Upward recharge through groundwater depression cone in piedmont plain of North China Plain

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SUMMARY

Whether a recharge was induced by groundwater depression cones is a crucial issue for water resource management. In the North China Plain, shallow groundwater had been over-pumped since 1970s and many groundwater depression cones formed. The groundwater depression cone, Daceying–Machang, occurred even in the piedmont plain. In the area, water levels of deep and shallow groundwater were observed since 2005 and field survey was conducted in the dry season 2010. The upward recharge induced by the depression cone is verified based on water level records, major ions, H2, O and kinds of statistical analyses. Since August 2006, the water level of the deep groundwater ascended by 1.9 mm/d. High correlations (r = 0.86, t = 0.67) between the water level series of shallow and deep groundwater were found by two distinct correlation analyses only in the center of depression cone. Further, the reversion of hydraulic gradient of the depression cone occurred in dry seasons since September 2008. Hydro-geochemical features of the shallow groundwater are consistent with deep groundwater in the center of depression cone, which was demonstrated by the fuzzy C-means clustering based on principal components and paired t test, respectively. It is concluded that the deep groundwater recharged the shallow groundwater from the center of the depression cone. As a result, the groundwater mixture occurred that improves the quality of the shallow groundwater. Seasonally changed flow of shallow groundwater enhanced the mixture. The persistent over-pumping of shallow groundwater and the large elevation difference (around 1200 m) between the recharge zone and the discharge point of deep groundwater facilitate the upward recharge.

1. Introduction

Large quantity of continuously groundwater pumping together with the absence of any integrated water resources management plan in an area forms regional groundwater depression cone and leads to a series of environmental and geological problems. Pacheco et al. (2006) demonstrated a widespread association of ground failure with water table declines. Zhang et al. (2007) illuminated that an identical hydrostratigraphic unit could present different deformation characteristics, such as elasticity, elasto-plasticity, and visco-elasticity, at different sites of the cone of depression or in different periods. By analyzing the volumetric evolution of the cone of depression, Rhode et al. (2007) illustrated the nature of volumetric weighted mean transmissivity within the cone of depression as a function of time. Shi et al. (2008, 2012) simulated regional land subsidence and indicated that about 3.08 × 107 m3/yr groundwater could be provided as emergency water source while meeting the land subsidence control target of 10 mm/a in Suzhou, China.

Furthermore, depression cones could impose great influences on the hydrodynamic and hydrochemical fields of a groundwater system. Petalas and Lambakis (2006) reported cation exchange phenomena and the degradation of the groundwater quality during salinization processes resulted by the permanent presence of a reverse regional cone of depression in the coastal area. Sun et al. (2007) analyzed the evolution of depression cones in Yinchuan, an inland city of China and identified that confined water was mixed with phreatic water and the water quality was deteriorated. Currell et al. (2010) found downward vertical hydraulic gradients in a cone of depression promoting downwards leakage of shallow water and high nitrate concentrations in deep groundwater in Yuncheng, China. Samborska and Halas (2010) illustrated dissolution of pyrite and its weathering products have a significant influence on chemical composition of water derived from the center of the depression cone, due to the enlarged aeration zone creating oxidation conditions in southern Poland. Nath et al. (2008) found that there is no conspicuous relationship between high groundwater As concentration and high groundwater abstraction, although the cone of depression has enlarged over 2 years in West Bengal aquifers India.
In the North China Plain (NCP), population, economic activities, and agricultural production have increased greatly over the last decades, which results in a growing water demand (Foster et al., 2004). Except for a few streams flowing seasonally, groundwater is the main source for industrial, agricultural, and domestic water supply. As a result, the aquifer systems were over-exploited which led to a regional decline of groundwater levels and the local formation of depression cones of the potentiometric surface in the area of large cities since the 1970s (Rohden et al., 2010). In order to achieve a sustainability of groundwater resource, many studies have addressed the water balance and recharge mechanisms (Chen et al., 2004, 2005; Kendy et al., 2004; Song et al., 2009, 2011; Yang and Tian, 2009; Yuan et al., 2011, 2012). The groundwater of the confined aquifer has been dated (Chen et al., 2003, 2005; Lu et al., 2008; Rohden et al., 2010). However, depression cones could change the hydrodynamic and hydrochemical fields of groundwater and complicate the groundwater flow systems. Consequently, the recharge induced by groundwater depression cones should be noticed.

Groundwater isotopes combined with chemistry can produce a reliable conceptual model of a groundwater flow system. In this study, the authors attempt to verify the existing of the vertical recharge induced by a depression cone and to identify influences on the groundwater systems on the basis of observations of water level and stable isotope compositions and major ion contents. It is expected that this study will enhance the understanding of the complication of the groundwater system impacted by a depression cone and support the sustainable management and protection of groundwater resource in the NCP.

2. Study area

2.1. General settings

The study area lies in the piedmont plain of the North China Plain. The study area covers an area of about 1500 km² including Baoding city, Mancheng county, Wanxian county, Qingyuan county, Xushui county and Wangdu county, as illustrated in Fig. 1. The climate is continental semi-arid with a mean annual temperature of about 13 °C. The mean annual precipitation during 1955–2009 at Baoding was 531 mm according to monitoring data from the Beijing Climate Center (http://www.bcc.cma.gov.cn). About 70% of the annual precipitation falls in the monsoon season from June to August. Rivers dried out since the 1970s. The land cover is mainly farmland.

Baoding is one of the serious water shortage cities in China. The amount of water resource occupation per capital of Baoding released by Baoding Institute of Hydrology and Water Resources Survey is just 273 m³/yr in 2005. Groundwater in the unconfined parts of the piedmont plain was strongly exploited over the last several decades. As a result, a depression cone of the shallow groundwater, with the name of Daceying–Machang, was formed. The center of the cone, Dongdianzhuang, is located in the west of Baoding, where water level decline reaches 44 m. The depression cone occupies an area extent of approximately 650 km², located mainly in Mancheng and surrounded by Wanxian, Wangdu, Qingyuan, Baoding, and Xushui.

2.2. Hydrogeological settings

The unconsolidated sediments of Quaternary constitute the main stratigraphy of the study area (Fig. 2). According to the features of the stratigraphy, it can be divided into four aquifer groups. The first and second aquifer groups (I and II) include aquifer of Holocene Qh4 with the depth of 10–20 m, the upper Pleistocene Qp3 with the depth of 50–70 m and the mid Pleistocene Qp2 with depth of 80–160 m. The third aquifer group (III) is the Lower Pleistocene Qp1 aquifer group with depth of 200–400 m. The fourth aquifer group (?) is Tertiary stratigraphy (Wang et al., 2009; Moiwo et al., 2010). The piedmont plain consists of many alluvial fans where the first and second aquifer groups have a close hydraulic connection (Rohden et al., 2010). Therefore, the two aquifer groups...
are considered as the shallow groundwater, while the third aquifer group is taken as the deep groundwater.

3. Methodology

3.1. Field survey and observation

The shallow and the deep groundwater systems are the main focus of the research. Dilution of chemical components is negligible in the end of dry seasons due to very limited precipitation. Therefore, field survey was carried out in May 2010. Two sampling transections were set crossing the depression cone area. One is along the elevation gradient (MQ), and the other is vertical to the elevation gradient (XW). Groundwater was surveyed in different sites along the transections (Fig. 1). Water level was measured before pumping. Then temperature, electrical conductance (EC) and pH value of water samples were measured in situ (DKK. TOA Corporation, model: WM-22EP). Shallow groundwater and deep groundwater were sampled in the same site. Shallow groundwater was collected from domestic wells, and deep groundwater was sampled from deep tube wells which were drilled by the local government for drinking purpose. Fifteen shallow groundwater samples and twelve deep groundwater samples were collected.

Groundwater was sampled and filtered immediately through a 0.45 μm cellulose-ester membrane into three 60 ml and one 100 ml high density polyethylene bottles, which were filled to overflowing and capped. The samples in the 100 ml bottles were used for titration of bicarbonate on the sampling day. The samples for cation analysis were acidified immediately (pH < 2) using high purity, concentrated HNO₃. The other samples were analyzed for anions, δD, and δ¹⁸O. Chemical and isotopic compositions of water samples were analyzed in the laboratory of Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences. The chemical composition was characterized by ICP-OES for cations (PerkinElmer Optime 5300DV) and Ion Chromatography (Shimadzu LC-10A) for anions with analytical precision of ±1 mg/L. Hydrogen and oxygen isotopes compositions of the water samples were analyzed by the Isotope Ratio Mass Spectrometer (Finnigan MAT-253) with TC/EA method. The δD and δ¹⁸O values are reported as per mill (‰) deviations from the international standard V-SMOW (Vienna Standard Mean Ocean Water). The δD and δ¹⁸O measurements were reproducible to ±1.0‰ and ±0.2‰, respectively.

Water level was monitored in the depression cone area from 2005 to 2011. Two observation boreholes were installed for the shallow groundwater. One is located around the center of the depression cone (DC01), and the other is seventeen km away from the center (DC02). A deep groundwater observation borehole (DC03) was installed thirteen kilometers away from the center (Fig. 1). Water level was read every 60 min by the automatic instruments (KADEC MIZU II, Japan).

3.2. Water level verification based on correlation analyses and trend analyses

A close hydraulic connection between two aquifers usually produces similar fluctuations and trends of water level. The similarity of fluctuations can be tested by correlation analyses. The confirmation of a trend can be gained by Mann–Kendall test and Sen’s slope method.

Correlation analyses were performed in terms of the Pearson correlation coefficient (r) and the Kendall rank correlation coefficient (τ). The Pearson correlation coefficient is widely used as a measure of the strength of linear dependence between two variables. The Kendall rank correlation coefficient is a measure of rank correlation: that is, the similarity of the orderings of the data when ranked by each of the quantities. The formula for r is

$$r = \frac{1}{n-1} \sum_{i=1}^{n} \left( \frac{X_i - \bar{X}}{s_X} \right) \left( \frac{Y_i - \bar{Y}}{s_Y} \right)$$

where n is the sample size; $X_i$ and $Y_i$ (i = 1, 2, 3, ..., n) are samples of two variables; $\bar{X}$ and $\bar{Y}$ are sample means; $s_X$ and $s_Y$ are sample standard deviations. The formula for τ is (adjusted for ties)

$$\tau = \frac{n_c - n_d}{\sqrt{(n_0 - n_1)(n_0 - n_2)}}$$

where $n_0 = n(n - 1)/2$ is the total number pair combinations; $n_c$ is the number of concordant pairs; $n_d$ is the number of discordant
pairs; $t_1$ and $t_2$ are numbers of ties for the samples of two variables, respectively. The two coefficients must be in the range from $–1$ to 1.

Trend analyses were implemented using the non-parametric Mann–Kendall (MK) test and Sen’s slope, respectively. In the Mann–Kendall test, the Z-statistic is used to test the null hypothesis, $H_0$, that the data is randomly ordered in time, against the alternative hypothesis, $H_1$, where there is an increasing or decreasing monotonic trend (Kuo et al., 2011; Martinez et al., 2012; Ogununde et al., 2011; Zhang et al., 2011b). Then the true slope of an existing trend was estimated using the Sen’s slope method (Dinapahoh et al., 2011). The procedures of MK trend test and Sen’s slope follow Kendall (1975) and Sen (1968), respectively.

The non-parametric Mann–Kendall–Sneyers test (Moraes et al., 1998) was applied to locate the approximate starting point of a trend within the data series. The null hypothesis meant that the sample under investigation did not have a beginning developing trend. When the statistic value rejected the null hypothesis, there was a change trend. The formula determining the test statistic was illuminated by Zhang et al. (2011a).

3.3. Geochemical verification: a fuzzy C-means clustering based on principal components

The principal component analysis (PCA) was carried out on the basis of hydrochemical variables of water samples. The objective of PCA is reducing the possibly correlated variables into a smaller number of uncorrelated variables, called principal components (Crespo et al., 2012). PCA method reveals the internal structure of the data in a way that best explains the variance in the data. Generally, the first few principal components could explain the most part of variance in the data. Therefore, the first few principal components enhance the major features of the data and facilitate clustering to find near-optimal solutions.

The fuzzy C-means clustering (FCM) was performed based on the first few principal components. FCM calculates the degree of membership of each site into each cluster and allows sites to belong to more than one cluster simultaneously (Güler et al., 2012). It opposed to traditional clustering which results in mutually exclusive clusters (Maharaj and D’Urso, 2011). For this reason, the FCM is very suitable for the mixing case.

The FCM algorithm assumes the attributes are from a vector space. The objective is to achieve a minimized total intra-cluster variance function $D_v$

$$D_v = \sum_{k=1}^{K} \sum_{j \in S_k} |x_j - C_k|^2$$

where $C_k$ the mean point (centroid) of all the points in cluster $k$; $K$ is the total number of clusters; $S_k$ is the set of points in the $k$th cluster; $x_j$ is the standardized vector for site $j$. The FCM algorithm starts by making an initial set of $k$ groups. It then calculates the mean point of each set. The next step is construction of a new partition by associating each point with the closest centroid. Then the centroids are recalculated for the new clusters and the algorithm is repeated by alternate application of these two steps until convergence. Partial membership is permitted in FCM, meaning that each point has a degree of membership in each of the clusters. Thus points on the edge of a cluster may be in that cluster to a lesser degree than points in the center of a cluster.

The degree of belonging of site $i$ in the $k$th cluster is equal to the inverse of the distance of site $i$ to the centroid of cluster

$$b_k(i) = \frac{1}{d(C_k, i)}$$

where $b_k(i)$ is the degree of belonging of site $i$ in the $k$th cluster; $d(C_k, i)$ is the distance of site $i$ to the centroid of cluster $k$. The coefficients are normalized so that the sum of membership of one site of interest to all different clusters is unity.

$$\forall i \left( \sum_{k=1}^{K} U_k(i) = 1 \right)$$

where $U_k(i)$ normalized coefficient of site $i$ in the $k$th cluster. Each site is assigned to the cluster with which it has the highest degree of membership. By the cluster analysis, the geochemical impact and the degree of the impact between groundwater systems could be verified.

3.4. Further geochemical verification: Paired $t$ test

Deep groundwater and shallow groundwater were sampled in the same site nearly simultaneously. Samples of different groundwater systems in the same site form a pair. For this case, the paired $t$ test can offer a further verification of geochemical similarity of different groundwater systems.

The paired $t$ test typically consists of a sample of matched pairs of similar units. It is most commonly applied when the samples would follow a normal distribution. A non-parametric test, one sample Kolmogorov–Smirnov test could serve as the test for normality of the sample distribution under the null hypothesis that the sample is drawn from the reference distribution. The null hypothesis of the paired $t$ test is that the means of two normally distributed populations are equal. The statistic of the paired $t$ test is calculated by

$$t = \frac{D}{S_D}$$

where $t$ is the statistic for equality of means, $D$ is the mean of the differences between the paired data; $S_D$ is standard error of the differences (David and Gunnink, 1997). One sample Kolmogorov–Smirnov test and paired $t$ test were performed in SPSS software.

4. Results

4.1. Distribution of depth to water level and variance of water level

According to Baoding Institute of Hydrology and Water Resources Survey, the average depth to water level in the study area changed between 21.34 m and 24.15 m and the mean in the center of the cone varied between 43.76 m and 44.95 m in 2010. The depth to water level measured during the field survey varied between 21.44 m and 39.78 m. The shallowest one was observed in the site of G7 that is 25.5 km away from the center of the cone. While the deepest one appeared in the site of G3 that is 3.9 km away from the center of the cone. The observation period of water level is from March 2005 to May 2011 (Figs. 4 and 5). About half year’s records before March 2010 missed due to failure of batteries in the instruments. In addition, water level lower than −12.55 m was not recorded for DC01 before July 2007, because the probe was hanged too high in the well pipe.

The records show that the shallow groundwater has evidently daily fluctuations. The well of DC01 with a depth of 70 m is located in the pluvial fan of Jie River that is the water source area for Baoding city. As a result of periodic development of groundwater,
The water level reached the climax in 7 am and arrived at the bottom in 5 pm. Then the water level remained stable until the pumping stopped in about 6 pm which shows that the shallow groundwater was recharged continuously. The well of DC02 with a depth more than 40 m is a domestic well. The daily variation of water level changed little besides some sudden drops occurred in 12 am or 8 pm. The deep groundwater has a stable water head which varied daily within 8 cm on average. At the same time, the mean daily variations are 1.05 m and 0.63 m for DC01 and DC02 respectively.

In a whole hydrological year, groundwater regime shows two cycles in the observation wells. Water level fell down in April and rose in July. In October water level descended again. In December the second ascending occurred. The same dynamic regimes indicate the similar recharge and discharge in the shallow and the deep groundwater. It is suggested that plenty rainfall in rainy season and smelted snow in early April formed two rapid lateral recharges to the groundwater systems.

During the observation period, the water level shows an ascending trend in DC01 and DC03, while the water level presents a descending trend in DC02. The average water levels are –8.4 m, –5.3 m and 2.9 m in DC01, DC02, and DC03 respectively. The hydraulic head of the deep groundwater is far higher than that of the shallow groundwater.
the shallow groundwater. The hydraulic condition for the upward recharge is satisfied. The most important thing is that water level in DC01 was higher than that in DC02 from September 2008 to April 2009 and from August 2010 to April 2011. During the two periods (dry seasons), the hydraulic gradient in the cone of depression was reversed, which means the sink becomes a source.

4.2. Geochemical features

The hydrochemical and stable isotopic characteristics of water samples are shown in Tables 1 and 2. The average of pH is 8.0 ± 0.29 in the shallow groundwater, while the mean is 8.2 ± 0.14 in the deep groundwater. In general, the pH value of shallow groundwater is lower than the one of deep groundwater. The averages of EC and δD are 802 ± 258 μS/cm and -62 ± 3‰ in the shallow groundwater, while the means are 531 ± 103 μS/cm and -71 ± 6‰ in the deep groundwater. The shallow groundwater is originally saltier and isotopic heavier than the deep groundwater. Mg\(^{2+}\) is one of dominated cations in the shallow groundwater, and Na\(^+\) concentration is relatively high in the deep groundwater. In addition, the contents of Cl\(^-\) and NO\(_3^-\) mainly from anthropogenic input are about four times higher in the shallow groundwater (in average 48 mg/L and 23 mg/L, respectively) than those in the deep groundwater. The compositions of major ions are mainly Mg-Ca-HCO\(_3^-\) and Ca-Mg-HCO\(_3^-\) type in the shallow and Na-Ca-HCO\(_3^-\) and Ca-Mg-HCO\(_3^-\) type in the deep groundwater respectively (Fig. 8). Consistent with the results of former researches (Song et al., 2011; Yuan et al., 2011; Zhuang et al., 2011), the deep groundwater has high pH values and light isotopic compositions, while the shallow groundwater has high EC values and contents of Cl\(^-\) and NO\(_3^-\).

However, the geochemical similarity between the shallow and the deep groundwater is evident. More than half of the samples from shallow groundwater have the similar pH values with the deep groundwater. Many samples of the shallow groundwater have the similar EC values, chemical types and isotopic compositions with the deep groundwater (Figs. 6–8). The distribution of data points is loose especially for deep groundwater, although a

![Fig. 6. The plot of EC versus δD of water samples.](image-url)
part of the points follows the LMWL line closely in Fig. 7. In deep aquifers, there are fossil groundwater that have obviously different isotopic compositions with modern precipitation (Chen et al., 2005). Also, isotope exchanges that would cause data points away from the meteorological water line could happen by interactions of water and rock in deep aquifers. In this case, it seems that the deep groundwater induced a loose distribution of data points of shallow groundwater.

The variances of major ion contents of the shallow groundwater were presented along the transections for illumination of evolution of the shallow groundwater (Fig. 9). In the cone of depression, the deep groundwater has an average of EC about 531 \textmu S/cm and distinctly low ion contents of NO$_3^-$, Cl$^-$, and Mg$^{2+}$. When the deep groundwater recharge the overlying shallow groundwater under the upward vertical hydraulic gradient, the EC value and the corresponding ion concentrations in the shallow groundwater decreased greatly. Along the MQ transection, EC value of the shallow groundwater decreased from 824 \textmu S/cm in the edge of the cone (G1) to 544 \textmu S/cm in the center of the cone (G3), and then increased to 1349 \textmu S/cm and 1077 \textmu S/cm in G4 and G5 where is close to the metropolis Baoding. After G5, the EC value almost maintained stable with a little variation between 752 \textmu S/cm and 748 \textmu S/cm. The variations of contents of Ca$^{2+}$, Mg$^{2+}$, Na$^+$, HCO$_3^-$, SO$_4^{2-}$, and Cl$^-$ follow the same changing trend and give an explanation to the EC fluctuation. The same evolution was observed when the XW transection extends through the cone of depression, ion contents and also EC values were dropped evidently into a low value interval (G11, G12 and G13).

In the center area of the cone, the major ion contents and EC value of shallow groundwater (G3) are very similar with the local deep groundwater (G3d) but obviously lower than the averages of the shallow groundwater (Tables 1 and 2). In addition, the isotopic composition of G3 ($\delta^{18}O = -10.45\%$, $\delta$D = -62.8\%) is almost the same with G3d ($\delta^{18}O = -10.46\%$, $\delta$D = -65.2\%) considering the rational measurement errors, which suggests the same origination of waters. It is suggested that deep groundwater has occupied the phreatic aquifer in the center of the depression cone.

The difference of $\delta^{18}O$ between the G3d ($-10.46\%$) and the G1 ($-8.09\%$) reveals that the recharge zone elevation of the deep groundwater is higher than 1200 m based on the altitude gradient of $\delta^{18}O$ = 0.2\%/100 m (Liu et al., 2010). The large elevation difference between the recharge zone and the discharge point of the deep groundwater offers the upward vertical hydraulic gradient. The great upward vertical hydraulic gradient promotes the upward recharge.

5. Discussion

5.1. Evidence from water level analyses for the upward recharge

In the center of the depression cone, the water level is very low (average −8.4 m, minimum −15.2 m), while the water level of deep groundwater is relative high (average 2.9 m, maximum 4.3 m). Under the hydraulic condition, it is possible that shallow groundwater was recharged by the deep groundwater. If the recharge happened, the fluctuation and even the trend of water level series of shallow groundwater will be controlled mainly by the

![Fig. 7. The plot of $\delta^{18}O$ versus $\delta$D of water samples. The local meteoric water line (LMWL) follows Yuan et al. (2012).](image)

![Fig. 8. The Piper plot of water samples.](image)
Deep groundwater. The deduction was verified by correlation analyses and trend analyses of time series of water level. Daily water level series were analyzed. The time series of daily water level were produced by extracting the water level on 4 am when the water level had been recovered and remain stable. The Pearson correlation analysis was executed within ±30 time lags (day) and the max correlation coefficient was obtained. The result shows that there is a strong hydraulic connection between the deep and the shallow groundwater in the center of the depression cone. The strong hydraulic connection is presented by high correlation coefficients ($r = 0.86$, $\tau = 0.67$ with no time lags) between water level time series of DC01 and DC03 (Table 3). Furthermore, the correlation is weak between DC01 and DC02 which means different mechanisms of water level fluctuation in different sites of the depression cone. It is suggested that the fluctuation of water level of shallow groundwater in the center of depression cone was controlled by deep groundwater.

The variation trends were evaluated based on the daily series of water level. First, the non-parametric Mann–Kendall–Sneyers test was used to locate the approximate starting point of a trend (Fig. 10). The forward sequence curve does not intersect the backward sequence curve within the confidence interval ±1.96 ($z = 0.05\%$) for the DC01 and DC02 time series. It is confirmed that no changing point exists in the series and variation trend of water level is monotonous. However, there is a changing point occurred on August 2006 for the DC03 time series. Therefore, it is necessary to test the trend before and after the changing point respectively. The significance and magnitude of water level series trends were determined using the non-parametric Mann–Kendall test and Sen’s slope method, respectively. The results indicate that there are different trends in different sites of the cone of depression. In the center region of the depression cone (DC01), the water level of shallow groundwater presented an upward trend with a slope about 6.9 and 7.0 mm/d. At the same time, the water level of deep groundwater also showed an upward trend with a slope about 1.9 and 1.0 mm/d in the corresponding periods (Table 4). By contrast, the water level of shallow groundwater exhibited a downward trend at the site of DC02 from April 2005 to September 2009, and then it varied with no significant trends from March 2010 to May 2011. The strong influence of deep groundwater on the water level of shallow groundwater in the center of the depression cone is confirmed.

The impacts of deep groundwater on the fluctuation and the trend of water level of shallow groundwater are the results of the recharge from deep groundwater to shallow groundwater in the center region of the depression cone. The shallow groundwater was over-pumped for more than 40 years, and the water level declined persistently. At the same time, the water level of deep groundwater ascended at a rate of 1.9 mm/d since August 2006. The largest hydraulic head difference between the deep and the shallow groundwater occurred in the center of the depression cone. Finally, the shallow groundwater was recharged by the deep groundwater. As a result, the water level of shallow groundwater in the center of the depression cone presents an ascending trend and a close correlation with the deep groundwater (Tables 3 and 4). The sink became a source. Since September 2008, the water level of DC01 was higher than that of DC02 in dry seasons when the hydraulic gradient in the cone of depression was reversed. The shallow groundwater flowed from the center of the cone to the edge which makes the decline trend of DC02 ceased (Table 4) and the correlation between the two sites became stronger (the time lags of max $r$ decreased from 7 days to 2 days, shown in Table 3). As a result of the enlarged recharge, the ascending trend of the deep groundwater slowed down from 1.9 mm/d to 1.0 mm/d (Table 4).

5.2. Evidence from integrated analyses of geochemical data for the upward recharge

As a result of the upward recharge, the hydro-geochemistry of the shallow groundwater would be changed considering the

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**Table 3**

<table>
<thead>
<tr>
<th>Observation wells</th>
<th>Periods</th>
<th>Number of data</th>
<th>Pearson correlation Lags (day)</th>
<th>Max $r$</th>
<th>Kendall correlation $	au$</th>
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<td></td>
<td>2010/3–2011/5</td>
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<td>2</td>
<td>0.65</td>
<td>0.43</td>
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<td>DC01–DC03</td>
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<td>0.86</td>
<td>0.67</td>
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<td></td>
<td>2010/3–2011/5</td>
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<td>1</td>
<td>0.70</td>
<td>0.46</td>
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<td>DC02–DC03</td>
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<td>−0.26</td>
<td>−0.19</td>
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<td></td>
<td>2010/3–2011/5</td>
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<td>−1</td>
<td>0.25</td>
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different geochemical characteristics between the shallow and the deep groundwater. The fuzzy C-means clustering based on principal components was employed to clarify the influences and to assure the recharge further. First, the PCA analysis was carried out for the twelve variables (pH, EC, $\delta^{18}$O, $\delta^{2}D$, Ca$^{2+}$, Mg$^{2+}$, Na$^{+}$, K$^{+}$, HCO$_3$/$CO_3^{2-}$, SO$_4^{2-}$, Cl$^{-}$, NO$_3^{-}$) of water samples to achieve principal components. The results show that EC, HCO$_3$/$CO_3^{2-}$, Cl$^{-}$ and Mg$^{2+}$ have a strong effect on the value of the first principal component. The first principal component explains 93.3% of the variance of the original variables. It is confident the first principal component could present comprehensively the geochemical features.

The FCM clustering for two groups was carried out based on the first principal component. The iterative procedure of FCM algorithm generated a fuzzy membership matrix (Table 5). A fuzzy membership is a probability of belonging to clusters for a sample. All deep groundwater samples are classified into group B. In addition, five samples out of fifteen samples of shallow groundwater also belong to group B. The rest samples of shallow groundwater are classified into group A. The five samples are all located in the area of the depression cone. It is confirmed that shallow groundwater in the area of depression cone is similar with the deep groundwater in hydro-geochemistry. The result also suggests that

**Fig. 10.** Mann–Kendall–Sneyers test for detecting change points in daily water level series with forward sequence curve (ufk, solid line) and backward sequence curve (ubk, dashed line). The horizontal lines represent the 5% significance level. (a) DC01, (b) DC02, and (c) DC03.

**Table 4**
The results of trend analysis of water level series.

<table>
<thead>
<tr>
<th>Observation well</th>
<th>Periods</th>
<th>Number of data</th>
<th>Z value</th>
<th>Sen’s slope (mm/d)</th>
<th>Trend</th>
</tr>
</thead>
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<td>DC01</td>
<td>2007/7–2009/8</td>
<td>778</td>
<td>18.99</td>
<td>6.9</td>
<td>Upward trend detected</td>
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<td></td>
<td>2010/3–2011/5</td>
<td>413</td>
<td>8.62</td>
<td>7.0</td>
<td>Upward trend detected</td>
</tr>
<tr>
<td>DC02</td>
<td>2005/4–2009/9</td>
<td>1603</td>
<td>-31.73</td>
<td>-1.9</td>
<td>Downward trend detected</td>
</tr>
<tr>
<td></td>
<td>2010/3–2011/5</td>
<td>413</td>
<td>0.48</td>
<td>No significant trend</td>
<td></td>
</tr>
<tr>
<td>DC03</td>
<td>2005/3–2006/7</td>
<td>502</td>
<td>-1.19</td>
<td>No significant trend</td>
<td></td>
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<tr>
<td></td>
<td>2006/8–2009/10</td>
<td>1163</td>
<td>32.47</td>
<td>1.9</td>
<td>Upward trend detected</td>
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<tr>
<td></td>
<td>2010/3–2011/5</td>
<td>412</td>
<td>8.80</td>
<td>1.0</td>
<td>Upward trend detected</td>
</tr>
</tbody>
</table>
shallow groundwater is evidently impacted by the recharge of deep groundwater in the region of depression cone.

For a further validation of the geochemical similarity, paired t test was carried out in this case. In this case, the shallow and the deep groundwater sampled in the same sites are the matched pairs and the variables (Ca\(^{2+}\), Mg\(^{2+}\), Na\(^+\), K\(^+\), HCO\(_3\)\(^-\), SO\(_4\)\(^{2-}\), Cl\(^-\), NO\(_3\)\(^-\), $\delta^{18}$O) are the units. The null hypothesis of the test is that the geochemical differences between the shallow groundwater and the deep groundwater are insignificant. The result of the one-sample Kolmogorov–Smirnov test confirms that all variables fit the normal distribution well at the significant level of 0.05. Finally, four pairs including G3/G3d, G11/G11d, G13/G13d, and G12/G12d were found. The result of paired t test shows that the null hypothesis cannot be rejected for those variables besides Cl\(^-\) at the significant level of 0.05 (Table 6). It is verified that there is a very similar hydrochemistry between the shallow and the deep groundwater in the area of depression cone. The content of Cl\(^-\) in shallow groundwater is related to anthropogenic input at individual points. Consequently, it labeled the differences in hydrochemistry between the shallow and the deep groundwater.

Geochemical differences between the shallow and the deep groundwater are originally evident as mentioned before. However, the hydrochemical features of the shallow groundwater within the depression cone are significantly similar with the deep groundwater. While the geochemical features of the shallow groundwater in the margin of the depression cone are significantly distinct with the deep groundwater. The phenomenon offers a geochemical proof confirming the recharge from the deep groundwater to shallow groundwater in the center of the depression cone.

6. Conclusions

Due to persistent over-pumping of the shallow groundwater for industrial, agriculture and domestic consuming, the groundwater depression cone (Daceying–Machang) occurred and expanded even in the piedmont plain of the North China Plain. The existence of Daceying–Machang depression cone induced the recharge from deep groundwater to shallow groundwater in the center of the depression cone, which changed hydrodynamic and hydro-geochemical fields of the shallow groundwater greatly. Since 2008, the hydraulic gradient of the depression cone was reversed in dry seasons which enhances the groundwater mixture and complicates the flow in the depression cone in spatial–temporal scales. The high contents of Cl\(^-\) and NO\(_3\)\(^-\) in shallow groundwater were diluted. Water quality of the shallow groundwater is improved. The persistent over-pumping of shallow groundwater and the large elevation difference (around 1200 m) between the recharge zone and the discharge point of deep groundwater facilitate the upward recharge.

Statistical analyses, such as fuzzy C-means clustering based on principal components, paired t test, trend analysis and correlation analysis are very useful and economical tools to verify the interaction between groundwater systems and could be considered as an important assist for the routine analyses of groundwater hydrology.

Acknowledgements

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Table 5

<table>
<thead>
<tr>
<th>Site</th>
<th>Type</th>
<th>Membership matrix $U_i(t)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Group A</td>
</tr>
<tr>
<td>G10'</td>
<td>S</td>
<td>0.988</td>
</tr>
<tr>
<td>G10</td>
<td>S</td>
<td>0.961</td>
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<tr>
<td>G5</td>
<td>S</td>
<td>0.949</td>
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<tr>
<td>G9</td>
<td>S</td>
<td>0.949</td>
</tr>
<tr>
<td>G15</td>
<td>S</td>
<td>0.843</td>
</tr>
<tr>
<td>G1</td>
<td>S</td>
<td>0.837</td>
</tr>
<tr>
<td>G4</td>
<td>S</td>
<td>0.808</td>
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<tr>
<td>G14</td>
<td>S</td>
<td>0.629</td>
</tr>
<tr>
<td>G6</td>
<td>S</td>
<td>0.543</td>
</tr>
<tr>
<td>G7</td>
<td>S</td>
<td>0.523</td>
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<tr>
<td>G10d</td>
<td>D</td>
<td>0.342</td>
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<tr>
<td>G12</td>
<td>S</td>
<td>0.089</td>
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<tr>
<td>G4d</td>
<td>D</td>
<td>0.070</td>
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<tr>
<td>G14d</td>
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<tr>
<td>G8d</td>
<td>D</td>
<td>0.048</td>
</tr>
<tr>
<td>G13d</td>
<td>D</td>
<td>0.042</td>
</tr>
<tr>
<td>G11</td>
<td>S</td>
<td>0.039</td>
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<td>G3</td>
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<tr>
<td>G9d</td>
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<tr>
<td>G8d</td>
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<tr>
<td>G12d</td>
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<td>0.007</td>
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<tr>
<td>G5d</td>
<td>D</td>
<td>0.002</td>
</tr>
<tr>
<td>G3d</td>
<td>D</td>
<td>0.001</td>
</tr>
<tr>
<td>G11d</td>
<td>D</td>
<td>0.001</td>
</tr>
<tr>
<td>G13</td>
<td>S</td>
<td>0.000</td>
</tr>
<tr>
<td>G2</td>
<td>S</td>
<td>0.000</td>
</tr>
<tr>
<td>G6d</td>
<td>D</td>
<td>0.000</td>
</tr>
</tbody>
</table>

* Membership of 1.000 means very close to 1.
  b S represents shallow groundwater.
  c D represents deep groundwater.

Table 6

<table>
<thead>
<tr>
<th>Site</th>
<th>Type</th>
<th>Mean</th>
<th>Std. error</th>
<th>$t$</th>
<th>$p$ Value (2-tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCO(_3) (^-)</td>
<td>10.3</td>
<td>20.1</td>
<td>0.513</td>
<td>0.644</td>
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<tr>
<td>Ca(^{2+})</td>
<td>6.1</td>
<td>11.5</td>
<td>0.533</td>
<td>0.631</td>
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<tr>
<td>NO(_3) (^-)</td>
<td>1.5</td>
<td>2.5</td>
<td>0.579</td>
<td>0.603</td>
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<tr>
<td>K(^+)</td>
<td>0.4</td>
<td>0.5</td>
<td>0.869</td>
<td>0.449</td>
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<tr>
<td>Na(^+)</td>
<td>-4.4</td>
<td>4.0</td>
<td>-1.095</td>
<td>0.353</td>
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</tr>
<tr>
<td>SO(_4) (^{2-})</td>
<td>1.9</td>
<td>1.5</td>
<td>1.307</td>
<td>0.282</td>
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<tr>
<td>$\delta^{18}$O</td>
<td>2.1</td>
<td>1.8</td>
<td>1.316</td>
<td>0.280</td>
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</tr>
<tr>
<td>$\delta^{13}$O</td>
<td>0.4</td>
<td>0.3</td>
<td>1.442</td>
<td>0.245</td>
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</tr>
<tr>
<td>Mg(^{2+})</td>
<td>6.9</td>
<td>3.4</td>
<td>2.050</td>
<td>0.133</td>
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</tr>
<tr>
<td>Cl(^-)</td>
<td>9.1</td>
<td>2.6</td>
<td>3.485</td>
<td>0.040</td>
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</tr>
</tbody>
</table>

* The degree of freedom is 3.


Yuan, R. et al., 2012. Rate and historical change of direct recharge from precipitation constrained by unsaturated zone profiles of chloride and oxygen-18 in dry river bed of North China Plain. Hydrological Processes 26 (9), 1291–1301.


