe River recharge, the exploitation in each of the previous literature is larger, which is unfavorable for the re-outflow of Jinci Spring, and the possibility and risk of groundwater level decline are still great. Although the purpose of the predecessors was to protect Jinci Spring, the exploitation of previous design is not optimal. Therefore, it can be affirmed that the three designed scenarios of the present study are more in line with the re-outflow requirements of Jinci Spring than the previous design. However, from the perspective of ecological re-outflow protection, only scenario 1 is optimal.

It should be noted that in the three scenarios of the present study, the rainfall used for simulation is the average annual rainfall of 464.49 mm. Under other conditions unchanged, if the rainfall in the model is greater than the average annual rainfall, the ecological re-outflow of Jinci Spring will be realized in advance for the three scenarios. This is because with the increase of rainfall, the infiltration recharge of karst groundwater increases. In the same time, the increase in groundwater storage is relatively larger, which will weaken the impact of groundwater abstraction on karst groundwater level, and ultimately lead to a relatively larger rise rate of the karst groundwater level. If the rainfall in the model is less than the average annual rainfall, the ecological re-outflow of Jinci

Spring will be lagged for the three scenarios. This is because with the decrease of rainfall, the infiltration recharge of karst groundwater decreases. During the same time, the increase in groundwater storage is relatively less, which will enhance the impact of groundwater abstraction on karst groundwater level, and eventually result in a relatively smaller rise rate of the karst groundwater level. Thus it can be seen that the impact of the change of rainfall on karst groundwater in Jinci Spring catchment is obvious, it is positive in large rainfall and negative in small rainfall. From the perspective of climate change caused by global warming, once the future rainfall continues to decrease, the impact on the ecological re-outflow of Jinci Spring will be severe, and it must be given sufficient attention by the water resources management department of Shanxi.

In addition, none of the three scenarios of the present study consider the impact of coal mining drainage on karst groundwater. Under other conditions unchanged, if there is drainage of karst groundwater by coal mining in the simulating model, the ecological re-outflow of Jinci Spring will also be lagged for the three scenarios. This is due to the coal mining drainage of karst groundwater is equivalent to an increase in well pumping. At the same time, the karst groundwater storage increases relatively less. It will aggravate the impact of groundwater abstraction on karst groundwater level. Therefore, the discharge of karst groundwater in coal mines is very detrimental to the ecological re-outflow of Jinci Spring. The water resources management department of Shanxi must draw lessons and take measures to close all coal mines in Jinci Spring catchment, which is beneficial to the ecological re-outflow of Jinci Spring.

In summary, to meet the ecological re-outflow protection of Jinci Spring, in the implementation of artificial recharge of the Fenhe River, neither can the pumping wells be completely closed nor can the groundwater abstraction be too large; otherwise, the water resources will be wasted due to the higher karst groundwater level or the re-outflow time of Jinci Spring will be lagged and the ecological criteria will not be met. It must be emphasized that the rainfall recharge also plays an important role in the rise of the karst groundwater level and/or the ecological re-outflow of Jinci Spring. For the later ecological re-outflow program, when the re-outflow of Jinci Spring runs above the ecological water level restriction for early warning (803.35 m asl) and/or the basic ecological spring flow

(0.393 m^3/s), the artificial recharge of the Fenhe River can be stopped, but it must be adjusted to a reasonable sustainable yield of karst groundwater to accommodate the long-term ecological protection of Jinci Spring.

5.10 Summary

The numerical modeling results show that the artificial recharge of the Fenhe River leads to the rise of karst groundwater level, while the groundwater abstraction results in the decline of karst groundwater level. Both of them play important roles in the ecological re-outflow protection of Jinci Spring. This verifies that the groundwater abstraction and the artificial recharge of the Fenhe River have significant impacts on the karst groundwater level. Compared with scenario 2 and scenario 3, scenario 1 (the artificial recharge of Fenhe River of 0.9 m^3/s and groundwater abstraction of 0.42 m^3/s) is optimal, and it is the re-outflow protection scheme that meets the ecological criteria for Jinci Spring. It must be emphasized that the rainfall recharge also plays an important role in the rise of the karst groundwater level and/or the ecological re-outflow of Jinci Spring. In the implementation of the artificial recharge of the Fenhe River, neither can the pumping wells be completely closed nor can the groundwater abstraction be too large. Otherwise, the water resources will be wasted due to the higher karst groundwater level or the re-outflow time of Jinci Spring will be lagged and the ecological criteria will not be met. When the re-outflow of Jinci Spring runs above the ecological water level restriction for early warning (803.35 m asl) and/or the basic ecological spring flow (0.393 m^3/s), the artificial recharge of the Fenhe River can be stopped, but it must be adjusted to a reasonable sustainable yield to accommodate the long-term ecological protection of Jinci Spring.

Chapter 6

Summary and Recommendation

6.1 Summary

Through the retrieval and analysis of some 200 local and international publications, this thesis 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. The thesis 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. On the basis of the data of karst groundwater done over a long-term monitoring programme in Jinci Spring catchment, the thesis investigates the causes of the drying up of Jinci Spring by using the capture principle. The study has assessed the sustainable yield of karst groundwater, quantified the sustainability threshold of karst groundwater and determined the ecological water level restrictions for early warning and water supply of Jinci Spring catchment. In addition, a simple 2D numerical model of karst groundwater in Jinci Spring catchment is used to design three different re-outflow protection scenarios, to forecast the dynamics of karst groundwater level, and to optimize the re-outflow protection scheme that meets the ecological criteria for Jinci Spring. Consequently, the main conclusions of the thesis are presented as follows.

Factors affecting the karst springs in Shanxi

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. The impact of climate change on Shanxi karst springs was mainly manifested in the form of reduced precipitation. Karst water quality in parts of Shanxi spring catchments has been polluted in many places to various extents, which warrants necessity of protection zoning.

Problems in the study of karst springs in Shanxi

The research results of the karst springs in Shanxi 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.

Causes of the drying up of Jinci Spring

The drying up of Jinci Spring is the biggest water ecological environmental problem in Jinci Spring catchment. It has not only lowered the tourism resource value of the Jinci Temple, but also caused the contradiction between supply and demand of water resources and the degradation of aquatic ecological environment in the downstream of the spring. It is also a typical case of governance failure of karst groundwater in Shanxi and China. The correlation coefficient of karst groundwater level of spring and groundwater exploitation is

0.8112, while the correlation coefficient of karst groundwater level of spring and rainfall is 0.0992. The capture principle is used to confirms that when the exploitation cannot be balanced by capture, the karst aquifer storage is continuously consumed, causing the drying up of Jinci Spring. Climate change and the long-term consumption of karst aquifer storage are the key causative factors of the drying up of Jinci Spring.

Sustainable yield of karst groundwater in Jinci Spring catchment

This research derives the capture equation of karst groundwater in Jinci Spring catchment as $Q_{exploitation} = \Delta R_{induced\ leakage\ recharge} - \Delta D_{reduced\ spring\ flow}$. It can be seen that the sustainable yield of karst groundwater is determined by the leakage recharge of the overlying fissure aquifers and the reduced spring flow induced by groundwater exploitation, rather than natural recharge. The sustainable yield under ecological constraints is not a single and fixed value, but has a series of permissible values that range from 0.622 to 2.35 m^3/s.

Sustainability threshold of karst groundwater in Jinci Spring catchment

The sustainability threshold of Jinci Spring catchment is a limited range of the total exploitation of karst groundwater for industrial, agricultural and domestic water uses. The sustainability threshold of karst groundwater in Jinci Spring catchment is [12.35×10^8 m^3, 13.91×10^8 m^3]. Unfortunately, since 1990, the total exploitation of karst groundwater for many years in Jinci Spring catchment has crossed the sustainability threshold.

Ecological water level restrictions of Jinci Spring catchment

Jinci Spring flow is restricted by the groundwater level at the mouth of spring. The basic ecological spring flow in Jinci Spring catchment in dry season and other periods are 0.393 and 0.32 m^3/s, respectively. The ecological water level restriction for early warning and the ecological water level restriction for water supply are 803.35 and 803.21 m asl, respectively. The long-term monitoring of the karst groundwater level and Jinci Spring flow should be continuously strengthened after the ecological re-outflow of Jinci Spring.

Protection for ecological re-outflow of Jinci Spring

The numerical modeling results show that the artificial recharge of the Fenhe River leads to the rise of karst groundwater level, while the groundwater abstraction results in the decline of karst groundwater level. Both of them play important roles in the re-outflow protection of Jinci Spring. This verifies that the groundwater abstraction and the artificial recharge of the Fenhe River have significant impacts on the karst groundwater level. Compared with scenario 2 and scenario 3, scenario 1 (the artificial recharge of Fenhe River of 0.9 m^3/s and groundwater abstraction of 0.42 m^3/s) is optimal, and it is the re-outflow protection scheme that meets the ecological criteria for Jinci Spring. The rainfall recharge also plays an important role in the rise of the karst groundwater level and/or the ecological re-outflow of Jinci Spring.

Comments on the case study of Jinci Spring

The numerical modeling results show that the analysis of the causes of the drying up of Jinci Spring by using the capture principle is correct. The capture principle and numerical modeling improve the conceptual understanding of the karst groundwater flow system in Jinci Spring catchment, which subsequently help the ecological re-outflow protection of Jinci Spring and the sustainable management of karst groundwater resources. The research on the causes of the drying up of Jinci Spring and its protection for ecological re-outflow provides a template on how study similar karst systems elsewhere in Shanxi and China.

6.2 Recommendation

Based on this study, a number of recommendations for future studies and attentions of interest are presented,

1. 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, the 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 re-outflow 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.

2. 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.

3. 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.

4. For the ecological re-outflow of Jinci Spring, in the implementation of the artificial recharge of the Fenhe River, neither can the pumping wells be completely closed nor can the groundwater abstraction be too large. Otherwise, the water resources will be wasted due to the higher karst groundwater level or the re-outflow time of Jinci Spring will be lagged and the ecological criteria will not be met. When the re-outflow of Jinci Spring runs above the ecological water level restriction for early warning (803.35 m asl) and/or the basic ecological spring flow (0.393 m^3/s), the artificial recharge of the Fenhe River can be stopped, but it must be adjusted to a reasonable sustainable yield to accommodate the long-term ecological protection of Jinci Spring.
5. The numerical model established in Chapter 5 ignores the vertical flow process and cannot fully reflect the flow of karst groundwater in Jinci Spring catchment. In the follow-up work, it is recommended to establish a detailed hydrogeological conceptual model and a three-dimensional numerical model to further analyze the impact of different scenarios on the protection for ecological re-outflow of Jinci Spring.

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Appendix A Publication

Carbonates and Evaporites
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REVIEW

Review: karst springs in Shanxi, China

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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

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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

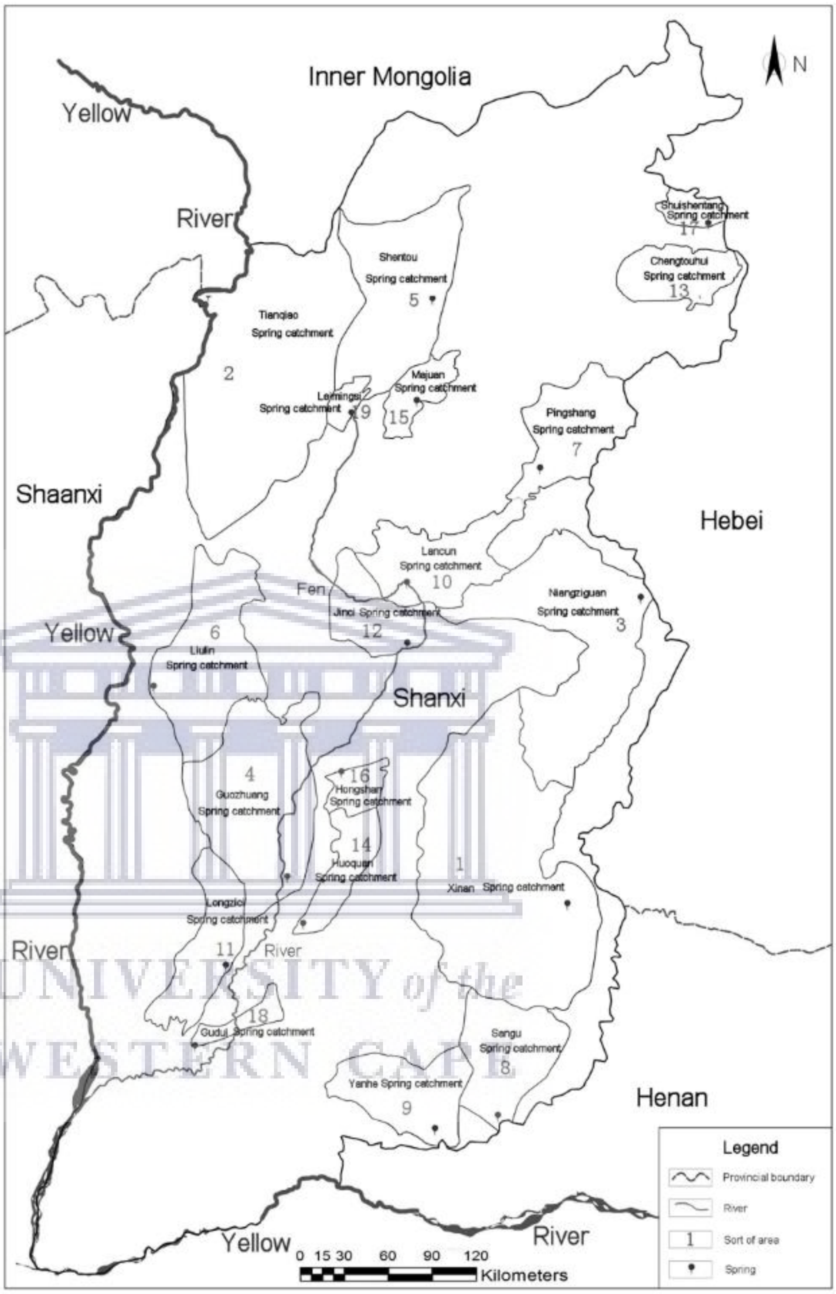

Fig. 1 Nineteen big karst springs in Shanxi Province, China

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

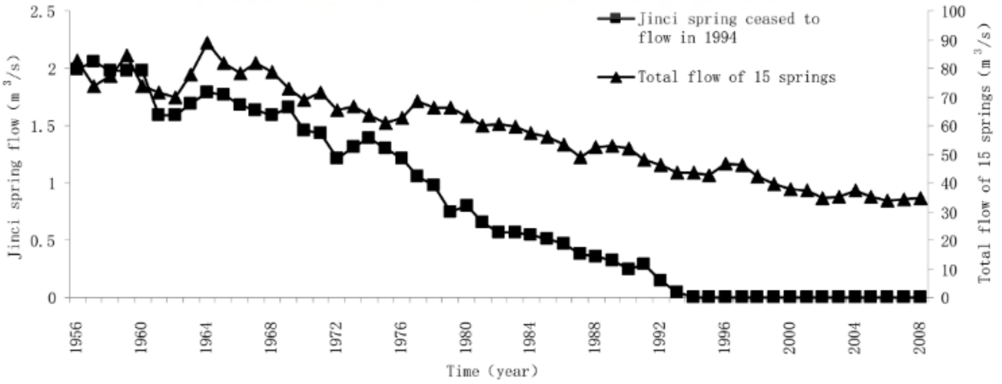

Fig. 2 The annual flow of Jinci spring and the total of 15 springs

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

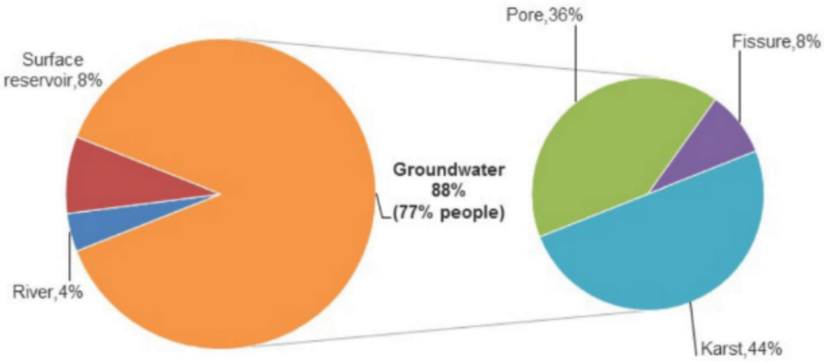

Fig. 3 Distribution of water supply sources

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

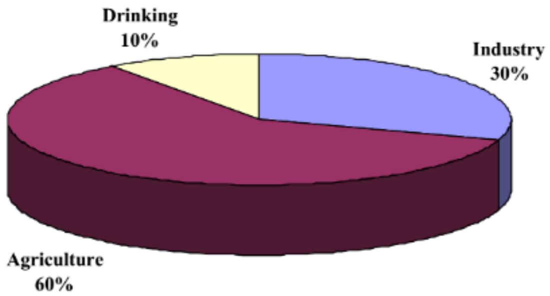

Fig. 4 The karst water consumption in industry, agriculture and drinking water

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.

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

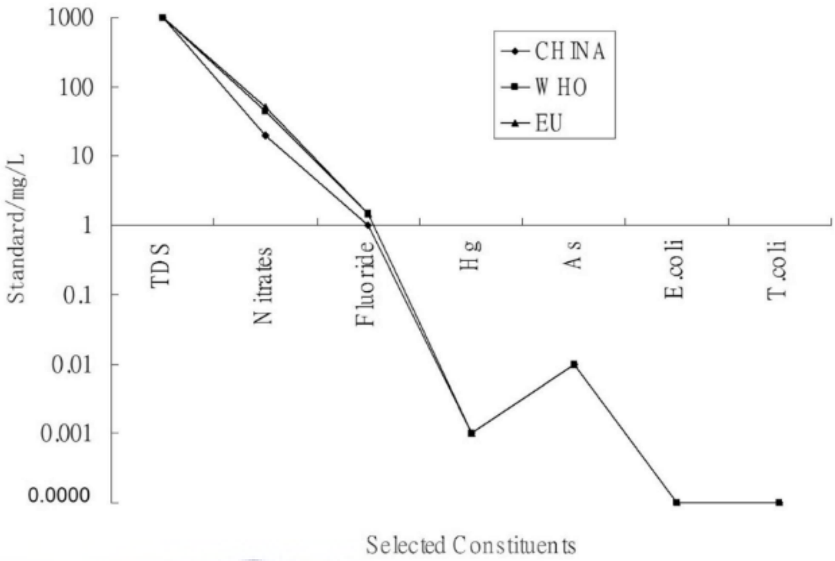

Fig. 5 The standards comparison of drinking water of China, EU and WHO

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

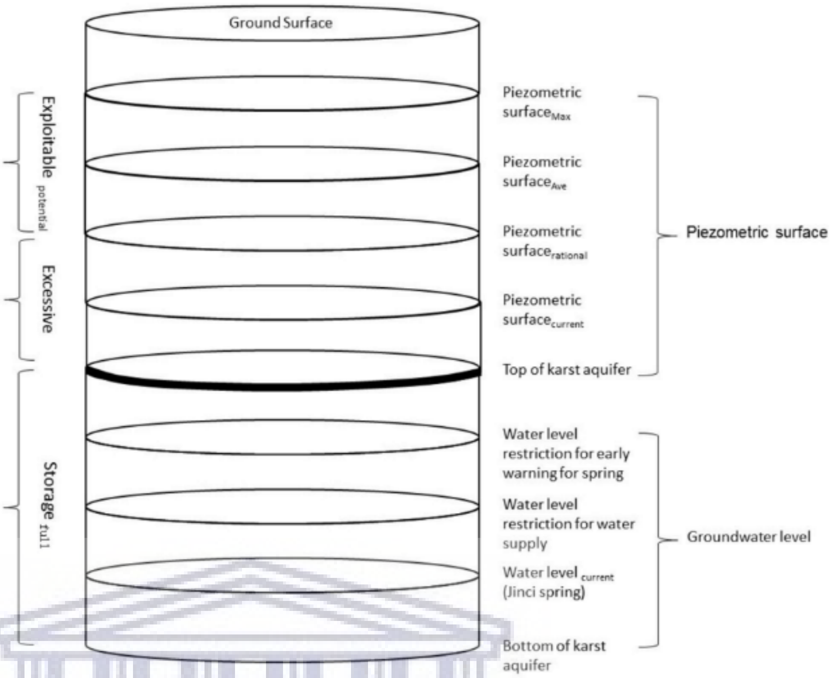

Fig. 6 Conceptualized exploitable water resources in karst aquifer system

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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ORIGINAL PAPER

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

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Abstract

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

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

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Introduction

Groundwater is a valuable resource in arid and semi-arid regions of the world. It plays a vital role in local agricultural, industrial, and domestic water uses. With global warming, it will further intensify the shortage of groundwater resources in arid and semi-arid areas (Scanlon et al. 2010). In addition, due to the increasing demand for water resources in economic and social development, overexploitation of groundwater (Custodio 2002), coupled with the drainage of sewage resulting from the acceleration of industrialization, has brought a very serious negative impact on groundwater resources; the declines of groundwater level and groundwater contamination and pollution in aquifers are very common, threatening the sustainable use of groundwater and the health of residents. In many water source areas, the monitoring wells have been explored and drilled, and many valuable groundwater monitoring data have been obtained. In order to avoid the shortage of groundwater resources and deterioration of water quality, it is very necessary for researchers

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to analyze the changes in the quantity and hydrochemistry of groundwater resources in aquifers based on groundwater monitoring data, and to identify and quantitate the relevant trends to draw reliable conclusions. This not only gives us a clear understanding of the current state of groundwater resources, but also allows us to predict the future changes of groundwater based on the status quo. It is of great significance for the protection of the quality and quantity of groundwater resources and the sustainable utilization of groundwater.

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

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

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

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

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

Description of Study Area

Location and Climate

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

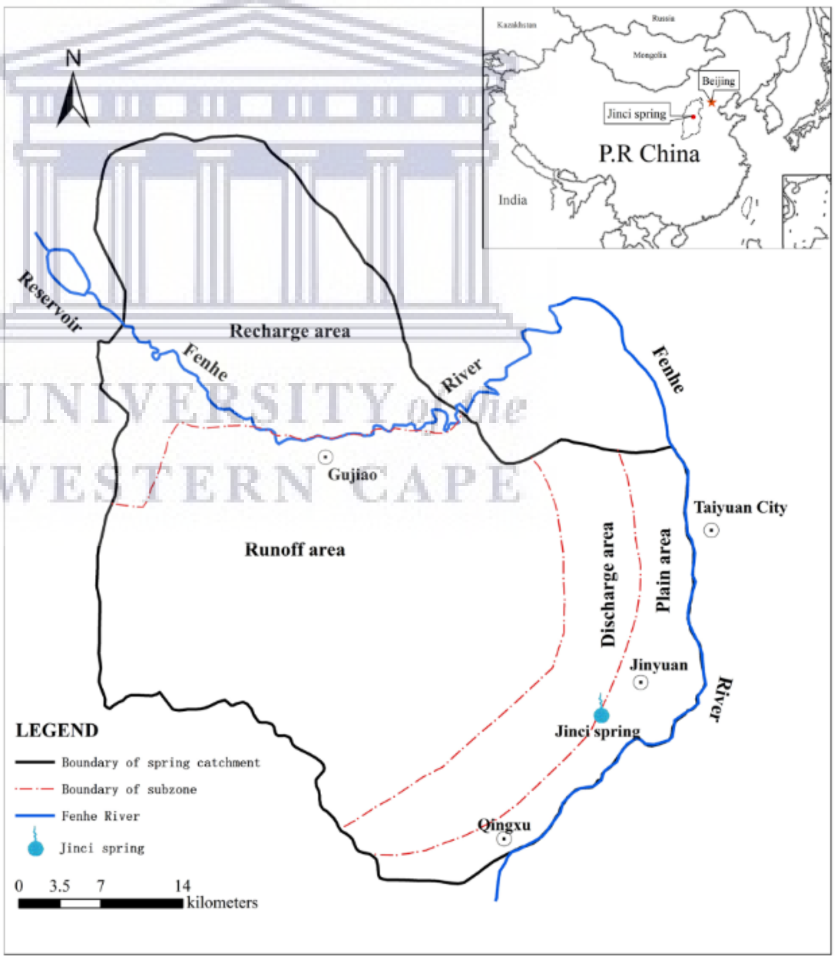

Fig. 1 Location of study area

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

Geology and Hydrogeology

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

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

Materials and Methods

Data Acquisition and Analysis

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

Mann–Kendall Trend Test

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

Results and Discussion

Variations in Groundwater Level

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

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

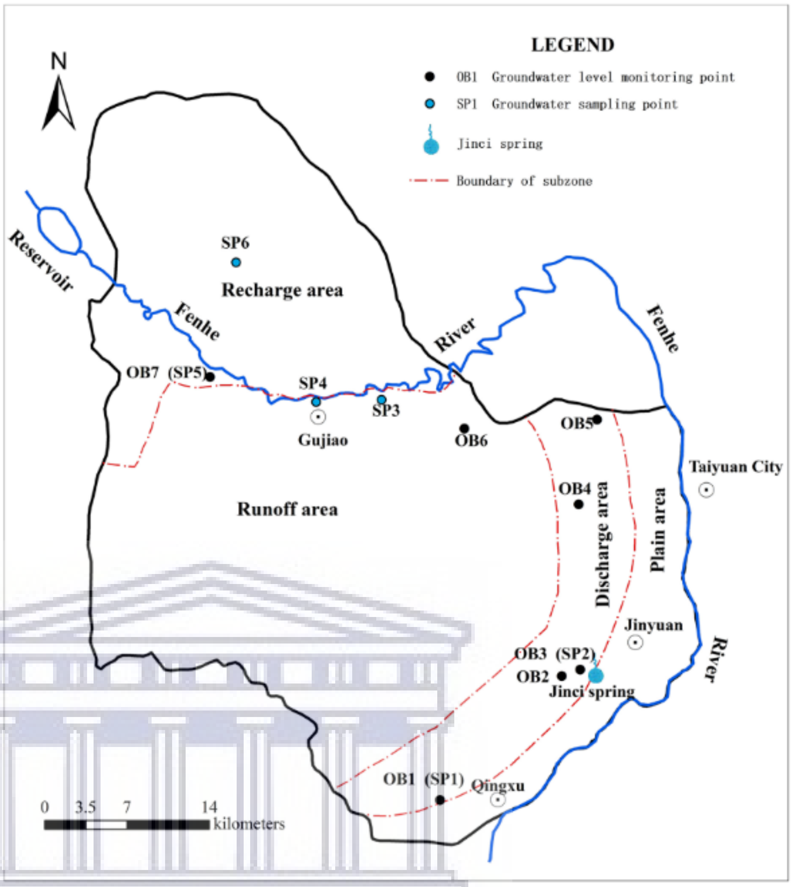

Fig. 2 Locations of groundwater level monitoring wells and groundwater sampling points

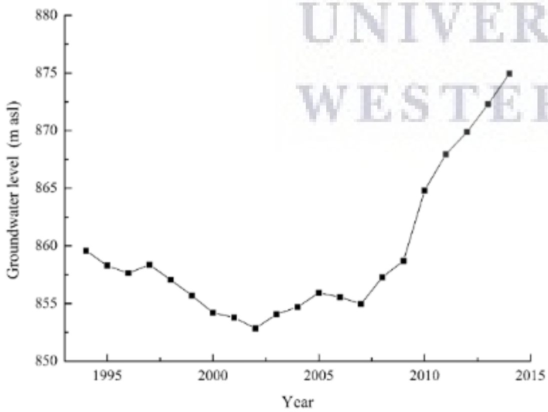

Fig. 3 Groundwater level of karst aquifer based on 7 piezometers

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

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

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

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

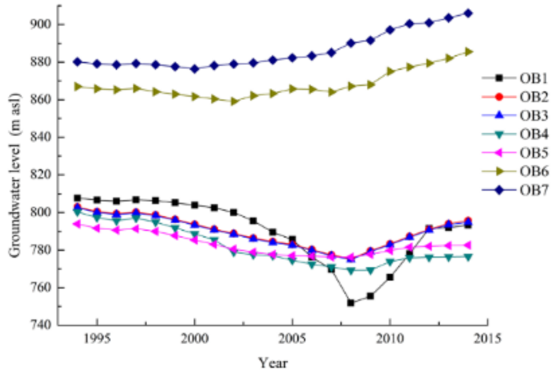

Fig. 4 Groundwater levels of 7 piezometers in the recharge, runoff, and discharge areas

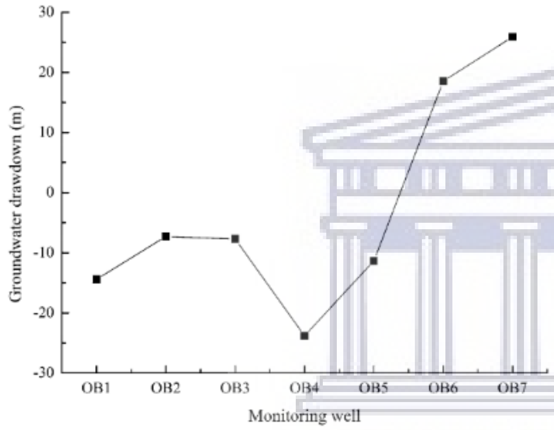

Fig. 5 Drawdown of groundwater level in 7 piezometers

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

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

Trend of Groundwater Level Variation

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

Table 1 Annual groundwater level and drawdown in 7 piezometers

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

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

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

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

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

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

The Relationship Between Groundwater Level Drawdown and Rainfall

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

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

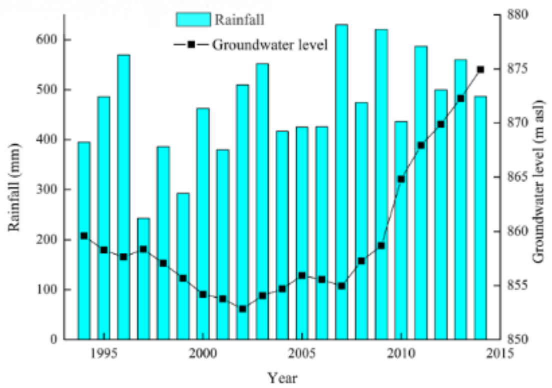

Fig. 6 The relationship between groundwater level and rainfall

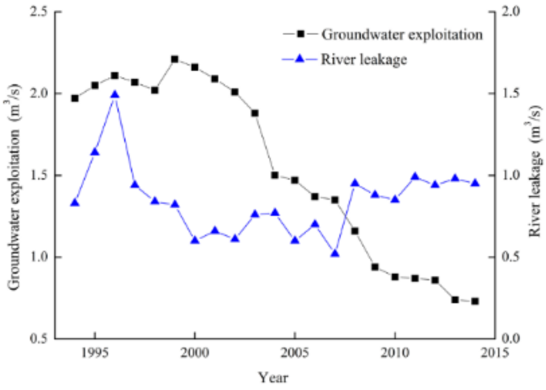

Fig. 7 Groundwater exploitation and the Fenhe River leakage in 1994–2014

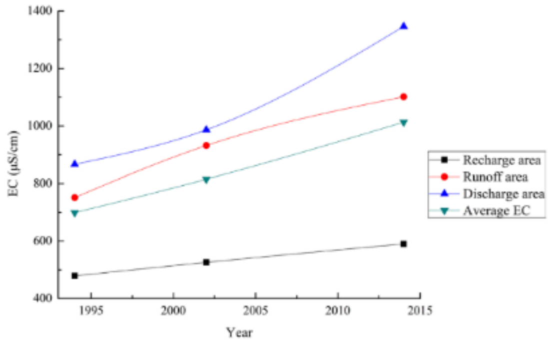

Fig. 8 EC values in recharge, runoff, and discharge areas and average EC values

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

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

Temporal Change in the EC of Groundwater

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

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

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

Table 3 EC values in different areas and average EC values

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

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

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

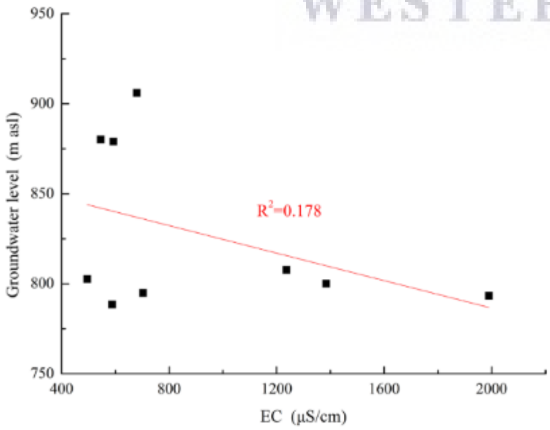

Fig. 9 The relationship between groundwater level and the EC

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

Spatial Change in the EC of Groundwater

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

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

Changes in Groundwater Chemistry and Acidity

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

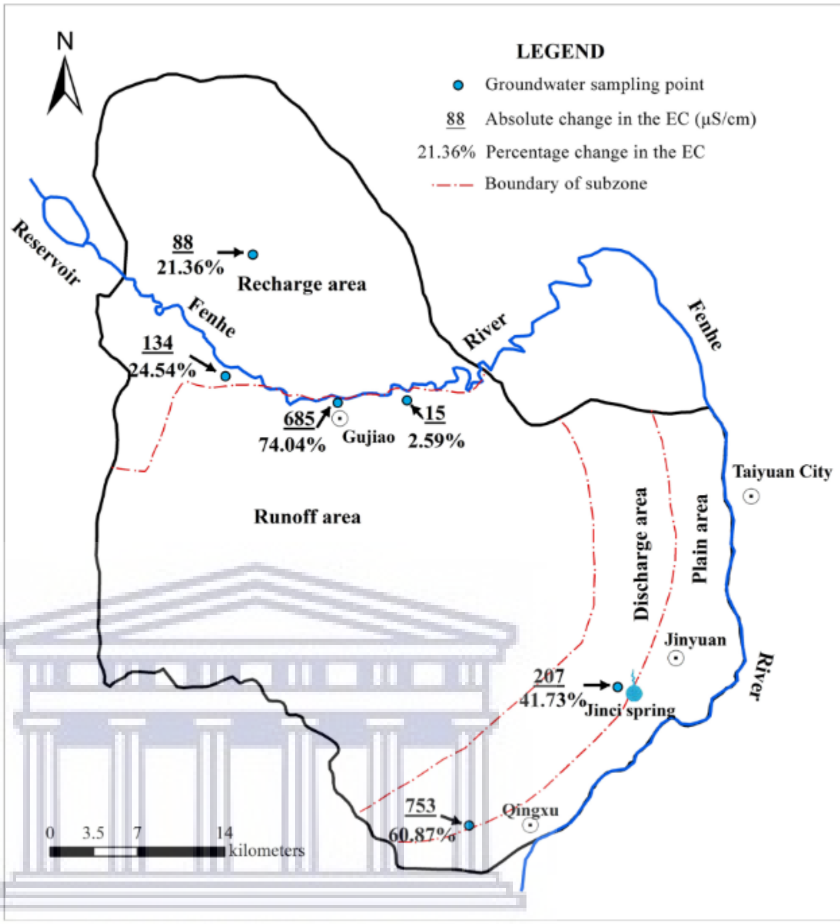

Fig. 10 Absolute increase and percentage increase in the EC between 1994 and 2014

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

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

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

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

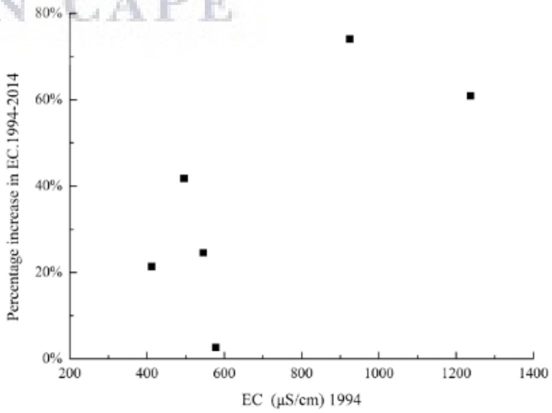

Fig. 11 The relationship between percentage increases in EC during 1994–2014 and EC in 1994

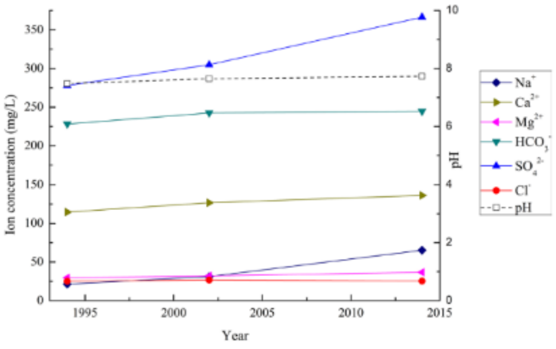

Fig. 12 Changes in major ions and pH

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

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

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

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

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

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

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

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

Conclusions

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

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

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

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

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

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

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

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Compliance with Ethical Standards

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

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