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Response of Groundwater to Climate Change under Extreme Climate Conditions in North China Plain

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ABSTRACT: The North China Plain (NCP) is one of the water shortage areas of China. Lack of water resources restricted the economic and social development of North China area and resulted in deterioration of ecosystem and natural environment. Influenced by the climate change and human activities, the water circulation of NCP was largely changed and the crisis of water resources was aggravated. Therefore, it is important to study the features of the extreme climate and the response mechanism of groundwater to climate change. We analyzed the trend of climate change and extreme climate features in the past 60 years based on the monitoring data of meteorological stations. And then the response characteristics of groundwater to climate change were discussed. The average temperature of NCP was in an obviously upward trend. The overall precipitation variation was in a downward trend. The climate change in this area showed a warming-drying trend. The intensity of extreme precipitation displayed a trend of declining and then increasing from north to south as well as declining from eastern coastal plain to the piedmont plain. Grey correlation degree analysis indicated that groundwater depth had a close relationship with precipitation and human activities in NCP. The response of groundwater level to precipitation differed from the piedmont alluvial-pluvial plain to the coastal plain. The response was more obvious in the coastal plain than the piedmont alluvial-pluvial plain and the middle plain. The precipitation influenced the groundwater depth both directly and indirectly. Under the condition of extreme precipitation, the impact would aggravate, in the forms of rapid or lag raise of groundwater levels.

KEY WORDS: climate change, groundwater, response, grey correlation, extreme precipitation.

1 INTRODUCTION

The research on the impact of climate change started in the 1970s and had drawn the attention from the community of international hydrology until the 1980s. With the occurrence of extreme climate, scientists have gradually been aware of the significance of climate change influence on water resources and focused on its impact on water cycle (Crosbie et al., 2010; Mileham et al., 2009; Woldeamlak et al., 2007; Arnell, 2003). Since climate change affects surface water resources directly through changes of climate variables such as temperature and precipitation, the relationship between the climate change and groundwater is quite complicated (Okkonen et al., 2010) and difficult to be quantified, which has become the research focus worldwide. Ferguson and George (2003) studied groundwater level trends of the Upper Carbonate Aquifer (UCA) near Winnipeg of Canada, and demonstrated thatshallow well hydrographs showed variations on the order of three to four years that were correlated with changes in annual temperature and precipitation at lags up to 24 months. Jyrkama and Sykes (2007) assessed the impact of climate change on groundwater by HELP3 in combination with a geographic information system to simulate the temporal and spatial characteristics of groundwater. Allen et al. (2004) used Visual MODFLOW to study the impact of climate change on aquifers in western Canada, and concluded that only minor impact was revealed from climate change on recharge and groundwater levels, while major impact from river water due to the close hydraulic interaction between river and aquifer. Therefore, the response of groundwater to climate change differs owning to the variance of hydrogeological properties.

North China Plain (NCP) is one of the most severe water shortage areas of China, with the lowest water consumption per person, especially in Beijing, Tianjin, Tangshan and Shijiazhuang. Lack of water resources restricted the economic and social development of the North China area and resulted in deterioration of ecosystems and natural environment. Under the background of global climate change, the annual precipitation in this area tends to decrease. A large number of meteorologists have made efforts on the climate change trends with different analysis models in NCP (Chen, 2012; Wang et al., 2012; Liu et al., 2008; Zhang et al., 2008; Ma and Fu, 2006). Meanwhile, several studies focused on the groundwater dynamic variation in light of large-scale exploitation in this area (Liu et al., 2012; Yang et al., 2011; Wang et al., 2009; Fei et al., 2005). However, research on the relationship between groundwater and climate

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change was scarce. Recently, a tentative study in Huang-Huai-Hai Plain indicated that variations of water table depths are more sensitive to precipitation variations than temperature variations, and the shallow water table is more sensitive to climate change than deep water table (Xie et al., 2009). Besides, a calibrated model based on GMS-MODFLOW was used to simulate the response of shallow groundwater levels to climate change and human activities in a test station of NCP, and the results showed that the slight increase of the precipitation would not slow down the drop of shallow groundwater obviously in the future (Chen et al., 2012). Most of the studies on the response of groundwater to climate change were on a small scale, and the regional features of extreme climate were not discussed appropriately. This research, based on abundant meteorological and hydrogeological data, aims to estimate the effect of extreme climate on groundwater. The results would supply reference for the sustainable utilization and management of water resources in NCP.

2 THE STUDY AREA

The NCP is situated in the east of the Taihang Mountains and the south of the Yanshan Mountains with a flat terrain. The weather of this area belongs to the warm temperate semiarid monsoon zone of the Eurasia continent. The climate is cold and dry in winter and spring while hot and rainy in summer. The annual mean precipitation is 500–600 mm and the precipitation is unevenly distributed throughout the year, with the major concentrated from June to September. For this reason, the area is likely to suffer drought in spring and floods in autumn. The NCP lies in the water basin of the Yellow River, the Haihe and the Luanhe River. There are about 60 rivers with different sizes in this area such as the Tuhaihe River and the Majia River that directly flow into the sea.

The plain inclines from north, west and south towards the Bohai Bay. The area from the mountain front to the coast forms an intact hydrogeologic section, which contains three parts from west to east: an alluvial-proluvial inclined plain in front of the mountains, an alluvial-lacustrine plain in the middle and an alluvial-marine coastal plain in the east. The Quaternary system of the piedmont plain area is mainly composed of the alluvial-proluvial deposits that come from Hutuo River, which form the overlapped alluvial-proluvial fan group. The Mid Pleistocene alluvial-proluvial fan counts for the largest proportion. The front edge of this fan extends to the eastern Shulu and Shen County. In contrast, the scales of Upper Pleistocene and Holocene fans are smaller; the front edge only reaches Shulu County-Anping County. The deposits from the Hutuo River are mainly characterized by coarse grains. The middle plain is mainly composed of alluvial deposits from the ancient Yellow River and Fuyang River as well as the deposits from lakes and spreads in the north-eastern direction. Because of the length of these rivers, the deposits in this area are characterized by fine grains. For the eastern and coastal plain area, the deposits are mainly attributed to the alluviation of the ancient Yellow River, estuary and delta depositions as well as lacustrine and marine sedimentation. The grains are finer and the deposits are in strip-like and flake-like distribution.

3 MATERIALS AND METHODS

3.1 Data Collection

The meteorological data used in this study were chosen from daily precipitation, temperature and evaporation data at 24 national weather stations for 61 years (1951–2011) of NCP, obtained from China meteorological data sharing service system. After strict quality control and data correction, more than 1.8 million valid data were selected. The time of extreme precipitation and the precipitation threshold of each weather station were defined by the percentile method recommended by the Commission for Climatology, World Meteorological Organization. The daily precipitation samples of each weather station were arranged in ascending order. The daily precipitation at the 95th percentile of the subsample greater than or equal to 0.1 mm was taken as the threshold of extreme precipitation and the standard for determining the time of extreme precipitation. The number of extreme precipitation events and the sum of precipitation amount of each station were named as the frequency of extreme precipitation and the amount of extreme precipitation, respectively. The extreme precipitation amount divided by the number of precipitation days was referred to as the intensity of extreme precipitation (Wang and Qian, 2009).

The observed groundwater depths as well as the exploitation data of NCP were collected from China geological environmental monitoring institute and local groundwater monitoring institutes.

3.2 Method of Grey Correlation

The data mentioned above were sorted to analyze the influential degree of rainfall and groundwater exploitation on groundwater according to the method of grey correlation, which is quantitative analysis for the dynamic trend of groundwater response to climate change.

Grey data processing should be performed before grey correlation coefficients can be calculated, and data in different units should be transformed to be dimensionless (Gau et al., 2006).

Let the parent sequence be represented as $\{X_0(i)\}$, i=1,2,...,N; and the subsequence as $\{X_k(i)\}$, k=1,2,...,m, i=1,2,…,N, where N is the total number of observation data, and m is the number of factors. The grey correlation coefficient is defined as (Yeh and Chen, 2004),

$$\xi_{0k}(i) = \frac{\Delta_{\min}+\zeta\Delta_{\max}}{\Delta_{0k}(i)+\zeta\Delta_{\max}} \tag{1}$$

where ζ is the distinguishing coefficient, $\zeta \in (0,1)$, generally taken as 0.5. $\Delta_{ok}(i)$ is the sequence of deviation of the parent sequence $X_0(i)$ from the subsequence $X_0(i)$; $\Delta_{ok}(i) = |X_0(i) - X_k(i)|$, Δ_{min} and Δ_{max} are the maximum and minimum of $\Delta_{ok}(i)$, respectively. The grey correlation grade is an average of the grey correlation coefficients, which could defined as,

$$r = \frac{1}{N}\sum_{i=1}^{N}\xi_{ok}(i) \tag{2}$$

when the r-value is more than 0.5, it could be considered that there is correlation between the parent sequence and the subsequence. The higher of the r-value, the better the correlation is

(Zhang et al., 2000).

In the correlation degree calculation, the groundwater depth was used as the parent sequence and the groundwater exploitation amount together with the precipitation were used as the subsequences to analyze the response degree of groundwater to climate change in NCP.

4 RESULTS AND DISCUSSIONS

4.1 Trends of Climate Change in NCP

The average air temperature over 60 years in NCP represented in an obvious upward trend, with an increment speed of 0.2 ℃/10 a (Fig. 1). The increase of air temperature would influence precipitation (Lu, 2011) as well as the evaporation of surface water and shallow groundwater in a long term, slightly, but inevitably.

The precipitation in NCP showed an obvious interannual variation. For the past 60 years, the overall precipitation variation was in a downward trend with the decrease rate of 12 mm/10 a (Fig. 2). As shown in Fig. 3, the year-to-year change of extreme precipitation amount in NCP exceeding the 95% threshold was in a declining trend. Particularly, the declining trend became much more obvious and the extreme precipitation amount was basically below the mean level since 2000. The highest value of extreme precipitation amount occurred in the year of 1963. The high frequency of the extreme precipitation was concentrated in the 1960s, mid 1970s and mid 1990s in a decreasing order. Correspondingly, there were flooding disasters occurring in 1963, 1975 and 1996. In addition, relevant data (Zhang et al., 2008) showed that in the last 100 years there were twice abrupt climate changes in the North China area. Specifically, the precipitation was evidently reduced after 1914 compared with that before 1914. The precipitation began to increase slightly in 1950s and reached the peak in 1963. However, it started to decline again in 1964 and reached to the minimum value in 1980s. Since 1997, continuous drought struck the NCP. These two abrupt changes further aggravated the water resource crisis of North China area in the later 20th century and led to increasingly severe aridification.

As mentioned above, the interannual changes of temperature and precipitation indicated a warming–drying trend of climate in NCP.

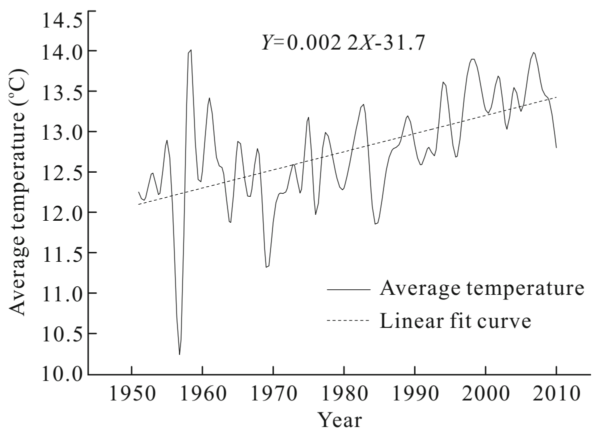

Figure 1. The variation of the average temperature in NCP.

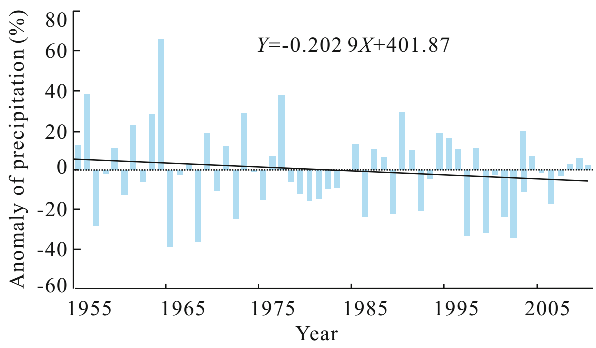

Figure 2. Anomaly of precipitation in NCP.

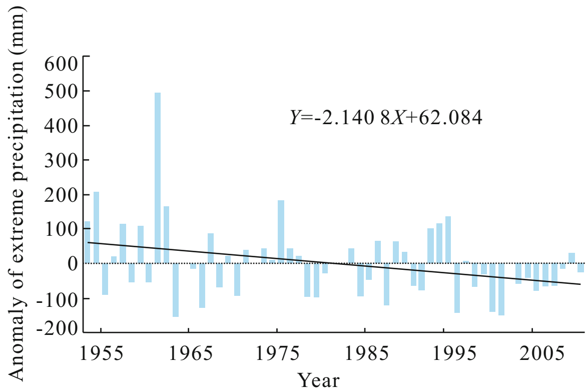

Figure 3. Variation of extreme precipitation in NCP.

The precipitation in NCP showed clear spatial distribution characteristics. The intensity of extreme precipitation first declined from north to south (Beijing-Hebei) and then increased (Hebei-Henan). In Hebei Province, the Shijiazhuang area demonstrated the lowest intensity of extreme precipitation; while the Xingtai and Hengshui area ranked the second (Fig. 4). Due to the influences of land and sea climates, the intensity of extreme precipitation of coastal area generally exceeded that of the inland area and showed a decreasing trend from the coastal plain to the piedmont plain. Furthermore, the intensity of extreme precipitation of coastal area and areas near the Yellow River was much higher than that of the piedmont area and mid plain area. The zones of high extreme precipitation were mainly located in coastal areas such as Tianjin and Cangzhou.

4.2 Correlation between Groundwater Level and Precipitation in NCP

The groundwater level of NCP is mainly controlled by precipitation and human activities. The historical data of precipitation, groundwater depth and exploitation are shown in Fig. 5. Before the mid 1970s, the groundwater depth was basically steady with a balanced exploitation. During this period, the precipitation was abundant and the groundwater exploitation increased slowly. The effects of them on groundwater resources counteracted each other. However, since 1977, the precipitation was evidently reduced, and the groundwater exploitation was largely increased, which resulted in significant increase of groundwater depth. By 1984, the decreasing speed of groundwater level reached 0.37 m/a. After that, due to gradual increase of precipitation and steady growth of exploitation, the lowering

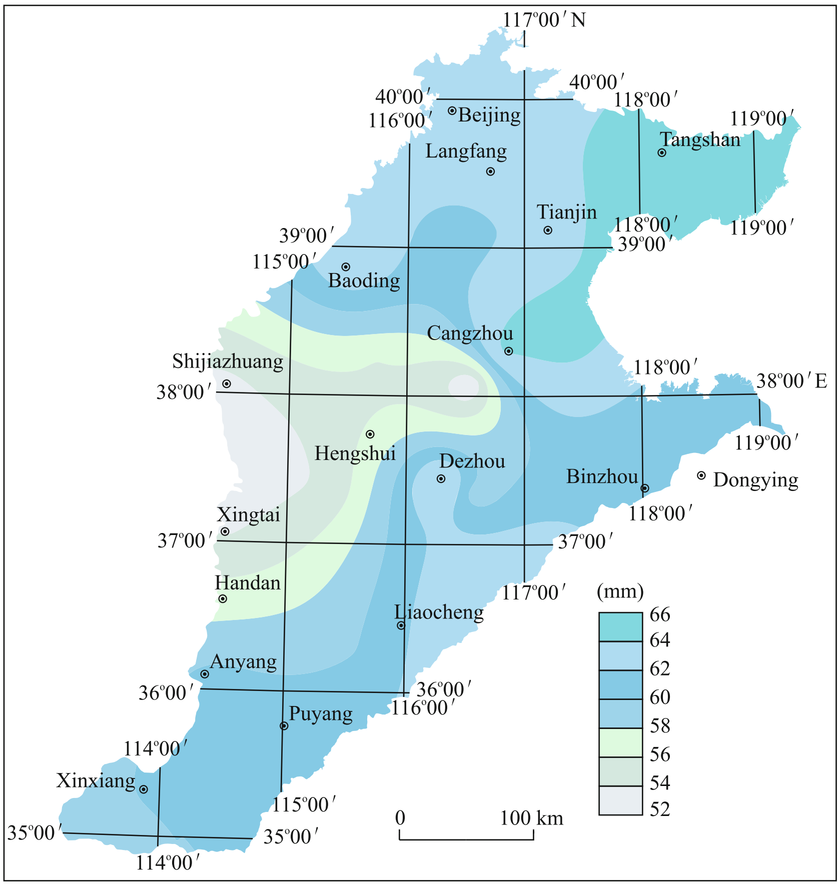

Figure 4. The contour map of intensity of extreme precipitation in NCP.

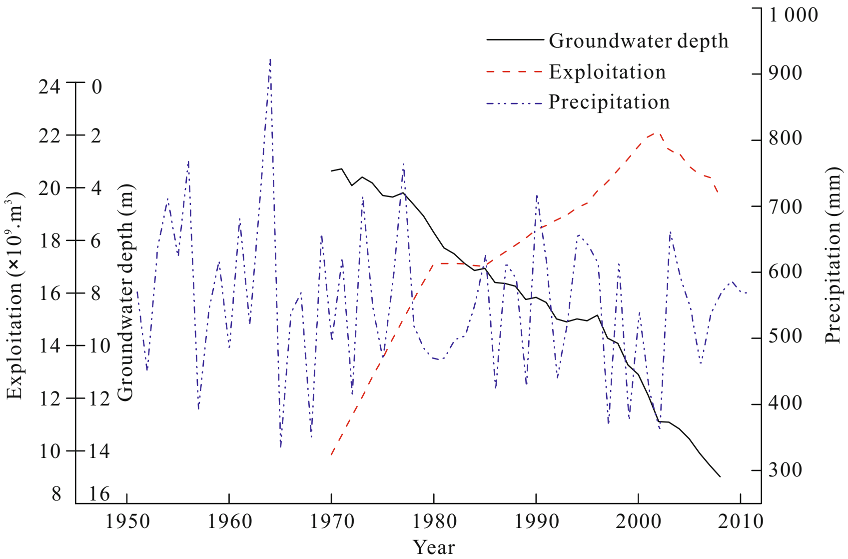

Figure 5. The variation trend of precipitation, exploitation and shallow groundwater depth in NCP.

speed of groundwater level was reduced, and reached as low as 0.20 m/a by the year of 1992. In the period of 1992–1996, with the continuously increasing exploitation of groundwater and stable precipitation, groundwater depth showed little fluctuation. However, since 2002, the groundwater level was evidently lowered in spite of the reduction in groundwater exploitation, and the lowering speed reached up to 0.47 m/a. The crisis of groundwater resources began to deteriorate.

Groundwater depth which could be monitored frequently was selected as the quantitative index of groundwater's response to climate changes and human activities. The grey correlation degrees for groundwater depth vs. precipitation and groundwater depth vs. exploitation of the shallow groundwater of NCP (1970–2008) were calculated. Two correlation degrees, $r1$ (the grey correlation degree for precipitation vs. groundwater depth) and $r2$ (the grey correlation degree for exploitation vs. groundwater depth), were obtained as 0.64 and 0.69, respectively. It is clear that both *r*1 and *r*2 are greater than 0.60, which indicates that the dynamics of shallow groundwater is closely related to both groundwater exploitation and precipitation; *r*2 is greater than *r*1, indicating that groundwater exploitation is more influential to the groundwater level changes. However, the groundwater in NCP is mainly used for agriculture irrigation. The water consumption for agricultural purpose accounted for 76% of the total groundwater consumption (according to the data in the year of 2000). It is reported (Zhang et al., 2006) that, the exploitation quantity consumed in agriculture has a strong response to precipitation. Therefore, the groundwater exploitation is bound to increase in drought years. In other words, the exploitation amount of groundwater depends on the amount of precipitation to a large extent. Hence, the precipitation impacts the groundwater level in direct and indirect ways. Firstly, the amount of precipitation recharging the groundwater will be changed as a result of direct influence. Secondly, the groundwater level will be affected indirectly when pumping amount, irrigation amount and surface water diversion amount get changed as a result of precipitation fluctuation. Under extreme weather conditions, the influence of precipitation on groundwater will be further intensified. On one hand, extreme arid climate could lead to the growth of groundwater exploitation and increase the declining amplitude of groundwater level, accordingly (Chen et al., 2012). Extreme precipitation, on the other hand, could increase the amount of groundwater recharge, accelerate the restoring of groundwater level or reduce the declining amplitude.

4.3 Response of Groundwater Level to Precipitation

To better explain the response mechanism of groundwater in NCP, three stations which are representatives of piedmont alluvial-pluvial plain, middle plain and coastal plain, were illustrated in this paper.

In piedmont alluvial-pluvial plain, Luancheng station in Shijiazhuang was selected to analyze the changes of shallow groundwater depth and precipitation since 1960s (Fig. 6). Influenced by groundwater exploitation, the groundwater level was generally in a downward trend with an average lowering speed of 0.65 m/a. However, the sudden changes of groundwater level occurred in early 1960s, mid 1970s and mid 1990s, corresponding to the three extreme precipitation events, respectively.

In early 1960s, the groundwater exploitation was small in Shijiazhuang area. The groundwater was basically in a natural condition and the groundwater level dynamics were mainly under the control of precipitation and evaporation. Because of the shallow groundwater depth and good lithologic permeability of the aerated zone, the groundwater recharge was synchronized with precipitation, which means that the groundwater level would change accordingly along with the change of precipitation (Fig. 7a). Such change was particularly significant in the cases of extreme precipitation. For instance, there were three extreme precipitation events in 1963 with duration of 1d, 2d and 5d in this area, respectively. The precipitation of these extreme events accounted for more than 80% of the total precipitation of that year. The extreme precipitation event caused a rapid rising of groundwater level, with an increase amplitude as high as 1.5–2 m.

In mid 1990s, the lowering amplitude of groundwater level was great due to large-scale exploitation. The shallow groundwater level was lowered by 10–30 m, which induced the

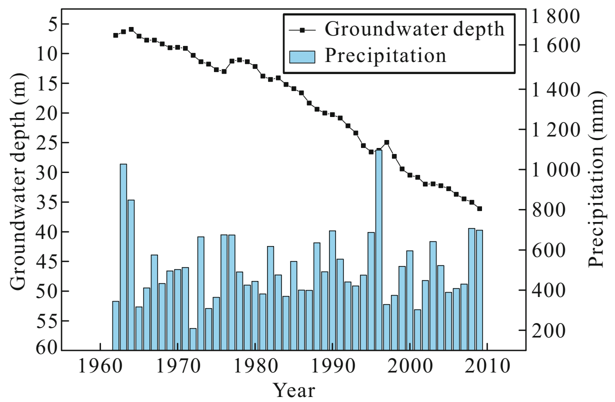

Figure 6. The change of precipitation and shallow groundwater levels over time (year) in the area of Shijiazhuang.

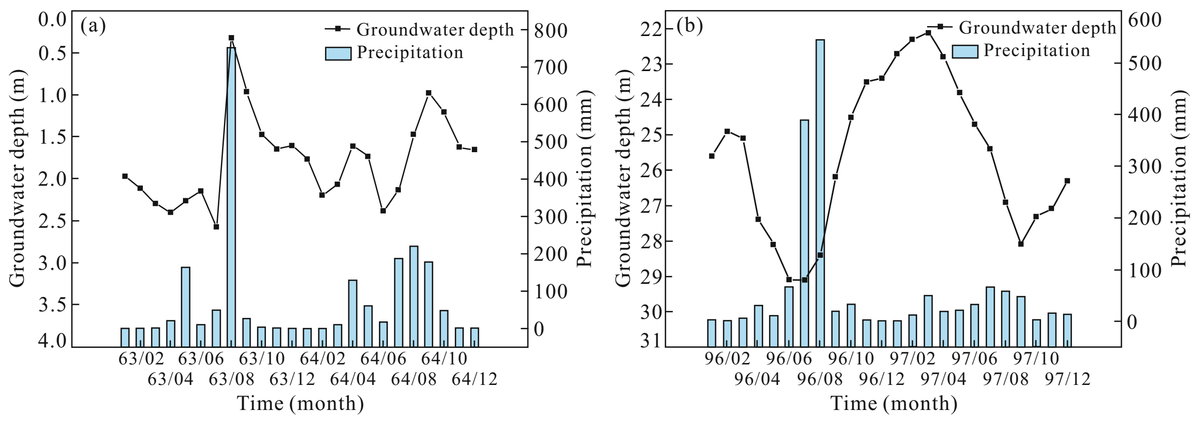

Figure 7. (a) The variation curve of shallow groundwater depth at the natural status and precipitation within the year in Shijiazhuang; (b) the variation curve of shallow groundwater depth after a long period of exploitation and precipitation within the year in Shijiazhuang.

formation of extensive groundwater cone of depression in Shijiazhuang area. With the lowering of groundwater depth, groundwater recharge seemed to lag behind the precipitation (Fig. 7b). In this area, the rainy season begins in June and the maximum precipitation appears in July and August. However, the rising of groundwater level starts from July and reaches the maximum in March of the following year (Liu et al., 2012). The extreme precipitation could cause the groundwater level to rise by 4–6 m.

In the middle plain of NCP, the change trends of shallow groundwater depth and precipitation in Hengshui station were analyzed. As can be seen in Fig. 8, the decline rate of groundwater level in the common water period was 0.25 m/a, while in the wet period, the groundwater level rose in the rate of 0.11 m/a, with a lagged response to precipitation.

As the representative of the coastal plain of NCP, Cangzhou was selected to analyze the response mechanism. From Fig. 9, the decline rate of groundwater level in common water period was 0.13 m/a. After that, the recovery of groundwater level was presented around the year of 1995. While in the continuous dry period; the decline rate of shallow groundwater level was reached up to 0.42 m/a. The rapid response of groundwater level to precipitation in Cangzhou may result from the shallow depth and low degree of exploitation of groundwater.

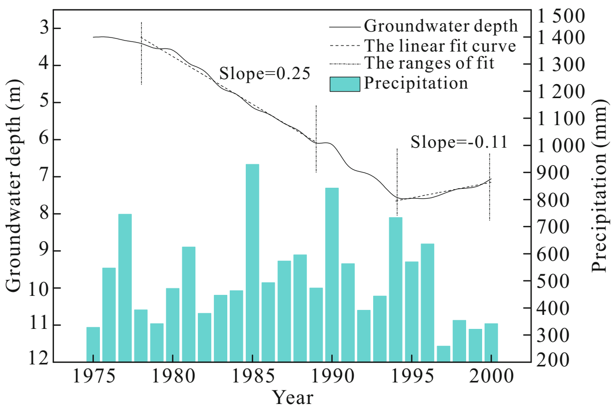

Figure 8. The change of precipitation and shallow groundwater levels over time (year) in the area of Hengshui.

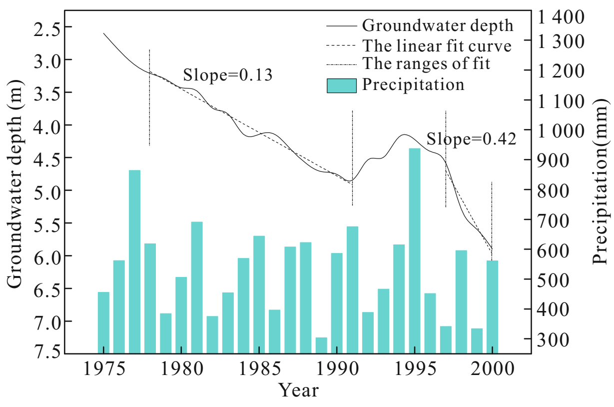

Figure 9. The change of precipitation and shallow groundwater levels over time (year) in the area of Cangzhou.

Due to the extensive exploitation of deep fresh groundwater in the middle and east areas of NCP since 1970s, the exploitation of shallow groundwater decreased accordingly. Therefore, the precipitation may contribute more than exploitation to the shallow groundwater levels of middle plain and coastal plain in these years, as demonstrated by Zhang et al. (2000).

Although the extreme precipitation could cause recovery of groundwater levels to some degrees, overexploitation of groundwater had destroyed the equilibrium state of groundwater system, and the shallow groundwater level descended continuously on the whole. Finally, the crisis state of groundwater resources was exacerbated.

5 CONCLUSIONS

The results of this study showed that the climate change presented a warming-drying trend in NCP. The analysis of the meteorological data shows that the average temperature of NCP is clearly in an upward trend. The overall precipitation variation is in a downward trend. The intensity of extreme precipitation firstly declines from north to south and then increases, and shows a decreasing trend from the coastal plain in the east to the piedmont plain.

The grey correlation analysis shows that groundwater levels had a close relationship with precipitation and human activities in NCP. The precipitation influenced the groundwater level both directly and indirectly. The response of groundwater level to precipitation differed from the piedmont alluvial-pluvial plain to the coastal plain. The response was more obvious in Cangzhou than the other two areas. Under the condition of extreme precipitation, the impact would aggravate, in the forms of rapid or lag rise of groundwater levels. However, overexploitation of groundwater resulted in the falling of water levels continuously and exacerbated the crisis state of groundwater resources.

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