Journal of Contaminant Hydrology 179 (2015) 132–147

Contents lists available at ScienceDirect

Journal of Contaminant Hydrology

journal homepage: www.elsevier.com/locate/jconhyd

Effect of groundwater quality on sustainability of groundwater resource: A case study in the North China Plain

Ming Wu [a], Jianfeng Wu [a,*], Jie Liu [b], Jichun Wu [a], Chunmiao Zheng [b]

[a] Key Laboratory of Surficial Geochemistry, Ministry of Education, Department of Hydrosciences, School of Earth Sciences and Engineering, Nanjing University, Nanjing 210023, China

[b] Center for Water Research, College of Engineering, Peking University, Beijing 100871, China

ARTICLE INFO

Article history:
Received 26 December 2014
Received in revised form 28 April 2015
Accepted 1 June 2015
Available online 6 June 2015

Keywords:
North China Plain (NCP)
Exploitation intensity
Nitrogen transformation
Reactive transport model
Simulation-optimization model
Sustainability

ABSTRACT

The North China Plain (NCP) is one of the most severe water shortage areas in China. Due to the scarcity of surface water in the NCP, groundwater system is seriously over-exploited and use of nitrogen fertilizers is greatly increasing year by year to improve soil fertility and crop production, causing a variety of environmental issues in the processes of abstracting groundwater. Considering that previous research was limited on approaches to assess sustainability of groundwater through flow modeling and water level decline, this study focuses on addressing the implications of groundwater contaminant for water resource sustainability in the central part of NCP. Based on the previously developed groundwater flow model, a reaction modular code for the reactive transport in three-dimensional aquifers (RT3D) is developed for simulating the reactive process of nitrogen species transport in groundwater system. The management optimization model coupled with the nitrogen reactive transport model under consideration of water quality constraints is then conducted to quantify and improve the sustainability of groundwater utilization in the study area. Thus, the optimal pumping well locations and pumping rates that lead to the maximum total yield or the minimum total management costs subjecting to a series of groundwater level constraints are obtained from the optimization models. Compared with the optimization model without water quality constraints, this study could provide a more useful tool for developing cost-effective strategies for sustainable management of groundwater resource in the NCP, and greatly improve groundwater management level and water quality.

1. Introduction

The North China Plain (NCP), with an area of 350,000 km^2, is a growing region of industrial production and one of the most important centers of agricultural production in China. Further, the NCP is the home to more than 200 million people, and is the seat of the nation's capital (Fig. 1) (Kendy et al., 2003a; Liu et al., 2001; Wang et al., 2008). Actually, due to the economic and political importance, the commonly used NCP is the narrower region which ranges from Yan Mountain to Yellow River in the north–south direction, from Bohai Gulf to Taihang Mountain in the east–west direction (Liu et al., 2008). The overall topography of the area is quite flat, and the thick alluvial deposits are very fertile, which are good for the development of farming. The average annual rainfall is about 500–800 mm (Kendy et al., 2003b), a majority of which comes in summer. In this climate, per capita renewable water resources only account for 335 m^3 (Liu et al., 2008), approximately one third of the threshold value (1000 m^3 per capita) adopted in the widely used Falkenmark indicator or “water stress index” (Falkenmark et al., 1989). Totally crop annual evapotranspiration is about 800–900 mm, which greatly exceeds the annual rainfall. Moreover, the majority of NCP's population relies on groundwater for drinking, agricultural and industrial requirements

* Corresponding author. Tel.: +86 25 89680853.
E-mail addresses: jfwu@nju.edu.cn, jfwu.nju@gmail.com (J. Wu).

http://dx.doi.org/10.1016/j.jconhyd.2015.06.001
0169-7722/

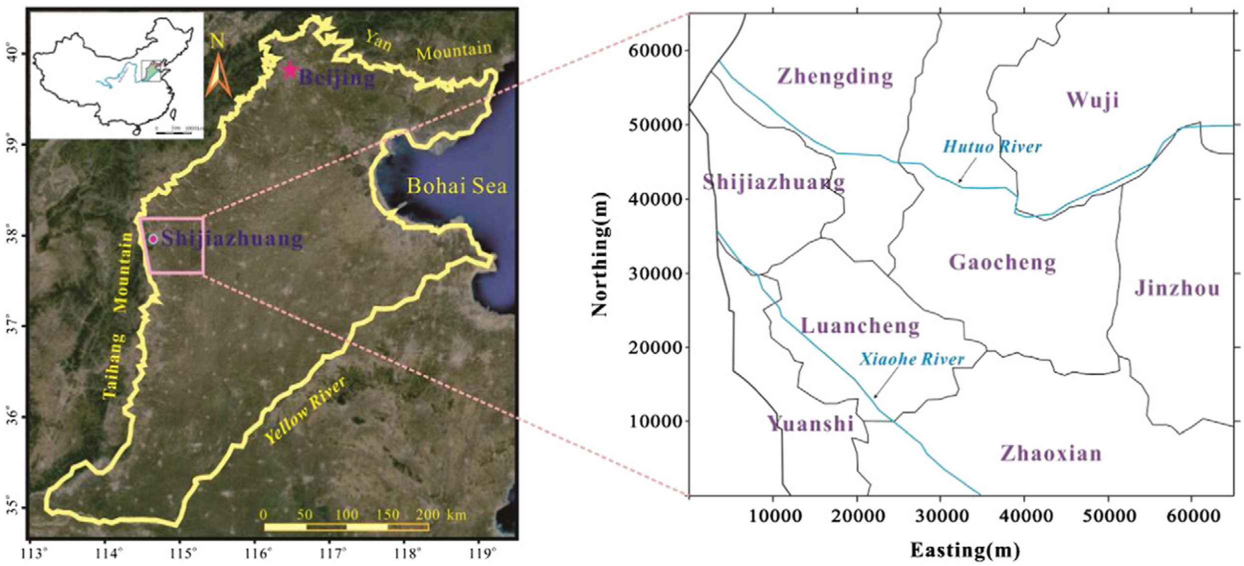

Fig. 1. Location of North China Plain and this study area.

because of lack of surface water resources (Guo et al., 2004; Hu et al., 2010).

As one of China's most important social, economic, and agricultural regions, both population and economic activities have grown markedly in the past years. With the increasing pressures in population and food demand, use of nitrogen fertilizer continues to rise rapidly. Use of nitrogen fertilizer for a long time in the NCP has markedly led to the agricultural growth in the past few decades, while much of this development was heavily dependent upon high rates of nitrogen fertilization (Li et al., 2011; Liu et al., 2013; Ma et al., 2012; Sutton and Bleeker, 2013; Xu et al., 2011). From 1961 to 2004, global crop yield per unit area increased by a factor of 2.3 (Cao et al., 2013), but the consumption of nitrogen fertilizer has reached 450–600 kg/ha, which was much greater than that needed nitrogen for the crop growth in the area. Since the 1970s, use of fertilizer has continued to increase substantially in the NCP. For example, in 1970, the average use of fertilizer is only 14.6 g per kilogram of crop yield, but after entering the 1980s, use of fertilizer has increased sharply, achieving up to 56.1 g in 1985 and 80.6 g in 1995 per kilogram of crop yield, respectively (Li et al., 2011; Ma et al., 2012; Xu et al., 2011).

For the large quantities of nitrogen fertilization, less than half of them applied in agriculture were taken up by crops, and the rest largely entered the environment in soil and groundwater, which just has resulted in serious nitrogen contamination for ecosystems, especially for those dependent on the groundwater environment (Ernesto et al., 2014; Gao et al., 2014; Li et al., 2011; Liu et al., 2013; Ma et al., 2012; Sutton and Bleeker, 2013; Xu et al., 2011). In spite of the great increase of land productivity, the growing nitrogen fertilization is destroying the environment and threatening human health (Ernesto et al., 2014; Gao et al., 2014; Liu et al., 2013; Sutton and Bleeker, 2013). Recent years have observed a growing concern for nitrogen contamination in the environments, especially in soil–groundwater systems (Ernesto et al., 2014; Gao et al., 2014; Velthof et al., 2014). A high price has been paid for nitrogen contamination mostly induced by agricultural fertilization. When ammonium is oxidized to nitrate, which is known to cause cancer and methaemoglobinemia syndrome (Bosch et al., 1950; Dorsch et al., 1984; Li et al., 2010; NAS, 1978; Shuval and Gruener, 1977; White, 1983), serious ecosystem and environment problems will happen inevitably, such as eutrophication of rivers, deterioration of water sources and reduction of biodiversity. According to the recent studies (Liu et al., 2013; Sutton and Bleeker, 2013; Hietz et al., 2011), deposition of reactive nitrogen (N) from human activities can lead to soil acidification and alter availability of nutrients. For the past few years, nitrogen contamination has become a major environmental problem, leading to the negative impacts on most parts of the NCP, even whole China (Li et al., 2011; Liu et al., 2013; Ma et al., 2012; Sutton and Bleeker, 2013; Xu et al., 2011). From another point of view, social development relies heavily on groundwater in arid and semi-arid areas, for this reason, the exploitation intensity in the NCP is always higher than average level of irrigation (MWRC, 2001; Kendy et al., 2003b). Due to serious nitrogen contamination and high groundwater exploitation intensity, the NCP has become one of the most severe water shortage areas in China. Water shortages and environmental deterioration have become the common reasons that limit economic development.

How long such a resource can last under current rate of utilization? What can be done to slow down the depletion of groundwater resource, or even better, to make its use sustainable? What measures can be taken to protect groundwater from the contamination of nitrogen? High crop water-use and application of nitrogen fertilizer negatively would impact groundwater and the environment, while unreasonable reductions in crop water-use could adversely affect agricultural production (Hu et al., 2010; Zhang et al., 2012). Therefore it is urgently needed to evaluate nitrogen species reactive transportation process and optimize the groundwater utilization