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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, ^{2}H, ^{18}O and kinds of statistical analyses. Since August 2006, the water level of the deep groundwater ascended by 1.9 mm/d. High correlations ($r = 0.86$, $\tau = 0.67$) 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-elasto-plasticity, 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 3.08×10^{7} m^{3}/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 Lambrakis (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.

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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 km^2 including Baoding city, Mancheng county, Wanxian county, Qingyuan county, Xushui county and Wangdu county, as illustrated in Fig. 1. The climate is continental semiarid 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 m^3/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 km^2, 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

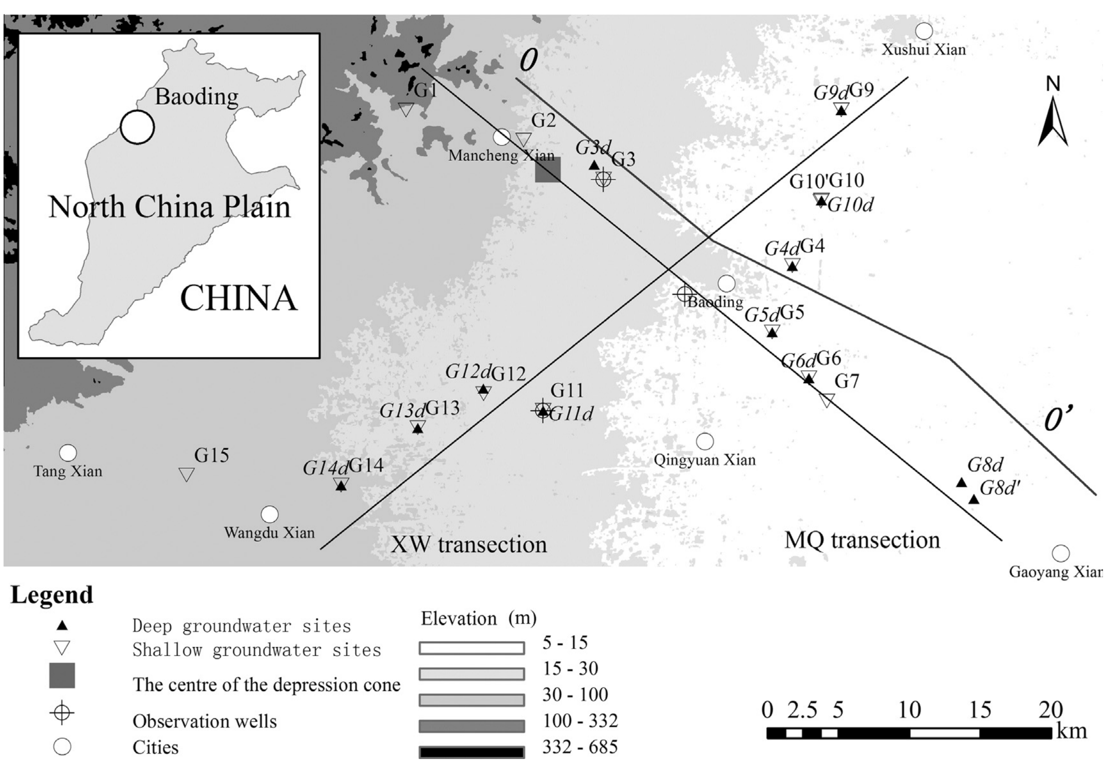

Fig. 1. The sampling sites and DEM model (ASTER) of the study area. The ASTER GDEM is a product of METI and NASA.