# Impacts of groundwater extraction on groundwater flow and arsenic distribution in the western Hetao Basin, Inner Mongolia, China

*Zhuo* Zhang[1,2], *Huaming* Guo[1,2,*], *Weiguang* Zhao[2], and *Haicheng* Weng[1,2]

[1]State Key Laboratory of Biogeology and Environmental Geology, China University of Geosciences, Beijing 100083, P.R. China
[2]MOE Key Laboratory of Groundwater Circulation & Environment Evolution & School of Water Resources and Environment, China University of Geosciences (Beijing), Beijing 100083, P.R. China

**Abstract.** Temporal variations in water levels are crucial for understanding As behaviour in groundwater systems. Groundwater levels were recorded in irrigation wells in non-irrigation and irrigation seasons. Groundwater samples were collected yearly in irrigation wells from 2014 to 2016 and in a multilevel well from 2015 to 2016 for analysing geochemical parameters. Results showed that groundwater flow direction was reversed due to groundwater pumping. The change of groundwater flow led to the surface water, as a new groundwater recharge source, which flushed the near-surface sediments enriched in soluble components and increased groundwater TDS. The labile organic matter introduced by the surface water recharge fueled dissimilatory reduction of Fe(III) oxides and further increased groundwater As concentration.

## 1 Introduction

High arsenic(As) groundwater has been found worldwide [1]. Some studies showed that groundwater extraction affected groundwater As via the changes of groundwater recharge source, the anomalous disturbance of sediments and the vertical groundwater mixing [2-5]. Previous studies showed that the reductive dissolution of Fe(III) oxyhydroxides led to As release from aquifer sediments in the Hetao basin [6-7]. However, few focus on effects of groundwater extraction on groundwater As distribution. This study aims at characterizing relationships between variations in groundwater flow pattern and groundwater chemistry and understanding effects of the extraction on groundwater As dynamics.

## 2 Study area

The study area is located in the northwest of the Hetao basin, including alluvial fans and flat plain (Fig. 1). According to our borehole loggings, shallow groundwater was considered to be hosted in aquifers overlying the clay layers around 40 m below land surface (BLS), while aquifers underlying the clay layers, being regarded as the semi-

* Corresponding author: hmguo@cugb.edu.cnc

confined aquifer, hosted deep groundwater [8]. Groundwater flowed from the piedmont area in the north to the drainage channel, which was locally the discharge area [9]. The diverted water from the Yellow River has been mainly used for agricultural irrigation since 50 years ago. Owing to high altitude and overuse of the water in the upstream of the irrigation channels, the diverted-Yellow River water is unavailable near the mountains and hence groundwater has recently been used for both irrigation and drinking in the study area.

# 3 Materials and methods

## 3.1 Groundwater levels measuring

Groundwater levels of 57 irrigation wells were measured regularly using an electronic water sensor (Model 101B, Solinst) in July 2016 (irrigation season) and March 2017 (non-irrigation season). The real-time kinematic difference global positioning system (RTK-GPS) was used to measure the elevations of all well heads.

According to measur~~ing~~ed data of groundwater levels/heads, the study area was divided into two zones: groundwater recharge area (Zone I) near the piedmont and surface water recharge area close to the Shahai Lake (Zone II).

## 3.2 Groundwater sampling and analysis

Groundwater samples were taken from six irrigation wells (three for Zone I and three for Zone II) every year from 2014 to 2016 and collected from three depths (14.5, 42.5 and 67.5 m) of a multilevel well in Zone II. Both field measurements (water temperature, EC, pH, Eh, alkalinity, Fe(II) and $NH_4$-N) and laboratory analyses (major cations, trace elements, As species, DOC) were carried out. Details can be found in our previous study [10].

# 4 Results and discussion

## 4.1 Changes in groundwater flow induced by groundwater extraction

Prior to the extensive groundwater extraction, groundwater mainly flowed from alluvial fans to the flat plain and discharged into the Shahai lake and the drainage channel. Due to shallow groundwater depths and the intense evaporation near the drainage channel, a large amount of salt accumulates in near-surface sediments. Since 2006, many wells have been gradually set up near the mountains for both irrigation and drinking. Intensive groundwater extraction causes a depression cone in the center of study area and further changes groundwater flow direction in Zone II. The Shahai lake and drainage channel are therefore converted into the recharge area of groundwater.

In terms of an irrigation cycle, no obvious change was observed on groundwater flow direction in two zones, but the groundwater level contours during the irrigation season is much denser than those during non-irrigation season in Zone II. During groundwater extraction, the water head difference between the top of the alluvial fans and the depression cone was around 3 m, while the water difference between the Shahai lake and the depression cone was up to 9 m (Fig. 1a). Prior to the next extraction, although the groundwater levels in the top of the alluvial fans and the depression ~~was~~ had recovered by 3 m, the general flow direction still kept unchanged (Fig. 1b). The water level difference between the Shahai lake and the depression cone decreased to 5 m from 9 m. Above all, the intensive groundwater extraction led to a sharp decline in the groundwater level in Zone I

and increased the recharge of surface water to groundwater in Zone II.

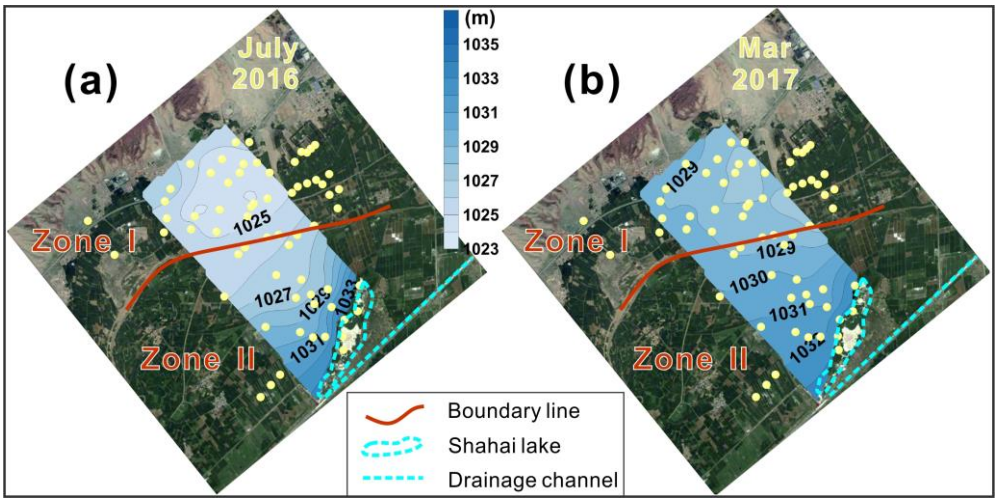


**Fig. 1.** Contour maps of groundwater levels of irrigation wells in (a) July 2016 and (b) March 2017. Yellow solid dots mean locations of irrigation wells for measuring water levels.

### 4.2 Horizontal changes in groundwater chemistry and As

Although the groundwater flow in Zone I was affected by the depression cone, the groundwater recharge source did not change. Groundwater TDS and major ions keep relatively unchanged from 2014 to 2106 (Table 1). A slight increasing trend in groundwater Eh is attributed to the declining groundwater level. No obvious variations in groundwater As and redox-sensitive components from 2014 to 2106 were observed.

**Table 1.** Mean values of groundwater chemical compositions from irrigation wells.

| Site | Date (year) | pH | Eh (mV) | TDS (mg/L) | DOC (mg/L) | $As_{tot}$ (μg/L) | Fe(II) (mg/L) | $NH_4$-N (mg/L) | Fe (mg/L) | Mn (μg/L) |
|---|---|---|---|---|---|---|---|---|---|---|
| Zone I | 2014 | 7.14 | 254 | 773 | 1.40 | 15.8 | 0.20 | 0.31 | 205 | 73.8 |
| | 2015 | 7.36 | 273 | 781 | 1.74 | 16.6 | 0.17 | 0.28 | 217 | 70.1 |
| | 2016 | 7.29 | 309 | 809 | 2.02 | 17.8 | 0.21 | 0.17 | 268 | 81.5 |
| Zone II | 2014 | 7.21 | 69.3 | 1812 | 2.63 | 237 | 1.46 | 3.58 | 2091 | 172 |
| | 2015 | 7.65 | 154.7 | 2233 | 2.65 | 249 | 2.06 | 4.87 | 2748 | 173 |
| | 2016 | 7.60 | 135.8 | 2376 | 3.26 | 273 | 2.06 | 3.76 | 3402 | 204 |

However, in Zone II, groundwater TDS and major ions increased significantly over time. Near-surface sediments contained soluble components [11]. The recharge from lake water flushed those sediments and carried a large amount of soluble components into groundwater after the extraction. In addition, from 2014 to 2016 groundwater As concentration increased by 15%, which was accompanied by the rise of groundwater DOC (24%) and Fe(II) (41%). The shift of the groundwater recharge source was believed to be primarily responsible for those variations. The infiltration of the Shahai Lake water introduced labile dissolved organic matter into aquifers, which readily fueled dissimilatory reduction of Fe(III) oxides [2,5].

### 4.3. Vertical changes in groundwater chemistry and As

Groundwater TDS increased with depth, reached the maximum in the intermediate layer, and then dropped rapidly. The entire aquifer basically maintained a weakly alkaline environment. Groundwater As decreased with depth, which is associated with higher contents of As and labile organic carbon in shallow sediments [5]. The lower Fe(II) and $NH_4$-N concentrations of shallow groundwater than intermediate groundwater was attributed to the oxic conditions. The intensive groundwater extraction led to infiltration of shallow groundwater into deep groundwater, which would increase As concentrations of deep groundwater.

**Table 2.** Chemical compositions of groundwater from the multilevel well of Zone II.

| Depth (m) | Date (year) | pH | Eh (mV) | TDS (mg/L) | DOC (mg/L) | $As_{tot}$ (μg/L) | Fe(II) (mg/L) | $NH_4$-N (mg/L) | Fe (mg/L) | Mn (μg/L) |
|---|---|---|---|---|---|---|---|---|---|---|
| 15.5 | 2016 | 7.87 | 183 | 1814 | 1.69 | 147 | 0.20 | 2.32 | 207 | 378 |
| | 2017 | 7.75 | 221 | 1636 | 1.92 | 99.1 | 0.15 | 1.76 | 142 | 382 |
| 42.4 | 2016 | 7.85 | 85.1 | 1940 | 2.99 | 46.1 | 1.33 | 3.52 | 1057 | 268 |
| | 2017 | 7.92 | 90.1 | 2357 | 4.03 | 78.9 | 4.00 | 3.44 | 1299 | 316 |
| 67.5 | 2016 | 7.82 | 48.1 | 501 | 2.17 | 21.7 | 0.90 | 0.70 | 93.6 | 93.7 |
| | 2017 | 7.80 | 83.5 | 631 | 3.58 | 32.4 | 0.29 | 1.44 | 330 | 155 |

From 2016 to 2017, shallow groundwater TDS decreased by around 10%, while intermediate groundwater TDS increased by 18%. Deep groundwater TDS had a moderate increase. With the extensive extraction, high-TDS shallow groundwater migrated downward and recharged the deep aquifer. Similar trends were also observed regarding groundwater As, Fe(II) and $NH_4$-N. The introduction of exogenous organic carbon induced by the extraction was believed to be responsible for the increase in groundwater As.

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