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Temporal variations of groundwater quality in the Western Jianghan Plain, China

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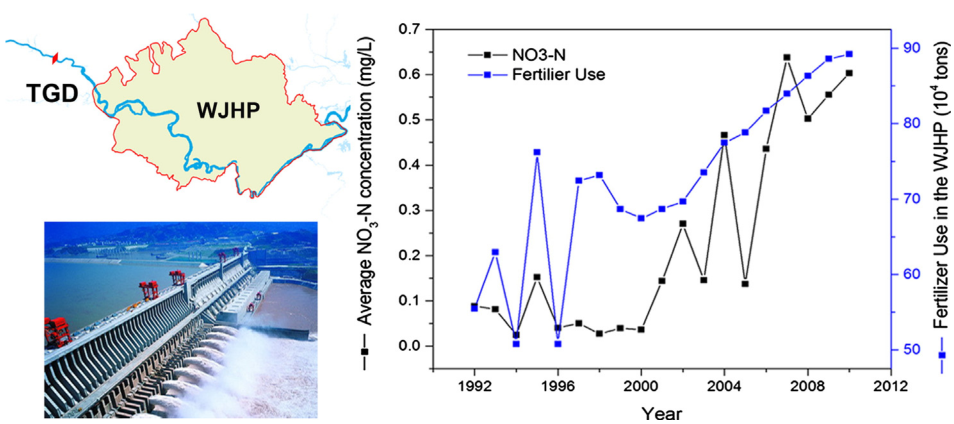
HIGHLIGHTS

- Spatial-temporal variations of groundwater quality were characterized.
- CO_2 degassing caused by groundwater extraction increased the groundwater pH.
- NO_3-N increased coincidently with the increased use of fertilizer.
- The Three Gorges Dam contributes partly to the variations of pH, NH_4-N and NO_3-N.

GRAPHICAL ABSTRACT



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ABSTRACT

The Western Jianghan Plain (WJHP) lies in the middle reaches of the Yangtze River. It has been impacted by anthropogenic activities during the past decades. The long-term variations of the WJHP's regional aquifer's hydrochemistry and groundwater quality have not been previously assessed. Sixteen physiochemical parameters at 29 monitoring wells within the Western Jianghan Plain were monitored during 1992–2010 and analyzed with multiple approaches. The confined groundwater is predominantly of the HCO_3-Ca-Mg type with Cl^-, SO_4^{2-}, NH_4-N, and NO_3-N showing remarkable spatial variations. Correlation analysis was used to identify the origins and contamination sources of groundwater. The seasonal Mann-Kendall test revealed that pH, NO_3-N, and Cl^- concentrations at 27, 26 and 15 wells, respectively, exhibited significant increasing trends during 1992–2010. The increase of pH may be attributed to CO_2 degassing caused by extensive groundwater extraction. Regional average NO_3-N concentrations of groundwater increased coincidently with the increased use of fertilizer, which suggests that nitrate pollution is caused by agricultural activities. Abnormally high values of Cl^- and SO_4^{2-} at some wells were induced by industrial chemicals. In addition, the similarity of the temporal variations of the regional average of pH, NH_4-N, and NO_3-N concentrations in groundwater with those in the Yangtze River at the outlet of the Three Gorges Reservoir (TGR) suggests that the variations of these parameters in the WJHP is partly due to water storage by the TGR. This study presents an analysis of temporal variations of groundwater quality in the WJHP that

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reveals a relation between the creation of the TGR and downstream groundwater quality. This paper's findings provide clues for measures that could be taken to protect the groundwater quality of the WJHP's aquifer.

1. Introduction

Groundwater constitutes a critical water source for domestic, industrial, and agricultural activities around the world (Aeschbach-Hertig and Gleeson, 2012; Huang et al., 2013; Xiao et al., 2014). China has relied heavily on groundwater for its development. This has caused the depletion of its groundwater resources in many regions and led to groundwater pollution during the past decades (Qu and Fan, 2010; Zhang et al., 2014). The groundwater chemistry and its characteristics are influenced by many factors that include the aquifer mineralogy, geochemical processes, overlying land uses, the source of recharge, and the inputs from anthropogenic sources (Freeze and Cherry, 1979; Gurunadha Rao et al., 2013; Hem, 1986; Kurilić et al., 2015; Sahraei Parizi and Samani, 2013; Wang et al., 2016). Numerous studies have been performed regarding hydrochemical changes of groundwater in various parts of the world, which have shed light on the processes governing groundwater quality and on effective management of groundwater resources (Bozdağ, 2016; Cao et al., 2014; Ledesma-Ruiz et al., 2015; Liu et al., 2015a; Martos-Rosillo and Moral, 2015).

The Western Jianghan Plain (WJHP) is a semi-closed basin in the middle reaches of the Yangtze River. It is the major farming area of Hubei Province in central China, where groundwater is a vital source for municipal supply and other activities (Zhou et al., 2013). Previous publications concerning the groundwater quality in the Jianghan Plain have concentrated on one specific contaminant or group of contaminants, such as arsenic (Schaefer et al., 2016), dissolved organic matter (Huang et al., 2015), and antibiotics (Yao et al., 2015). The lack of a comprehensive hydrogeochemical study in the WJHP has hindered the understanding of the long-term variations of groundwater chemistry and quality in the past decades, and how it has been affected by intense agriculture, groundwater withdrawal, and dam construction (Bozdağ, 2016). The Three Gorges Dam (TGD), the world's largest hydropower project, is located upstream of the WJHP and has caused worse-than-expected deterioration of water quality since its completion in 2003 (Stone, 2011). Groundwater in aquifers adjacent to the Yangtze River are inevitably affected by the operation of the TGD due to strong stream-aquifer interactions.

This study of the temporal variations of the hydrochemistry and groundwater quality in the WJHP relied on monitoring of 16 physicochemical parameters from 1992 to 2010 at 29 confined groundwater sampling sites followed by an ensuing analysis of the data with various statistical methods. The objectives of this study are to (1) characterize the spatial and temporal variations of groundwater quality in the WJHP; (2) assess the correlations among water-quality parameters to identify the origins and contamination sources of groundwater; and (3) identify the processes causing increases in pH, NO_3-N, and Cl^-, and the potential linkage between changes in regional pH and nitrogen concentrations and the operation of the TGD. This study contributes to the understanding of groundwater quality variations driven by human activities in the WJHP, which enhances China's capacity to take timely actions and effectively protect regional groundwater resources.

2. The study area

The Jianghan alluvial plain in central China was formed by the Yangtze River and its largest tributary the Han River. This work's study area is the western part of the Jianghan Plain (WJHP), which encompasses a total area of about 18,660 km^2 and lies between 29°25′–31°15′ N latitude and 111°30′–114°05′ E longitude, ranging from 70 km to 565 km downstream from the Three Gorges Dam along the Yangtze River (Fig. 1). The Yichang and Hankou sites are two key water quality monitoring stations in the middle reaches of the Yangtze River, shown in Fig. 1. The Yangtze River has an average annual flow of 900 km^3, the fifth largest in the world (Loáiciga, 1997). The study area exhibits a subtropical monsoon climate, with mild temperature (average annual temperature equals 17 °C) and plentiful precipitation (average annual equals 1214 mm). The terrain is very gently sloping, with rivers and lakes interweaving with each other and supplying plentiful groundwater recharge. The aquifer system has a vadose zone, a phreatic aquifer, a confining bed, and a confined aquifer. The confined groundwater is the main focus of this study. Located mostly in the plain's Holocene series (Q4), the groundwater is slow moving given the very small regional topographic slope. The Yangtze River flows through this area, whose thalweg is lower than the upper confining for most of the reach downstream from the TGD (Fig. 2, Zhao, 2005). Thus, the confined groundwater is hydraulically connected to the Yangtze River in the WJHP. This creates an unobstructed pathway for the exchange of chemical constituents between the river and the aquifer system.

Coal mining and washing, paper making, textile and dyeing, and chemical industries are traditional competitive industries in the WJHP (Zhu and Chen, 2010). Despite the improved wastewater treatment achieved in recent years, only 30–55% of the discharged industrial sewage in the WJHP during 1990s met China's Integrated Wastewater Discharge Standards. The untreated and sub-standard industrial/domestic wastewater infiltrates into the groundwater system. Additionally, groundwater, the main source of local drinking and industrial water supply, was extracted at a rate of about 1.5×10^8 m^3/yr during the past decades. Several groundwater depression cones have formed in concentrated exploitation areas in Zhijiang, Jingzhou, Shashi, Jingmen, Tianmen, and Xiantao. The groundwater level contours in Jingzhou city in 2006 distinctly illustrate the two groundwater depression cones (Fig. 3). Groundwater depression cones are broader and deeper in the summer (wet) season than that in winter (dry) season given that the textile and pesticide factories in Jingzhou City exploit groundwater for cooling primarily.

3. Material and methods

Groundwater quality monitoring was initiated in the WJHP in 1990. Water samples were collected twice in the year, namely, in December and July which are months in the dry season and wet seasons, respectively (Deng et al., 2014). Groundwater quality data of 16 parameters at 29 confined monitoring wells during 1992–2010 were obtained from the Geological Environmental Center of Hubei Province (wells are shown in Fig. 1). These 29 groundwater quality monitoring wells had water quality data spanning at least 15 years, which is considered suitable for distinguishing long-term changes due to anthropogenic impacts from natural fluctuations on a decadal scale (Knutsson, 1994). Monthly pH values measured at the Yichang station during 1998–2010, the outlet of the Three Gorges Reservoir (TGR), were obtained from the Yangtze River Water Resources Commission. Data on the annual crop yields and fertilizer use of the 15 involved counties (see Fig. 1) from 1992 to 2010 were extracted from the Hubei Rural Statistical Yearbooks published during 1993–2011, whose total represents the annual crop yields and fertilizer use of the WJHP. Data on the total discharge and the standard discharge rate of industrial wastewater are only available for 10 counties (Dangyang, Zhijiang, Songzi, Jingzhou, Shashi, Jiangling, Gongan, Shishou, Jianli, Honghu) in the southwest of