Environ Geol (2006) 50: 415–422
DOI 10.1007/s00254-006-0220-6

ORIGINAL ARTICLE

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Karst groundwater management by defining protection zones based on regional geological structures and groundwater flow fields

Received: 26 September 2005
Accepted: 6 February 2006

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Abstract In a semiarid region, the karst aquifer generally forms a large groundwater reservoir that can play an important role in regional water supply. But because of the specific physical properties of karst aquifers, they are vulnerable to pollution and anthropogenic impacts. Karst groundwater management strategies are vital. As representative of karst springs in a semiarid area, Niangziguan Springs is located in the east of Shanxi Province, China with an annual average rate of discharge of 10.34 m^3/s (1956–2003) (Y. Liang, unpublished data). The Niangziguan Spring Basin covers an area of 7,394 km^2 with an annual average precipitation of 535 mm (1958–2003) (Hao et al. in Carsologica Sinica 23(1):43–47, 2004). Over the past three decades, accelerated groundwater exploitation has caused water-table decline in the aquifer, reduction of the spring discharge, and deterioration of water quality. In this study, three protection zones were defined to ensure the quality and capacity of this resource. The confluence of the 11 spring systems and the discharge areas were defined as I protection zone, the recharge basin was II protection zone, and the slack water area where there is little surface recharge was the III protection zone. Management strategies for each zone were suggested and evaluated to provide a scientific foundation for sustainable utilization.

Keywords Karst · Groundwater management · Semiarid region · Groundwater flow · Niangziguan Springs Basin · China

Introduction

Karst regions, occupy approximately 25% of the land surface of the earth. Karst aquifers are often major sources of water supply in these areas. However, karst aquifers are generally considered to be particularly vulnerable to pollution and anthropogenic impacts. Large withdrawals of water in karst areas for municipal, agricultural, and industrial use may competitively affect water supply in surrounding areas; deterioration of surface water and groundwater quality from agricultural, industrial, or private development may occur; and improper injections of waste into a karst system may contaminate a water supply.

To utilize karst groundwater sustainably, measures for elimination of pollution sources and protection of groundwater are necessary. Typical preventative strategies include establishment of groundwater protection zones (Kacaroglu 1999). Doerfliger et al. (1999) described a new method of defining protection areas using a multi-attribute approach and GIS tools (EPIK method). This approach is based on vulnerability mapping of the catchment areas of water supply using data provided by springs or boreholes. The application at the Saint-Imier test site (Swiss Jura) resulted in recommendations for new boundaries for the protection-zone. Biondic et al. (1998) proposed the two criteria on which determination of karst aquifer protection zones in

Croatia is based: groundwater flow time and apparent velocity. Five basic protection zones have been distinguished in the Dinarides of Croatia.

In China, 9.5% of the landmass is karst terrain, which is generally concentrated in two regions. One of the regions encompasses the Shanxi Plateau and neighboring provinces, an area of about 470,000 km^2, and is in a semiarid climate zone. The other karst region is located in the southwest region of China, with an area of about 500,000 km^2, and is in a humid climate zone (Yuan 1994). Karstification is highly influenced by precipitation and terrain, which can cause large regional differences in karst spring flow. In semiarid areas of China, most carbonate aquifers are overlain by thick Permian carboniferous-sandstone and shale, and Quaternary sediments. Karstification in these areas is generally not very developed because of low precipitation and the thick overburden. One important characteristic of karst formations in semiarid areas is that caves and subsurface rivers are not typically present. In contrast, the karst systems in humid, southwest China are characterized by well-developed caves and highly connected underground flow channels (Yuan 1994). The ratios of maximum spring flow to minimum in semiarid areas are generally from 1.24 to 5.89, whereas the ratios are from 10 to 1,000 in humid regions (He et al. 1997). These ratios are indicative of a rapid response to precipitation in the humid regions. The areal extent of a karst ground water system in semiarid regions is usually up to several thousands of square kilometers. The pores in the carbonate rocks provide extensive storage for precipitation. Spring discharges in these semiarid regions generally lag behind precipitation by 2–10 years (Han et al. 1993; Ma et al. 2004). The springs in semiarid areas can be classified as slow-response springs according to the classification of karst springs by White (1988). As representative of springs in the semiarid karst areas of China, Niangziguan Springs was selected for investigating geological structure and groundwater flow field to determine adequate protection-zones and to suggest appropriate management strategies.

The hydrogeological setting of Niangziguan springs

Niangziguan Springs (E.115°, N.37°50′), one of the largest karst springs in north China, are located in the Mianhe River Valley, Taihang Mountains, Eastern Shanxi Province, China (Fig. 1). The springs discharge at an annual average rate of 10.34 m^3/s (1956–2003). The maximum annual recorded spring flow was 15.75 m^3/s in 1964 and the minimum was 5.73 m^3/s in 1995 (Fig. 2) (Y. Liang, unpublished data). Niangziguan Springs consists of 11 groups of springs named Podi Spring, Chengjia Spring, Chengxi Spring, Wulong Spring, Shibanmo Spring, Gunquan Spring, Hebeicun Spring, Qiaodun Spring, Jinqu Spring, Shuiliandong Spring, and Weizeguan Spring. The springs are distributed along the Mianhe River bank and the zone of discharge stretches approximately 7 km along the Mianhe River (Fig. 1).

The Niangziguan Springs receive water from a 7,394 km^2 basin that includes the city of Yangquan, the counties of Pingding, Heshun, Zuoquan, Xiyang, Yuxian, and Shouyang (Fig. 1). Small basins and gentle sloping river valleys are primary physiographic features, but extensive areas of the Niangziguan Spring Basin consist of rough hilly terrain where the altitude ranges from 1,200 to 1,600 m. The western part of the basin is higher than the eastern part, with the general topography of the basin inclining to the east. The Mianhe Valley, where Niangziguan Springs discharges, has the lowest altitude in the Niangziguan Springs Basin, ranging from 360 to 392 m.

In the Niangziguan Springs Basin, the annual average precipitation is 535 mm (1958–2003). The largest recorded annual precipitation was 847 mm in 1963 and the smallest 288 mm in 1972 (Fig. 2). As much as 60–70% of precipitation in a year usually occurs in July, August, and September. The annual mean air temperature of the Niangziguan Basin is 10.9°C. The highest recorded temperature is 40.2°C and the lowest is −28°C. The annual mean potential water surface evaporation is 1,202 mm (Hao et al. 2004).

Surface waters in the study area include Wenhe River, Taohe River (these two rivers converge to form the Mianhe River at Niangziguan town), Mianhe River, Songxihe River, Qingzhangdongyuan River, and Qingzhangxiyuan River (Fig. 1).

The Niangziguan Springs Basin is an independent hydrogeological unit (Fig. 3). The main aquifers of the basin are comprised of karstic Cambrian and Ordovician limestone and porous Quaternary sandstone sediment. The limestone and Quaternary sediment aquifers are hydraulically connected, with Permian carboniferous sandstone and shale interbedded. Karst groundwater flows toward Niangziguan Springs in the east (Fig. 1). In the discharge area around Niangziguan Town, owing to the incision of the Mianhe River and the elevation of lower permeability bedrock of clayey dolomite, the karst groundwater flow is blocked and discharges to the surface. The major components in the carbonate aquifer are bicarbonate, calcium, and magnesium, with a temperature of 15–16°C.

Utilization of the karst groundwater in the Niangziguan Springs Basin

Since the early 1970s, karst groundwater in the Niangziguan Basin has been exploited for irrigation,

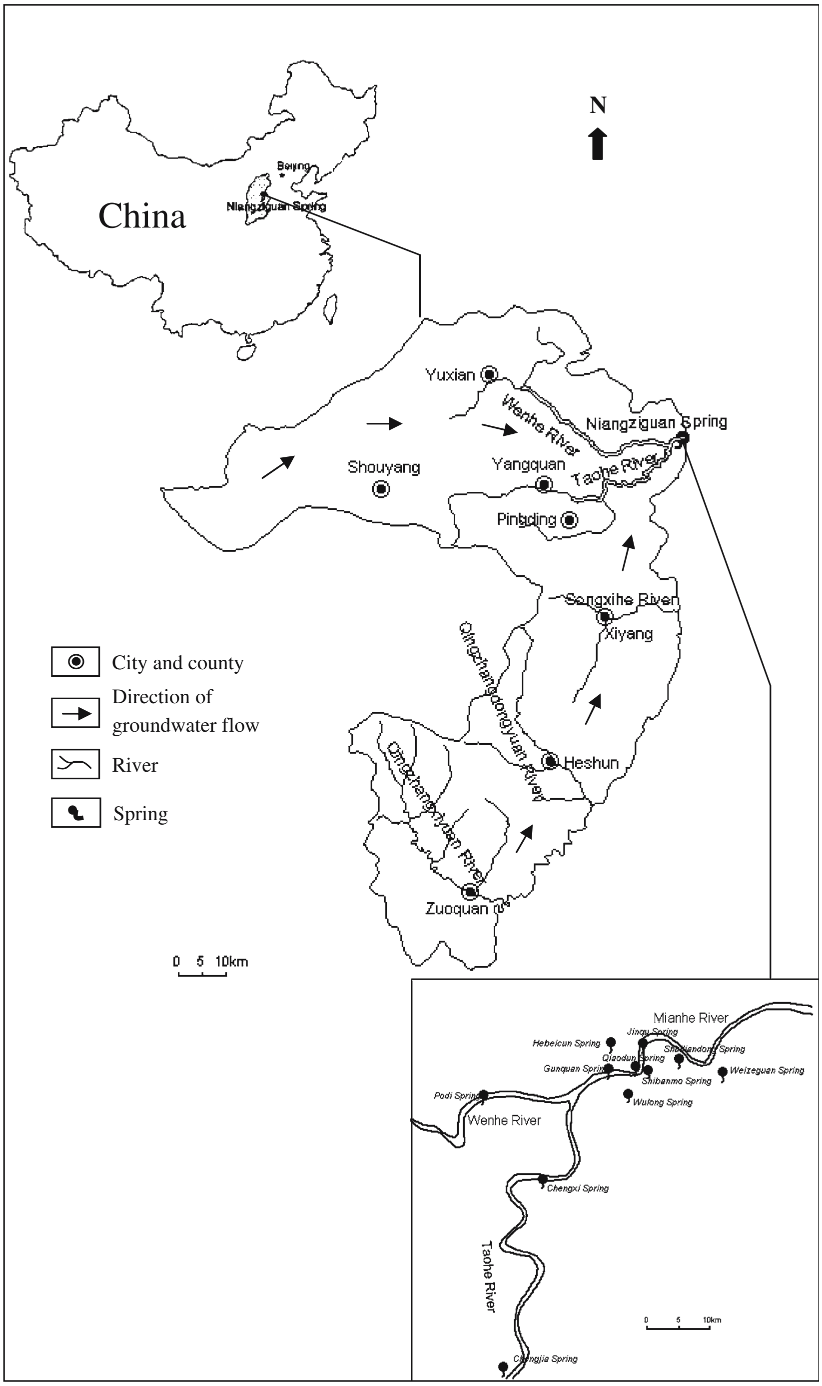
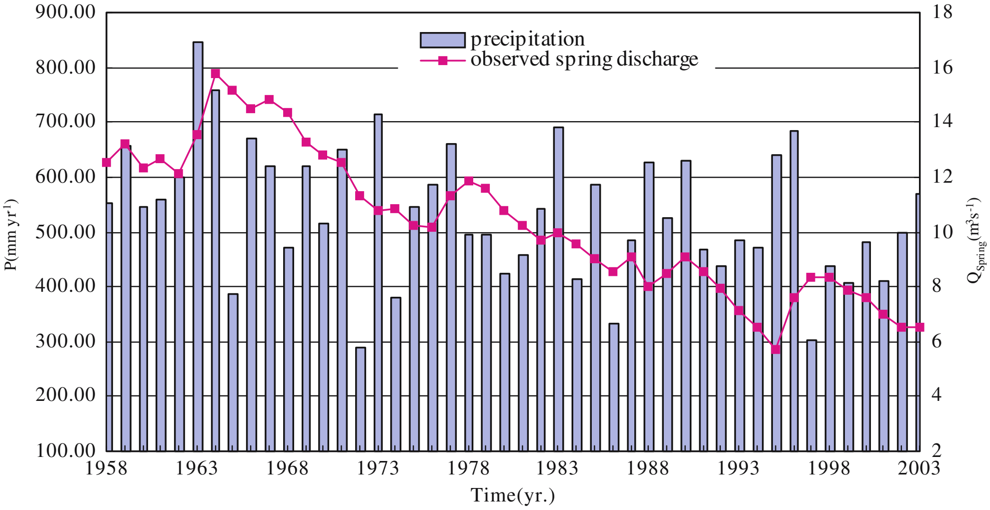


Fig. 1 Location of Niangziguan Springs, and a simplified geographic map of the Niangziguan Springs Basin, with an enlarged view of the distribution of springs

municipal use, and industrial water supply. Usage has accelerated since the 1980s. Nowadays, the karst groundwater is a major water source for the Niangziguan Springs Basin, one of the heavy industry regions in China for coal mining, power generation, chemical engineering, and metallurgy.

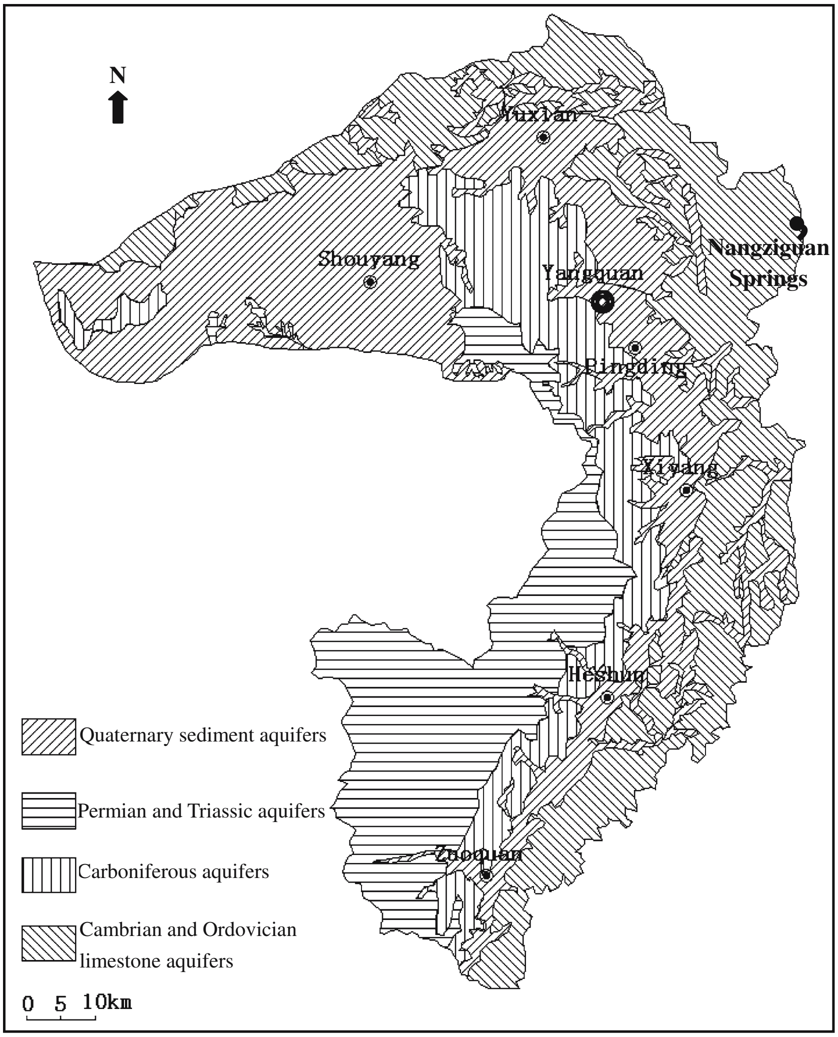
Karst groundwater in the Niangziguan Springs Basin is utilized from spring discharge and from wells. In 1998, the total volume of karst groundwater use was 149 million m^3, 82% of which came from spring outlets and 18% from wells. From 1980 to 2001, the annual volume of abstracted water from wells increased from 6.43 million to 30.8 million m^3 (Fig. 4) (Y. Liang, unpublished data). This enormous exploitation of groundwater has reaped large socio-economic benefits for the area, but has caused water quality and quantity

Fig. 2 Time series of the spring discharge and recorded precipitation during 1958–2003



problems. Over-exploitation, uncontrolled urban and industrial discharges, and agricultural intensification are causing increasingly widespread degradation of aquifers and reducing the discharge of springs. The discharge of Niangziguan Springs has steadily diminished during the period from 1956 to 2003 (Fig. 4). Attenuation of spring

Fig. 3 Simplified hydrogeologic map of the Niangziguan Springs Basin



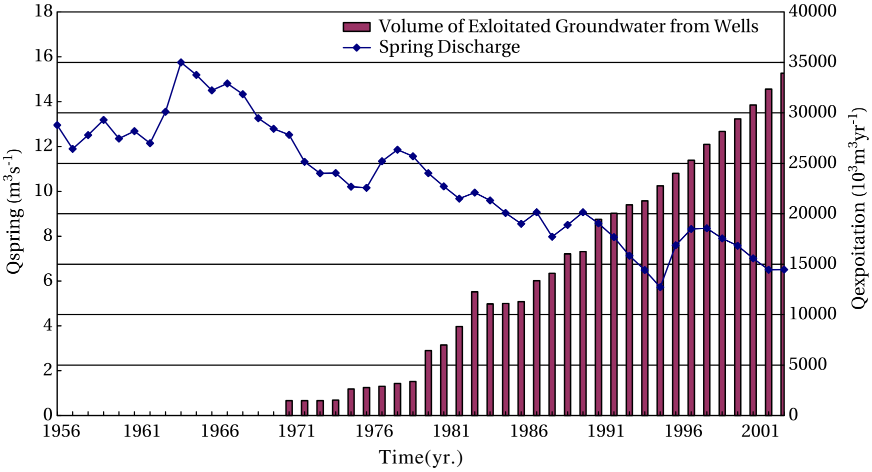


Fig. 4 Time series of spring discharge and volume of exploitation groundwater from wells during 1956–2003

discharge has become a major concern for local economic development.

In the Niangziguan Springs Basin, concentrated infiltration points such as faults, fractures, fissures, and conduits are connected to the karst network (Ning 1996). Hazardous substances from industries and disposal of waste products are potential threats to groundwater in karst aquifers. Table 1 presents Niangziguan Springs Basin groundwater quality parameters from 1979, a time when the groundwater was relatively unpolluted. Table 2 compares water quality parameters of 2003–1979 and indicates the urgent of the problem.

Definition of management zones

Ordovician carbonate rock with a thickness of more than 600 m comprises the principal aquifer. The aquifer generally outcrops in the east. The western part of Niangziguan Springs Basin is overlain by Permian and Triassic sandstone and shale with thickness of 90–1,200 m and a deeper Carboniferous coal-bearing limestone layer of 80–120 m overlying the Ordovician aquifer (Fig. 3).

In general, the further toward the west, the thicker the overlay. In the areas of overburden less than 200 m, karstification is well developed. Strong karst groundwater run-off belts can be found in this region. In areas with 200–500 m thickness of overburden, the karstification is less well developed. In the areas with a 500–1,000 m overlying layer, karstification is weak. When overburden exceeds 1,000 m, nonkarst areas are the primary land form (Han et al. 1993; Hao et al. 2004).

In the Niangziguan Springs Basin, the higher altitude west is the upper course of discharge and the east, at lower altitude, is midstream and downstream. Ground water recharge occurs mainly from infiltration of precipitation into outcropping limestone areas, river beds, sinkholes, and seepage from covering strata. In the west, with little water loss except for evaporation, precipitation becomes surface water and shallow groundwater. Most of the surface water flows to the east and enters karst groundwater by filtration. Through transportation and seepage, the shallow groundwater flows to the east and recharges karst aquifers. Very little becomes surface water. In general, groundwater in the Niangziguan Springs Basin flows to the east and discharges at the Niangziguan Springs system (Fig. 5).

Table 1 The average concentrations of groundwater quality in 1979 in the Niangziguan Springs (in mg/l)

Contents	HB	TDS	SO_4^{2-}	Cl^-	Fe	NO_3^-	F^-	CN	Pb
The concentrations	291.92	512.00	59.6	22.2	0.17	14.7	0.4	0.005	0.005

Table 2 The ratios of the groundwater quality concentration between 2003 and 1979 in the Niangziguan Springs Basin

Contents	HB	TDS	SO_4^{2-}	Cl^-	Fe	NO_3^-	F^-	CN	Pb
Recharge area	1.568	1.14	1.348	0.0	1.725	1.0	1.712	–	2.965
Discharge area	2.258	1.679	1.463	2.984	–	1.9	1.429	2.36	1.721
Confluence area	1.622	1.322	1.056	2.233	–	1.0	1.444	1.6	4.05

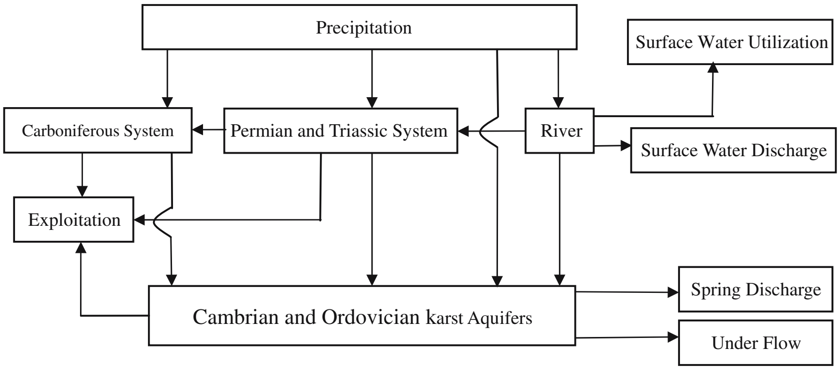


Fig. 5 The hydrological process in the Niangziguan Springs Basin

The Niangziguan Springs Basin encompasses four hydrodynamic areas: the slack water area, the recharge area, the confluence area, and the discharge area. The slack water area lies in the westernmost of the Niangziguan Springs Basin and includes Shouyang County, the southwest of Yangquan City, the west of Pingding County and parts of Xiyang County, Heshun County, and Zuoquan County (Figs. 1, 6). The slack water area covers an area of 2,880 km^2. It is overlain by Permian and Triassic sandstone and shale. In this region, there is basically no feed-flow from surface water to the karst groundwater owing to the thick overburden. The surface water generally flows to the east and much of it recharges to groundwater. In this area the degree of karstification is faint, karst groundwater storage is small, and groundwater flow is weak. Karst groundwater here is stagnant (Han et al. 1993). This zone has relative immunity to pollution by groundwater resources.

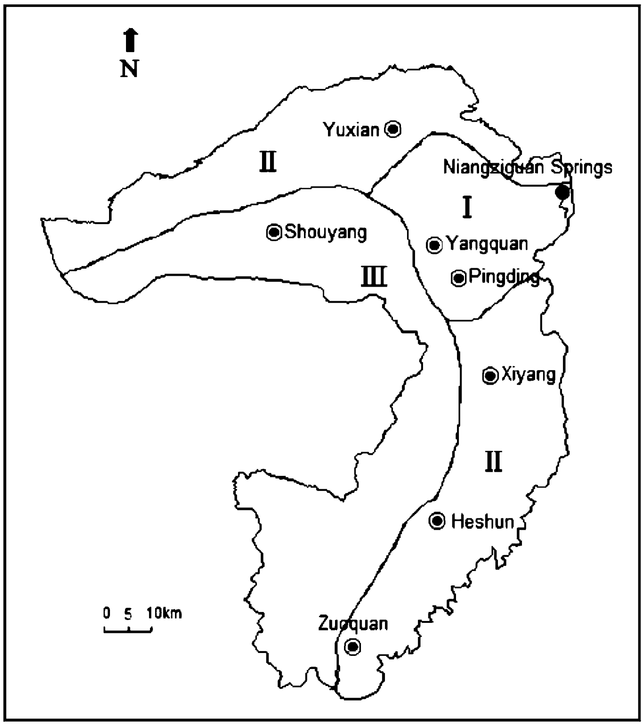


Fig. 6 Protection zones of the Niangziguan Springs Basin

The recharge area can be divided into north and south parts, bounded by the Taohe River and Wenhe River, an area which includes the south of Yuxian and Pingding Counties, the north of Shouyang County, together with the counties of Xiyang, Heshun, and Zuoquan, and occupies an area of 3,460 km^2 (Figs. 1, 6). The aquifers in the recharge area have a varying thickness from 10 m to several decameters. The groundwater level is 100–500 m under the surface. The groundwater hydraulic slope is about 0.76–0.9%. In this semiarid area, the velocity of groundwater flow is slow. The chief body of recharge water source is precipitation. Both horizontal movement and vertical movement exist. Water moves from the recharge area to the discharge area through long distances over a period of years. The spring discharge is closely related to precipitation of the latest 7 years (Qian 1981; Yang and Guo 1997). Once the karst groundwater here is polluted, contaminants will linger for a long time and diffuse over a large area.

The confluence area is in a triangular area between the Taohe River and the Wenhe River (Figs. 1, 6). The karst groundwater in this area is abundant. Aquifers in this zone have a thickness of 200–400 m. Karstification is well-developed and the groundwater hydraulic slope is less than 0.3% generally.

The discharge area is located at Niangziguan Town, in the northeast of the spring basin and covering an area of 50 km^2 (Figs. 1, 6). Karstic conduits are well-developed and are the major path of groundwater flow with outlet to springs. Filled with cobbles, the karstic conduits have an average diameter of 0.02 m, with 4.57 m being the largest known diameter (Han et al. 1993). The conduits are distributed unevenly and mainly develop from near the surface to 40 m depth. Regional groundwater is mainly confined water. The hydraulic slope is about 0.35%. Groundwater flow in some parts of the area is turbulent.

In the confluence and discharge areas, karstification has reached a mature stage with extensive dissolution of the limestone and full development of an arterial underground drainage system with flows in zones of high permeability. This zone is the most vulnerable area to pollution.

To conserve groundwater in the Niangziguan Basin, the confluence area and the discharge area are defined as the I protection zone, the recharge area is the II protection zone, and the slack water area is the III protection zone. Propriety for protection is assigned by the vulnerability of each zone.

Management strategies

Improved management of karst groundwater resources in the Niangziguan Springs Basin is urgently needed to mitigate actual and prevent potential degradation caused by excessive exploitation and inadequate pollution control. Unless groundwater is protected, scarcity of water and escalating water supply costs will be accompanied by potentially negative impacts on human health. Different management measures should be enforced in the different management zones based on their hydrogeological properties.

The I protection zone is susceptible to a greater range of environmental impacts due to its hydraulic and hydrogeologic characteristics. Some pollution threats are direct leaching of sewage flow into the groundwater. Stricter water environmental quality standards should be established for Zone I. Protecting groundwater resources against pollution demands (1) regulations for planning, location, and construction of settlements, houses, buildings, roads, and industrial plants, etc.; (2) prohibition of the direct or indirect disposal of untreated liquid wastes and waste water into underground; (3) prohibition of solid wastes storage in this area; (4) prohibition of the construction of sewage and waste water collection systems or pollutant treatment plants within this area unless high standards are used; (5) prohibition or restriction of the use and transportation of hazardous and toxic materials; and (6) prohibition of the over exploitation of the karst groundwater without license for water withdrawal.

In the II protection zone, accelerated development of the coal industry has brought about great social and economic benefits, but also many environmental problems. Dewatering for coal mining has created problems of groundwater subsidence that have impacted industrial, municipal, and agricultural areas. When the underground coal mining compartments were dewatered, nearby wells went dry and a large number of sinkholes formed. Polluted waters drained from coal mining areas may cause groundwater pollution. Direct discharge mining waste water should be forbidden. Stacking of gangues or mine waste materials should be forbidden. Appropriate land development policies should be put in place. Construction projects which produce pollutants should not be permitted without safeguards. Discharges originating from industrial factories should not be permitted unless the discharge water quality is in compliance with national environmental standards. Proper location, construction and operation of fertilizer and pesticide storage facilities, correct application of fertilizers and pesticides, and proper collection storage and treatment methods for solid wastes are also required.

The III protection zone, which appears to have greater relative immunity to pollution, is the most suitable zone for urbanization and development among the three zones. In this zone, construction of projects should be allowed, as well as the enlargement of urban areas, but even in this zone, discharge drainage must be restricted. Chemical industrial plants and their storehouses, waste-water leakage into the underground through open seepage pits, and injection of untreated industrial waste water into dry or decommissioned wells should not be permitted to avoid further environmental degradation.

Conclusions

The water resources system in the Niangziguan Springs Basin is composed of surface water and groundwater. Groundwater serves as an important source of fresh water in the Niangziguan Springs Basin, and supplies water for domestic, industrial, and agricultural use. Karst groundwater is prefered because of its lower cost and higher quality, compared to surface water, the use of which is diminishing due to contamination by industrial facilities and restriction in drought periods. Although groundwater resources are replenishable, they are not inexhaustible. Standardized effective protection measures and management recommendations are urgently needed to balance sustainable development demands.

The principle strategies to prevent degradation of the karst groundwater are restriction or prevention of activities which endanger the groundwater quality, the prevention of waste disposal, the elimination of pollution sources, and the establishment of protection zones to protect the entire aquifer or groundwater system. Establishing scientifically determined and reasonable protection zones is a significant aspect of water resources protection.

Government agencies need to be enabled as 'guardians of groundwater'—working flexibly with local stakeholders as partners in resource administration, protection and monitoring while also acting on broader water-resource planning and management strategies.

Enhanced public awareness and improved scientific understanding are important elements for improving the Niangziguan Springs Basin karst groundwater management and sustainable utilization.

Acknowledgments The authors would like to acknowledge the support of National Natural Science Foundation of China NSFC-40572150, the Fellowship of Shanxi Scholarship Council of China, and Science and Technology Development Program of Education Bureau of Shanxi Province. We are also grateful to Mr. Joseph Stefani of the University of Arizona for technical editing of this manuscript. Many thanks are extended to the two anonymous reviewers and the AE who have spent enormous efforts reviewing the manuscript and provided very encouraging, insightful, and constructive comments.

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