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Response of karst springs to climate change and anthropogenic activities: the Niangziguan Springs, China

Yonghong Hao,^{1*} Yajie Wang,² Yuen Zhu,^{3,4} Yi Lin,⁵ Jet-Chau Wen⁶ and Tian-Chyi J. Yeh^{7,8}

¹Key Laboratory of Water Environment and Resources, Tianjin Normal University, Tianjin 300387, China

²College of Computer and Information Engineering, Tianjin Normal University, Tianjin 300387, China

³College of Environment and Resources, Shanxi University, Taiyuan 030006, Shanxi Province, China

⁴School of Environment, Beijing Normal University, Beijing 100875, China

⁵Department of Mathematics, Slippery Rock University, Slippery Rock, PA 16057, USA

⁶Department of Safety, Health and Environmental Engineering, National Yunlin University of Science and Technology, Touliu, Yunlin 64045, Taiwan

⁷Department of Hydrology and Water Resources, The University of Arizona, Tucson, AZ 85721, USA

⁸Department of Resources Engineering, National Cheng Kung University, Tainan City 701, Taiwan

Abstract: Discharge from the largest karst spring in north China, the Niangziguan Springs, has been declining since the 1950s. This paper examines the response of these springs to climatic change and anthropogenic influence by attempting a model-based discrimination between phases in the stream discharge record. In Niangziguan Springs Basin, the exploitation of karst groundwater began in 1979. Accordingly, the spring discharge data were divided into two phases: pre-1979 and post-1979. In the first phase (1957–78) the spring discharge was believed to be affected solely by climate change, and in the second phase (1979–2007) the spring discharge was influenced by both climate change and human activities. Using grey system theory, a discharge model was estimated for the first phase. Extrapolating the model, we obtained a projection of the spring discharge during the second phase. Using a water balance calculation, we discerned the respective effects of climate

*Author for correspondence. Email: haoyhong@yahoo.com, haoyh@sxu.edu.cn

change and human activities on depletion of spring discharge for the second phase. The results show that the contribution of climate change to depletion of Niangziguan Springs is $2.30\text{m}^3/\text{s}$ and the contribution of anthropogenic activities ranges from 1.89 to $2.90\text{m}^3/\text{s}$, although this assumes a constant for the climate change effect. Accordingly, the anthropogenic effects have been approaching and surpassing the effects of climate change during the second phase. With respect to the impact of human activities on spring discharge, groundwater abstraction accounts for only about 34–52% of the declines; 48–66% of the declines are related to other human activities, such as dewatering from coal mining, dam building and deforestation.

Key words: anthropogenic influence, climate change, GM(1,1) model, grey system modelling, Niangziguan Springs.

I Introduction

During the twentieth century, the global environment has been subject to substantial change (Houghton *et al.*, 1990; Watson *et al.*, 2001). Climate change has become one of the major public concerns (Soon and Baliunas, 2003) and, with this, there is the potential redistribution of surface water resources on the earth (Waggoner, 1990). Since 1900, temperatures in the western USA have risen by $1\text{--}3^\circ\text{C}$ (US Global Change Research Program, 2001). The region has generally experienced significant increases in precipitation, with increases in some areas greater than 50%. However, a few areas such as Arizona have become drier and have experienced more droughts (Lioubimtseva, 2004). Similarly, based on the IPCC A2 scenario, the authors predicted that temperature in north China may increase by about 1°C over the next three decades. Accordingly, regional precipitation is likely to increase by about 20%, but Shanxi Province, where the Niangziguan Springs are located, may actually become drier (Tang *et al.*, 2008). Compared with surface water systems, groundwater systems tend to respond more slowly to variations in climate. Despite the slower response, groundwater systems are still influenced by climate change over both the short and long term, including changes in groundwater recharge, and possible increased demand on groundwater as a backup source of water supply (Alley, 2001). Karst aquifers are generally considered to be particularly vulnerable to environmental change

(White, 1988; Leibundgut, 1998). Thus, karst groundwater systems have been used as important indicators to assess climate change and anthropogenic effects on hydrological processes (Taminskas and Marcinkevicius, 2002; Guo *et al.*, 2005). However, climate change and hydrological processes remain subject to considerable variability and uncertainty (Mitchell and Hulme, 1999; Clifford, 2002).

Many models are used to study climate change and hydrological response. Based on the projected climate change scenarios determined by general circulation models, Loáiciga *et al.* (2000) simulated the potential impacts on groundwater in the Edwards Balcones Fault Zone (BFZ) karst aquifer in Texas, USA. Their simulations indicated that a scenario with doubled atmospheric CO_2 conditions could exacerbate negative impacts and water shortages in the Edwards BFZ aquifer, even if pumping does not increase above its present average rate. A cross-correlation analysis by Chen *et al.* (2004), which examines the importance of climate on groundwater level variation, indicates that both precipitation and annual mean temperature are strongly correlated with annual groundwater levels in the upper carbonate aquifer in southern Manitoba, Canada. Ma *et al.* (2004) applied a seasonal decomposition method to study response of the Shentou Springs in China to climate change, and conclude that the discharge responds remarkably closely to precipitation change, and that human activities are

secondary in affecting spring discharge. Hao *et al.* (2006; 2007) introduced grey system theory to simulation of karst springs flow, using a GM(1,2) model with timelags and a GM(1,1) decomposition model. The models were used to study the relations between precipitation and the Liulin Springs flow in China. The results showed that the influence of climate change on spring discharge at Liulin Springs is long-term and evident. All the models, in fact, were concerned with the combined effects of climate change and human activities on spring flow.

Few of these studies attempt to discern the anthropogenic effects from climate change on karst hydrological processes. However, there are many human activities that, intentionally or not, produce severe impacts in karst, often with irreparable damage (Parise and Gunn, 2007). For example, large withdrawals of water in karst areas for municipal, agricultural and industrial use may affect the water supply in surrounding areas and cause karst groundwater depletion (Xue *et al.*, 2005; Parise *et al.*, 2004). For regional water resources management, if the effects of human activities were neglected or underestimated, climate change might be used to justify continued over-exploitation and depletion of water resources. As a result, environmental problems may be exacerbated by human activities. Therefore, it is preferable to distinguish the effects of anthropogenic activities from climate change and evaluate the contribution of human activities and climate change to hydrological processes (Wilby, 1995). Accordingly, the purpose of this paper is to investigate the depletion of the Niangziguan Springs in northern China by discerning the respective effects of climate change and anthropogenic activities, and then quantifying the magnitude of the various impacts.

II The hydrogeological setting of the Niangziguan Karst Springs

China has some of the largest karst terrains in the world. A quarter of the world's carbonate

rock occurs in China. Carbonate rock outcrops cover 1.3 million km² or a seventh of China's area. If more deeply covered and buried karsts are included, up to a third of the country can be classified as karst, which is a total of 3,463,000 km² (Hua, 1981; Sweeting, 1995; Figure 1).

The karst terrain of China is concentrated in two regions: an area located in the semi-arid climate zone in the northern part of China; and a humid climate zone in the southwestern part of China (Yuan *et al.*, 1994; He *et al.*, 1997). Karstification is highly influenced by precipitation and topography, which can cause large differences in karst aquifers in different regions. In the northern part of China, annual precipitation is less than 800 mm, and most carbonate aquifers are overlain by thick Permian carboniferous sandstone and shale, and Quaternary sediments. Karstification in these areas is generally not very developed, in contrast to the karst systems in humid, southwest China, where well-developed caves and highly connected groundwater flow channels are abundant (Han *et al.*, 1993). However, in some areas of northern China, large karst basins do provide an inflow of more than 1 m³/s to many large karst springs. Since the 1950s, most of the spring flows have been declining in northern China (Guo *et al.*, 2005). Because groundwater is the main source of water supplies in northern China, these events have become a major concern of local governments.

The Niangziguan Springs complex, one of the largest karst springs in north China, is located in the Mianhe River Valley, Taihang Mountains, Eastern Shanxi Province, China (Figure 2). The springs discharge at an annual average rate of 10.06 m³/s (1957–2007). The maximum annual recorded spring flow was 15.75 m³/s in 1964 and the minimum was 5.73 m³/s in 1995 (Figure 3). The Niangziguan Springs consist of about 100 spring points, which are distributed along 7 km of the Mianhe River bank (Figure 2).

The Niangziguan Springs receive water from a 7,394 km² catchment that includes

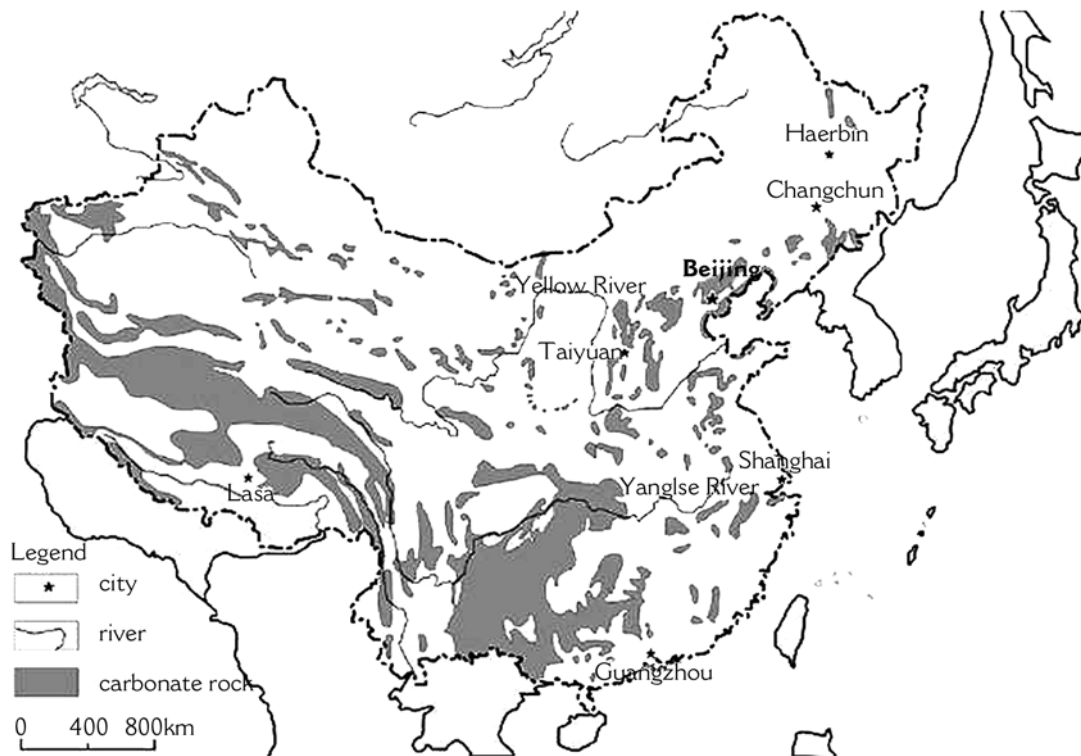


Figure 1 Surface outcropping and subsurface karst in China

Source: After Hua (1981).

the city of Yangquan, and the counties of Pingding, Heshun, Zuoquan, Xiyang, Yuxian, and Shouyang (Figure 2). Precipitation is believed to be the primary source of recharge to the aquifer in the Niangziguan Springs Basin. The annual average precipitation is 499.9 mm (1957–2007). The largest recorded annual precipitation was 715.7 mm in 1963 and the smallest 265.9 mm in 1997 (Figure 3). For most years, about 60–70% of the annual precipitation occurs in July, August, and September.

Small basins and gentle sloping river valleys are the primary physiographic features, but extensive areas of the Niangziguan Springs Basin consist of rough hilly terrain where the altitude ranges from 1,200 to 1,600 m above mean sea level. 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 the Niangziguan Springs discharges, has the lowest altitude in the Niangziguan Springs Basin, ranging from 360 to 392 m above mean sea level.

The main outcropping strata in the Niangziguan Springs Basin are Cambrian and Ordovician carbonate rocks, Carboniferous coal seams, Permian and Triassic detrital formations, and Quaternary deposits. The main aquifers of the basin are composed of karstic Cambrian and Ordovician limestone and porous Quaternary sandstone sediments (Figure 4). The limestone and Quaternary sediment aquifers are hydraulically connected, although Permian carboniferous sandstone and shale exist between them. Karst groundwater flows toward Niangziguan

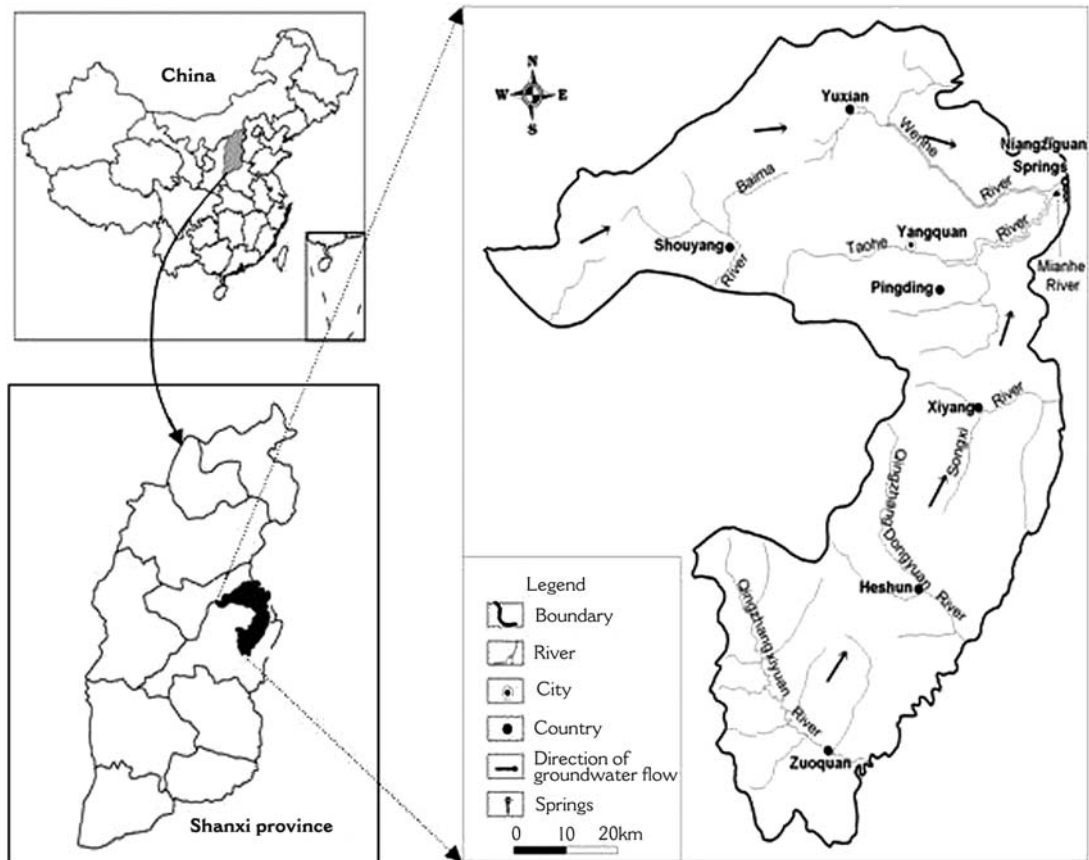


Figure 2 Location of Niangziguan Springs, and a simplified geographic map of the Niangziguan Springs Basin

Springs in the east (Figure 2). At the discharge area around Niangziguan Town, the springs arise from the occurrence of a geologic unconformity, where groundwater perches on low-permeable strata of dolomitic limestone, and eventually intersects the ground surface, thus creating the Niangziguan Springs.

III Methods

Hydrological processes are characterized as variability and uncertainty. Grappling with uncertainty is one of the most enduring aspects of hydrological research (Clifford, 2002). Chorley and Kennedy (1971) represent a paradigm for the study of physical geography based on systems approach. Chorley and

Kennedy used the term 'systems approach' in the sense of the organicist against the reductionist, where the whole is greater than its component parts so that attempting to build a science by studying its components in minute details and then combining the results can never be as effective as a study of the behaviour of the whole. After establishing the classification of systems and basic terms, Chorley and Kennedy associated each type of specific system with suitable analytic methods, such as regression models and analysis of variance, along with many illustrative examples. This paradigm shift has had a major impact in the research of physical geography (White *et al.*, 1992).

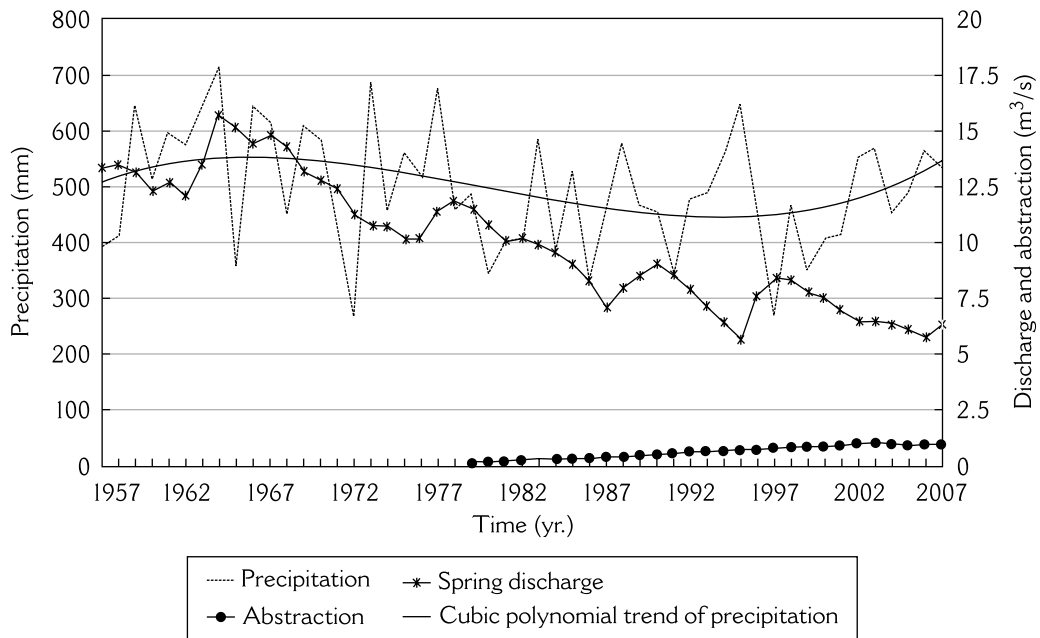


Figure 3 Precipitation, spring discharge, and abstraction in the Niangziguan Springs Basin

The method of grey system theory (Liu and Lin, 2006), as employed in this paper, was specifically developed for analysing general systems involving uncertainty (Deng, 1982). This method comes from a new system of methodology which is different from the analytic methods used in the 'classic' general systems approaches (Chorley and Kennedy, 1971; White *et al.*, 1992), although the basic classificatory terminology remains the same. In the 'classic' approaches, differential equation-based deterministic models, including difference equations and integral equations, and probabilistic stochastic models, including various ARIMA models that are more conventionally employed in modelling hydrological time series, are the major analytical tools. However, recent studies on systems (including weather) evolution and predictions of zero-probability disastrous natural events (Wu and Lin, 2002; OuYang *et al.*, 2002; Lin, 2008) indicate that these traditional mathematical methods are only useful for analysing normalized or regularized

information when the abnormal (or small-probability) information is ignored. This discovery has been very well supported by the constant failures in the predictions often seen in financial markets and in the forecasts of disastrous weather and other devastating natural phenomena. What has been shown is that the traditionally ignored small-probability information represents changes in systems' internal structures, and most likely possesses the ability to signal the forthcoming major disastrous events, caused by the shifting internal structures of the underlying systems.

In comparison with the traditional methods, either deterministic or stochastic, the grey system methodology does not ignore any available data. As long as there is no evidence proving that data values are erroneous, then each available data value is employed in the grey system modelling and analysis. Accordingly, the theoretical outcomes of grey system modelling and analysis produce more reliable results

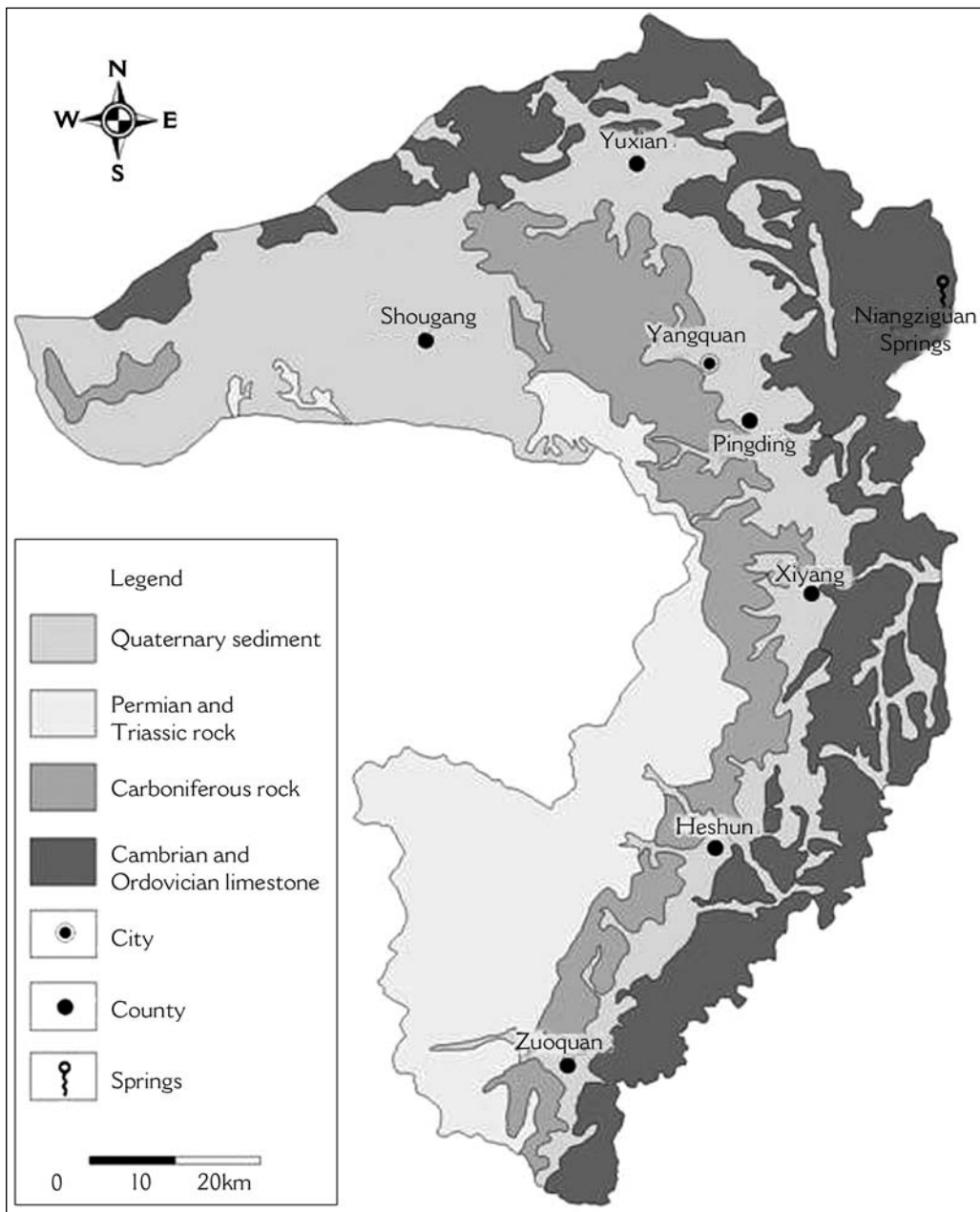


Figure 4 Simplified hydrogeologic map of the Niangziguan Springs Basin

than the conventional calculus-based or statistics-based methods, with improved representation of the changes in the internal structures of the systems of concern (Wu and Lin, 2002; OuYang *et al.*, 2002; Lin,

2008). Theoretical and empirical studies (Wu and Lin, 2002; OuYang *et al.*, 2002; Lin, 2008) have established the fact that, when transitional changes in the internal structures are understood, the relevant predictions or

extrapolations of the models will be more reliable.

Karst aquifers are highly heterogeneous in nature. They are dominated by secondary or tertiary porosity (ie, fractures or conduits, respectively) and may exhibit hierarchical permeability structures or flow paths (Yuan *et al.*, 1994). In karst systems, precipitation and runoff reach the subsurface water via infiltration, and, subsequently, groundwater emerges as springs. Based upon the grey system theory, a karst system by its nature is a grey system (Lee and Wang, 1998; Xia, 2000; Liu and Lin, 2006). This provides the theoretical foundation for our method of extrapolation using the GM(1,1) decomposition model (Hao *et al.*, 2007), fitted from initial observations of stream discharge in the period 1957–78, and extrapolated into the period 1979–2007. These two periods of record span significant alterations in spring water exploitation, and are used to infer the relative effects of anthropogenic and climate change on stream discharge.

1 Grey system GM(1,1) decomposition model

Examination of the karst spring discharge data over different timescales reveals different trends. The time series of spring flow $Q(t)$ generally includes three specific components at different timescales: (1) the long-term trend, $\hat{x}^{(0)}(t)$; (2) periodic variation, $S(t)$; and (3) random fluctuation $R(t)$. Based on this conceptualization, spring discharge can thus be expressed as:

$$Q(t) = \hat{x}^{(0)}(t) + S(t) + R(t) \quad (1)$$

where $Q(t)$ is defined as the spring discharge.

A grey system GM(1,1) model was used to simulate the long-term trend. By analysing the residuals of the long-term trend, we obtained the periodic variation and random fluctuation components (Hao *et al.*, 2007).

a Simulation of the long-term trend using the GM(1,1) model: GM(1,1) is set up by using a time series of raw data $x^{(0)}(t)$, the

spring discharge, to form an accumulating generation $x^{(1)}(t)$. The first-order differential equation for the accumulating generation is given by:

$$\frac{dx^{(1)}(t)}{dt} + ax^{(1)}(t) = b \quad (2)$$

where a is the development coefficient, and b is the grey action quantity (Liu and Lin, 2006; Hao *et al.*, 2007).

The approximate time response sequences of the GM(1,1) grey differential system are set up as:

$$x^{(1)}(t+1) = (x^{(1)}(0) - \frac{b}{a})e^{-at} + \frac{b}{a} \quad (3)$$

and, by restoring accumulation generation, we can express the restored values of $\hat{x}^{(0)}(t)$ as:

$$\hat{x}^{(0)}(t+1) = \hat{x}^{(1)}(t+1) - \hat{x}^{(1)}(t) \quad (4)$$

Equations (3) and (4) are thus the grey-predicted equations of the GM(1,1) model.

b Simulation of periodic variation: The periodic variation is acquired by analysing the residuals of long-term trend, then fitting the residuals in a sinusoidal pattern, and obtaining the periodic variation:

$$S(t) = A_i \sin \frac{2\pi \left[t \sum_{j=1}^i (j-1)T_j \right]}{T_i} \text{ for } \left[\sum_{j=1}^i (j-1)T_j \right] \leq t \leq \left[\sum_{j=1}^{i+1} (j-1)T_j \right] \quad (5)$$

where $S(t)$ is the simulation of the residuals in period i at time t , A_i is considered as the amplitude of period i , and T_i is the length of period i .

By combining the long-term $\hat{x}^{(0)}(t)$ and the periodic variation $S(t)$, we get the long-term and periodic trend of spring discharge $TS(t)$:

$$TS(t) = \hat{x}^{(0)}(t) + S(t) \quad (6)$$

c The calculation of random fluctuation: The random fluctuation was calculated as follows:

$$R(t) = x^{(0)}(t) - TS(t) \quad (7)$$

Because of the unpredictability of the random factor, we used the mean absolute value of the random fluctuations, $\overline{|R(t)|}$, instead of $R(t)$ in equation (1), so we have:

$$\hat{Q}(t) = \hat{x}^{(0)}(t) + S(t) \pm \overline{|R(t)|} \quad (8)$$

where $\hat{Q}(t)$ is the simulated spring discharge.

2 Water balance

Because intense groundwater development occurred only in recent decades (see below), the karst hydrological processes can be divided into two phases. The first phase is the karst system under the sole impact of climate change, when anthropogenic impacts were negligible. The second phase considers the combined impacts of climate change and human activities. In order to discern the effects of climate change from human activities on the depletion of spring flow, the water balance in the second phase was calculated.

Using spring flow data from the first phase, we set up the grey system GM(1,1) decomposition model. Extrapolating the model, we acquired a modelled projection of the spring recharge $\tilde{Q}(t)$ under the sole impact of climate change during the second phase (note, however, that this assumes that the climatic change component is constant between the two time periods). Accordingly, the water balance equation for karstic springs flow in the second phase is:

$$\tilde{Q}(t) = Q_{human}(t) + Q_{observation}(t) \quad (9)$$

where $Q_{human}(t)$ denotes the spring flow depletion by human activities and $Q_{observation}(t)$ denotes the observed spring discharge.

$$Q_{human}(t) = \tilde{Q}(t) - Q_{observation}(t) \quad (10)$$

By using the water balance equation (10), we can estimate the contribution of human activities to spring flow depletion.

IV Application

1 Spring flow sequence division

Because of technical limitations, karst groundwater development did not begin until 1979 in the Niangziguan Springs Basin (Figure 3). According to drilling records for the karst aquifer in the Niangziguan Springs Basin, the well depths range from 200 to 500 m and the depth to groundwater averages about 100 m below the ground surface – both depths for which drilling and pumping equipment did not support development before 1979. People mainly used surface river and spring water, as there are well-developed surface water systems in the Niangziguan Springs Basin (Figure 2). Accordingly, although the population removed water from the rivers and streams, which are certainly connected to the karst groundwater system, widespread pumping development of the karst aquifer did not occur until 1979, and we therefore assume that the karst groundwater system was negligibly impacted by anthropogenic influence prior to 1979.

Since that time, the regional economic development and population have been increasing (Figure 5) and karst groundwater has been exploited for irrigation, municipal use, and industrial water supply (Figure 3). We have thus divided the spring flow sequence into two phases: pre-1979 and post-1979. In the first phase (1957–78) the Niangziguan Springs discharge is assumed to be affected solely by climate change (ie, precipitation variation) and in the second phase (1979–2007) the springs discharge was influenced by both climate change and human activities. Furthermore, Figure 3 shows that a cubic polynomial trend of precipitation appears gently periodic from the first phase into the second phase. Accordingly, we can infer that regional climatic drivers to the hydrological cycle have remained essentially

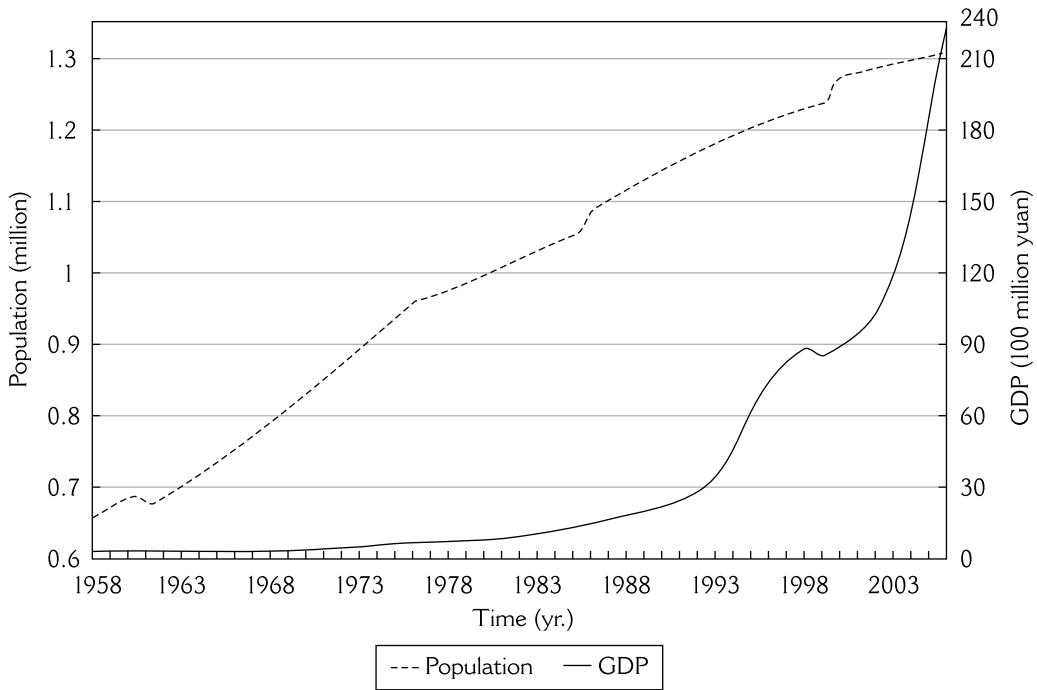


Figure 5 Population and GDP of the Niangziguan Springs Basin

constant over the two phases, and that the hydrological model derived from the first phase is appropriately extrapolated to assess climatic influences into the second phase.

2 Simulation of spring flow

In the first time period, the GM(1,1) decomposition model for Niangziguan Springs flow is based upon discharge data which may involve a large degree of uncertainty because of measurement errors. Thus, the flow series were pre-processed by a moving average method:

$$x^{(0)}(1) = \frac{3\tilde{x}^{(0)}(1) + \tilde{x}^{(0)}(2)}{4} \tag{11}$$

$$x^{(0)}(t) = \frac{\tilde{x}^{(0)}(t-1) + 2\tilde{x}^{(0)}(t) + \tilde{x}^{(0)}(t+1)}{4}, \tag{12}$$

$t = 2, 3, \dots, n-1.$

$$x^{(0)}(n) = \frac{\tilde{x}^{(0)}(n-1) + 3\tilde{x}^{(0)}(n)}{4} \tag{13}$$

where $\tilde{x}^{(0)}(t)$ denotes the original data of the spring flow.

Then we have $X^{(0)} = x^{(0)}(t), t = 1, 2, \dots, n$. By using the $X^{(0)}$, we set up the GM(1,1) model for the long-term trend. The parameters of the GM(1,1) model are $\hat{a} = (a, b)^T = \begin{pmatrix} 0.009 \\ 14.003 \end{pmatrix}$. The estimation model is thus expressed as:

$$x^{(1)}(t+1) = -1627.392e^{-0.009t} + 1640.077 \tag{14}$$

Figure 6 shows the long-term trend curves and the original spring flow. The curve accurately reflects the general trend of the Niangziguan Springs discharge over time, but does not correspond with its periodic fluctuation. Figure 7 shows the residual error curve of the long-term fit. The average absolute residual is $|\overline{\varepsilon(t)}| = 1.1 \text{ m}^3/\text{s}$, the average relative error $|\overline{q(t)}| = 8.54\%$.

By fitting the residual of the long-term trend, and using equation (5), the periodic variation, $S(t)$ was acquired for Figure 7, which shows that the fluctuation of the

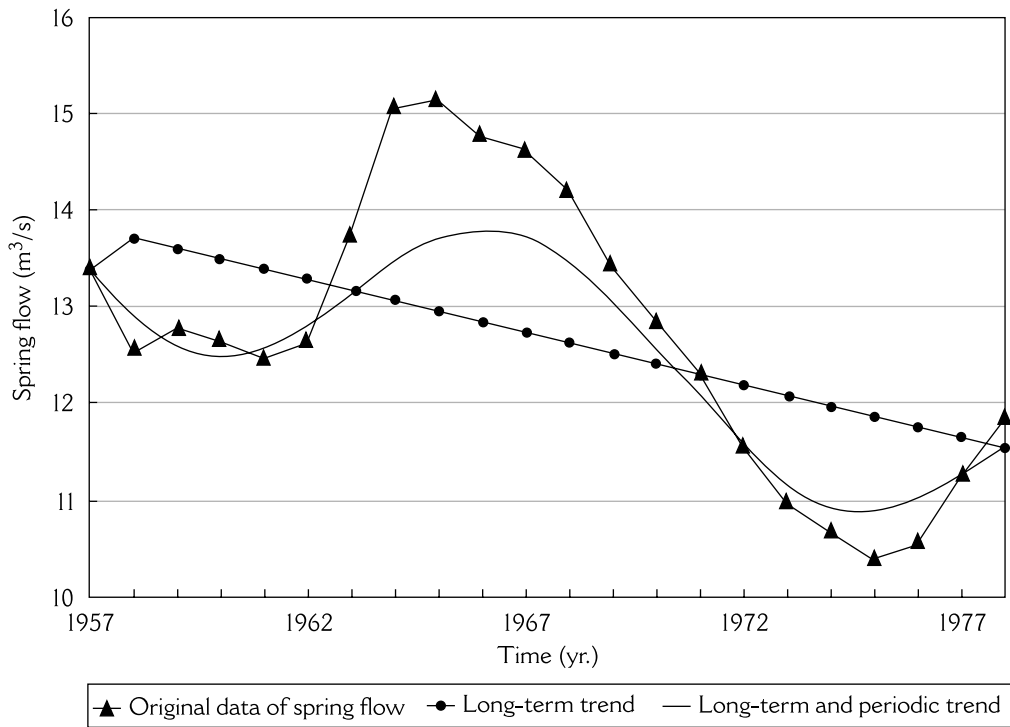


Figure 6 Observed data, long-term trend, and long-term and periodic trends of Niangziguan Springs

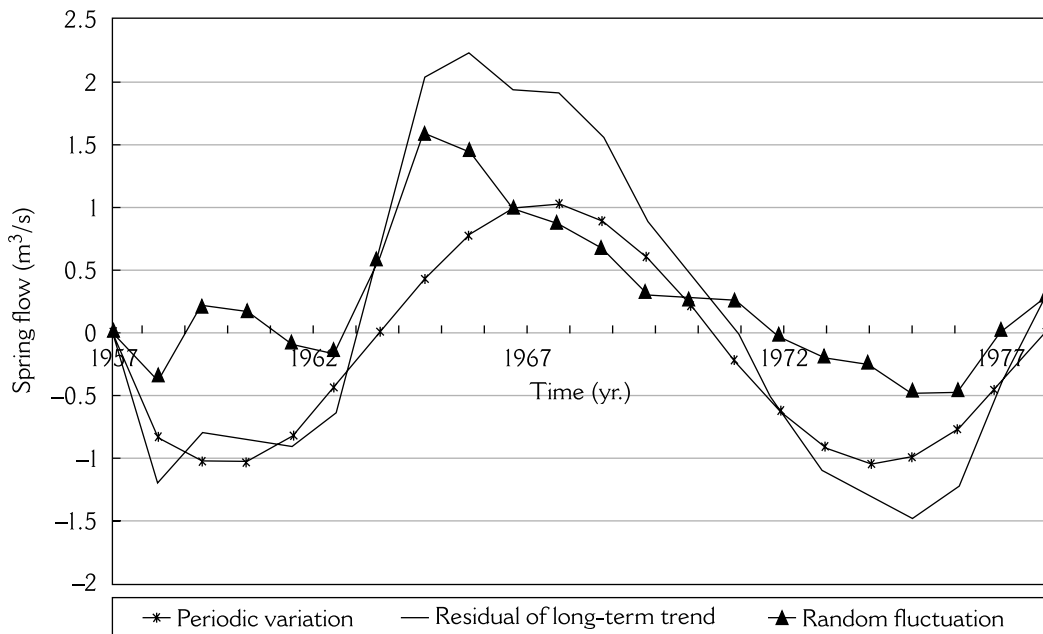


Figure 7 Residual of the long-term trend, periodic variation, and random fluctuation

residual series can be divided into two phases. In phase 1 (before 1963), the period $T_1 = 14$ years, and the amplitude $A_1 = |\overline{\varepsilon_1(t)}| = 0.66 \text{ m}^3/\text{s}$; in phase 2 (after 1963), the period length of curve $T_2 = 15$ years, and the amplitude $A_2 = |\overline{\varepsilon_2(t)}| = 0.63 \text{ m}^3/\text{s}$. The long-term and periodic trend, $TS(t)$, is obtained by combining the long-term trend, $\hat{x}^{(0)}(t)$, and the periodic variation, $S(t)$. The $TS(t)$ curve is displayed in Figure 6, which shows a significantly improved fit. In the $TS(t)$ curve, the average absolute value of the residual error is $|\overline{\varepsilon(t)}| = 0.49 \text{ m}^3/\text{s}$, and the mean relative error is $|\overline{q(t)}| = 0.28\%$. According to equation (7), the mean absolute value of the random fluctuations $|\overline{R(t)}| = 0.490 \text{ m}^3/\text{s}$.

From equation (8) and the GM(1,1) decomposition model, the first phase (1957–78) behaviour of the Niangziguan Springs discharge was obtained. This model described the spring flow of the Niangziguan Springs under the sole impact of climate change. Extrapolating the model, we can obtain the spring discharge of the Niangziguan Springs in the second phase (1979–2007) under sole impact of climate. Note that the random fluctuation in the GM(1,1) decomposition model is an interval from $-\overline{|R(t)|}$ to $\overline{|R(t)|}$; consequently the predicted spring flow is also an interval. Then, through the water balance equation (10), we discern the respective effects of climate change and human activities on the depletion of spring discharge in the second phase. Results are shown in Table 1 and Figure 8.

V Results and discussion

Table 1 and Figure 8 illustrate that the variance of the upper limit of simulated flow is $1.386 \text{ m}^6/\text{s}^2$, and the lower limit is $1.408 \text{ m}^6/\text{s}^2$ while the variance of observed flow is $2.434 \text{ m}^6/\text{s}^2$. In other words, the predicted spring flow does not fluctuate as dramatically as observed spring flow. This is caused by a simplification of the random fluctuation in the GM(1,1) decomposition model (see equation 8). Nevertheless, the predicted spring flow is associated with a range of

mean absolute random fluctuations reflecting the hydrological processes of karst spring discharge, which are essential to understand the springs' response to both climate change and human activities.

Table 1 and Figure 8 show that under sole impact of climate change the springs' discharge has been declining. The average spring flow intervals in the 1980s, 1990s, and the early twenty-first century are 10.76–11.74, 9.64–10.62, and 8.44–9.44 m^3/s , respectively. In other words, the spring flow reduction under sole impact of climate change is $2.30 \text{ m}^3/\text{s}$ in the second time period. Table 1 and Figure 8 also illustrate that the contributions of human activities in the 1980s, 1990s, and the early twenty-first century are 1.58–2.56 m^3/s , 1.94–2.91 m^3/s , and 1.89–2.90 m^3/s , respectively. By dividing 1.89 and 2.90 m^3/s by $2.30 \text{ m}^3/\text{s}$, we obtain a ratio of the influence of anthropogenic impact to the influence of climate change on the flow in Niangziguan Springs. If the influences were equivalent, we would expect the ratio to be 1. Values less than one indicate that anthropogenic effects are less than that of climate change, while values greater than one will indicate that anthropogenic effects have exceeded those of climate change. The specific values of the contributions to spring flow depletion from anthropogenic effects and climate change are thus calculated as 0.83 to 1.26 in the two time periods. Accordingly, the anthropogenic effects have been approaching and surpassing the effects of climate change during the second time period.

Regarding the contribution of human activities to spring discharge decline, groundwater abstraction only occupies about 34–52% of the declines; 48–66% of the declines are likely to be caused by other human activities (Figure 8). Several human activities are likely to have significantly impacted the regional hydrological processes. They include coal mining, dam building and deforestation. Coal mining is one of the largest industries in the Niangziguan Springs Basin. In the Niangziguan Springs Basin, there is a wide

Table 1 Contribution of anthropogenic activities to Niangziguan Springs depletion (m^3/s)

Year	Simulated flow (m^3/s)		Observed flow (m^3/s)	Contribution of human activities on flow attenuation (m^3/s)	
	Upper limit	Lower limit		Upper limit	Lower limit
1979	11.96	10.98	11.56	0.40	–
1980	12.27	11.28	10.81	1.46	0.47
1981	12.51	11.52	10.22	2.29	1.30
1982	12.62	11.64	10.23	2.39	1.41
1983	12.57	11.59	9.94	2.63	1.65
1984	12.34	11.36	9.60	2.74	1.76
1985	11.97	10.99	9.05	2.92	1.94
1986	11.50	10.52	8.29	3.21	2.23
1987	10.99	10.01	7.18	3.81	2.83
1988	10.52	9.54	7.98	2.54	1.56
1989	10.15	9.17	8.5	1.65	0.67
1990	9.93	8.95	9.07	0.86	0.00
1991	9.89	8.91	8.57	1.32	0.34
1992	10.01	9.03	7.96	2.05	1.07
1993	10.26	9.28	7.13	3.13	2.15
1994	10.58	9.60	6.49	4.09	3.11
1995	10.90	9.92	5.73	5.17	4.19
1996	11.15	10.17	7.59	3.56	2.58
1997	11.27	10.29	8.39	2.88	1.90
1998	11.23	10.25	8.35	2.88	1.90
1999	11.02	10.04	7.84	3.18	2.20
2000	10.66	9.68	7.58	3.08	2.10
2001	10.20	9.22	7.02	3.18	2.20
2002	9.70	8.72	6.50	3.20	2.22
2003	9.24	8.26	6.51	2.73	1.75
2004	8.89	7.91	6.42	2.47	1.49
2005	8.68	7.70	6.13	2.55	1.57
2006	8.90	7.82	5.79	3.11	2.03
2007	9.25	8.17	6.37	2.88	1.80

distribution of coal layers – up to 4,748 km^2 . The annual coal output reached 69.4 million tons in 2007. Because Carboniferous-Permian coal-bearing formations are above the elevation of the Ordovician karst aquifer in the Niangziguan Springs Basin, dewatering from coal mining artificially reduces the recharge of precipitation to the karst aquifer. Therefore, dewatering from coal mining is one of the important human activities that cause the depletion of the Niangziguan Springs flow.

Construction of hydraulic engineering has caused a decline in riverbed recharge.

Since the 1970s, 39 reservoirs with a storage capacity of 100 million m^3 , have been built in the Niangziguan Springs Basin. These reservoirs changed the regional hydrological processes, causing the decline of riverbed recharge to karst groundwater. In the Niangziguan Springs Basin, the annual recharge capacity of riverbeds was reduced from 2.25 m^3/s in the first time period to 1.73 m^3/s in the second.

Deforestation has also changed the underlying surface and the hydrological processes of the Niangziguan Springs Basin. Percentage of forest cover reduced from 32%

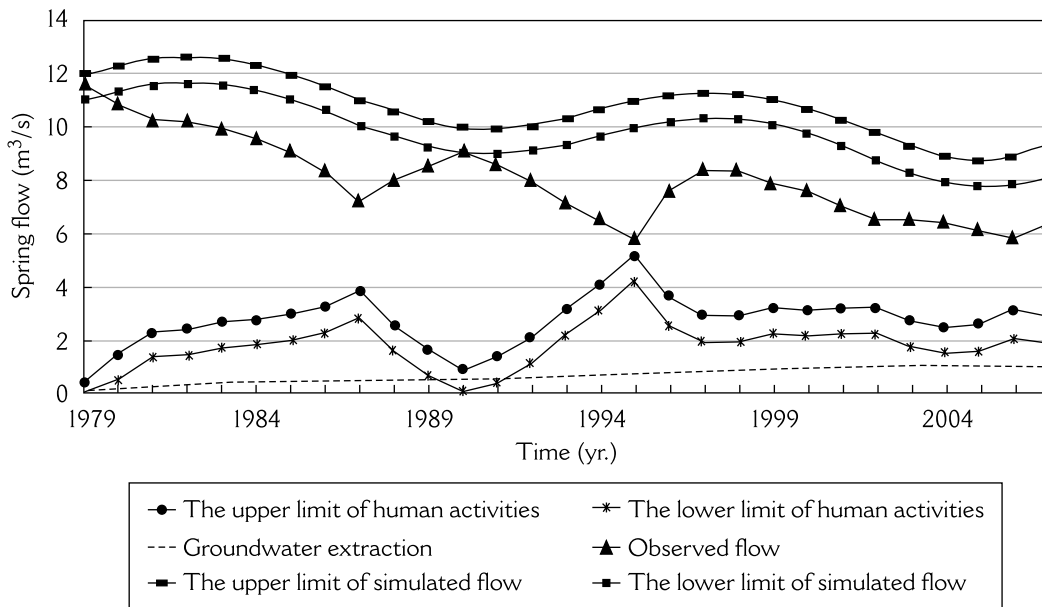


Figure 8 Contribution of human activities to the Niangziguan Springs flow attenuation

in the 1980s to 20% at the beginning of the twenty-first century. Consequently, the infiltration of precipitation to the karst aquifer has decreased, and this is suspected to be the main reasons for the spring flow depletion.

Together with our previous papers (Hao *et al.*, 2006; 2007) applying grey system theory to simulate spring flow in other systems, these results reveal that the effects of human activities make a large contribution in the spring flow depletion. In the case of the Niangziguan Springs, the effects of anthropogenic activities have surpassed those attributable to climate change. The findings are very important for water resources planning and management and to the appropriate regulation of groundwater development.

VI Conclusions

This work focused on the response of the Niangziguan Karst Springs, China, to climate change and anthropogenic influences, using inferences from the GM(1,1) decomposition model. In the Niangziguan Springs Basin, the

development of karst groundwater began in 1979. Based on the karst hydrological processes, the spring discharge data were divided into two time periods: pre-1979 and post-1979. In the first (1957–78), spring discharge was believed to be affected solely by climate change, and in the second (1979–2007), the spring discharge was influenced by both climate change and human activities. By using the spring flow data in the first phase, the GM(1,1) decomposition model was derived, which described the spring flow processes under climate change alone. Extrapolating the model, we obtained the spring discharge under the sole impact of climate in the second phase. Then, using the water balance equation (10), we inferred the respective effects of climate change and human activities on the depletion of spring discharge. The results show that the contribution of climate change to the depletion of Niangziguan Springs is 2.30 m³/s and the contribution of anthropogenic activities is 1.89–2.90 m³/s. The relative value of the contributions to spring flow

depletion from anthropogenic effects and climate change has been increasing from 0.83 to 1.26 times. Therefore, the anthropogenic effects have been approaching and surpassing the effects of climate change during the past three decades.

Regarding the contribution of human activities to spring discharge decline, ground-water abstraction only accounts for about 34–52% of the declines; 48–66% of the declines are likely to be caused by other human activities, including: coal mining, which artificially reduces the recharge of precipitation to the karst aquifer; dam building, which causes a decline in riverbed recharge; and deforestation, which has changed the underlying surface, and subsequently reduced the flood recharge to groundwater.

As a representative of karst springs in north China, the Niangziguan Springs processes reflect the variability of karst spring discharge and the history of groundwater development for the most recent five decades. Before the 1980s, karst hydrological processes were negligibly impacted by anthropogenic effects. After that time, economic development intensified, which caused additional spring discharge depletion. Furthermore, Niangziguan Springs Basin is the largest karst basin in north China, and the groundwater system has a strong ability to self-regulate its capacity in response to environmental changes. Thus, other karst springs in north China (ones those do not have the same ability to recover) are believed to be more vulnerable than the Niangziguan Springs. In other words, human activities are likely to have more serious effects on other karst springs than on Niangziguan Springs. Therefore, it may be hypothesized that, in the twenty-first century, human activities have significantly affected groundwater circulation and exceeded natural supply capacity in north China.

An appropriate and robust method is essential to study response of spring flow to climate change and anthropogenic activities. The GM(1,1) decomposition model

decomposes spring flow processes into three components (ie, long-term trend, periodic variation, and random fluctuation), which characterized the spring flow. In this paper, the GM(1,1) decomposition model was used as a first step to discern and quantify the effects of human activities from climate change. The GM(1,1) decomposition model is thus a useful tool in regional groundwater planning for sustainable development for the future.

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