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Driving mechanism and sources of groundwater nitrate contamination in the rapidly urbanized region of south China

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ABSTRACT

Nitrate contamination of groundwater has become an environmental problem of widespread concern in China. We collected 899 groundwater samples from a rapidly urbanized area, in order to identify the main sources and driving mechanisms of groundwater nitrate contamination. The results showed that the land use has a significant effect on groundwater nitrate concentration ($P < 0.001$). Landfill leakage was an important source of nitrate in groundwater in the PRD (Pearl River Delta) region, since landfill yielded the highest nitrate concentration (38.14 mg/L) and the highest ratio of exceeded standard (42.50%). In this study, the driving mechanism of groundwater nitrate contamination was determined to be urban construction and the secondary and tertiary industrial development, and population growth. This study revealed that domestic wastewater and industrial wastewater were the main sources of groundwater nitrate pollution. Therefore, the priority method for relieving groundwater nitrate contamination is to control the random discharge of domestic and industrial wastewater in regions undergoing rapid urbanization.
Capsule abstract.
The main driving mechanism of groundwater nitrate contamination was determined to be urban construction and the secondary and tertiary industrial development, and population growth.

1. Introduction

Nitrate (NO_3^-) is a primary contributor to groundwater pollution, due to its stability, high solubility and mobility. Nowadays, NO_3^- contamination in groundwater has become a widely concerned environmental problem (Xue et al., 2009). Several studies have shown that increased levels of NO_3^- in groundwater are primarily caused by anthropogenic activities such as the overuse of nitrogen fertilizers and animal manures, the discharge of domestic and industrial sewage, and the elevated atmospheric N deposition (Dubrovsky et al., 2010; Gu et al., 2012; Kaushal et al., 2011; Xue et al., 2009).

Groundwater NO_3^- contamination is a threat to human health (Gu et al., 2013). Drinking water containing elevated levels of nitrate has been associated with the risk of methemoglobinemia or 'blue baby syndrome' (Fan and Steinberg, 1996; Pastén-Zapata et al., 2014) and cancer through the formation of carcinogenic N-nitroso compounds (Weyer et al., 2001). In addition, the export of nitrate into surface water may lead to many ecological and environmental problems, including eutrophication and seasonal hypoxia (Li et al., 2010; Li et al., 2013). As a result of these issues, the World Health Organization (WHO) has set an upper limit of 50 mg/L for drinking water (WHO, 2011).

Nitrate concentrations above the WHO's maximum contamination level are relatively common in some regions, especially in the emerging developing countries (Burow et al., 2010; Gu et al., 2013). In China, the occurrence of serious groundwater nitrate pollution has accompanied the fast socioeconomic development in the country (Fu et al., 2007). According to the Ministry of Land and Resources, 90% of China's shallow groundwater is polluted, and nitrate being one of the main pollutants (Qiu, 2011).

The key step to effectively control nitrate pollution is to identify the factors affecting groundwater nitrate contamination.

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Several studies have examined nitrate contamination resulting from different agricultural practices and hydrogeological settings (Güler et al., 2012; Landon et al., 2011; Stigter et al., 2008). Lockhart et al. (2013) described the distribution of nitrate resulting from different land uses. Rankinen et al. (2008) evaluated the leaching of nitrate into shallow groundwater from a variety of agricultural fields under different cultivating practices. Researchers also found that the manure management (Lord et al., 2002), reduction–oxidation conditions (Landon et al., 2011), soil texture (Wick et al., 2012), atmospheric temperature (Wick et al., 2012), and precipitation surpluses (Salo and Turtola, 2006) influence the concentration of nitrate leached into groundwater. However, we do not fully understand the relation between groundwater nitrate concentration elevation and the rapid urbanization and economic development (Gu et al., 2013), which lead to a serious impact on management of groundwater nitrate pollution.

One major region of China that has recently seen accelerated urbanization is the Pearl River Delta (PRD), which is situated in the southern part of Guangdong Province. Economic growth and urbanization have accelerated in the last two decades around the Pearl River Delta, as a result of the drastic economic reform initiated in the early 1980s (Mai et al., 2002). The water supply of this region relies almost entirely on surface water due to abundant rainfall and the well-developed river network. However, rapid population and economic growth have led to deterioration of the quality of surface water through pollution and declining river discharge (Cheung et al., 2003). Therefore, surface water alone can no longer meet the needs of the region, and people are looking to groundwater as an alternative supply. With the increasing exploitation of the groundwater in the PRD, it has been found to be contaminated with total dissolved solids (TDS) of over 10 g/L, seawater intrusion, As contamination, etc. (Huang et al., 2013; Wang et al., 2012). However, the study of groundwater nitrate pollution in this region has not been reported.

This study expands on previous work using a large area and sample size across wider land uses. The main aims of this study are 1) to analyze the relationship between the groundwater nitrate levels and socioeconomic development parameters by using regressions analysis (RA), 2) to identify the main driving mechanism of groundwater nitrate contamination in a rapidly urbanized area by using principal component analysis (PCA), and 3) to identify the most likely sources of nitrate by using water chemistry theory.

2. Materials and methods

2.1. Description of study area

2.1.1. Geographical conditions

The PRD covers an area of 41,600 km^2 in south China, extending between longitudes of 111°59′42″–115°25′18″E and latitudes of 21°17′36″–23°55′54″N, and as of 2008 had a permanent population of over 47 million. The study area includes 9 major cities: Guangzhou, Shenzhen, Dongguan, Zhongshan, Foshan, Huizhou, Zhaoqing, Jiangmen and Zhuhai (Wong et al., 2002). The area experiences humid subtropical weather with an annual average temperature and rainfall of 22 °C and 1690 mm, respectively. The mild climate facilitates agriculture, allowing an annual production of 10–15 crops of vegetables and three crops of grains.

2.1.2. Hydrogeological setting

The PRD is largely covered with Quaternary sediments, and has an elevation ranging from 6 to 9 m above sea level in the north to 1–2 m near the coast (Wang et al., 2012). The basement rocks include shale, sandstone, limestone, dolomite, granite, and gneiss ranging in age from Cambrian to Tertiary. The types of groundwater include loose stratum pore water, bedrock fissure water and carbonate karst cave water. Hydrochemical dominant types of groundwater are HCO_3–Ca–Na, HCO_3–Cl–Ca–Na, HCO_3–Ca, Cl–Na and Cl–HCO_3–Na–Ca (Supplemental Fig. 1). Groundwater is mainly recharged by vertical infiltration from precipitation and agricultural irrigation, as well as by the lateral flow from rivers and floods during the wet season. Aquifers in this area are associated to fractures, with spring flowrate range from 4.32 m^3/day to 86.4 m^3/day. In most wells of this area, flowrate can reach 1000 m^3/day. In addition, at high tide, salt water from the sea penetrates as a wedge underneath the freshwater of the river, which is the reason for the seawater intrusion in this area (Huang et al., 2013). The general direction of groundwater flow in the aquitard and aquifer follows roughly the major river flow, which is from northeast to the coast (GHST, 1981).

2.1.3. Land use

Since the reforms and opening-up policy of China, land use has been changing in the PRD region for decades. For instance, the previously plentiful cultivated lands, fish ponds, gardens and woodland in the study area have been urbanized and industrialized. Nowadays, land use in the PRD is complex, where nearly half of the land (49.61%) is devoted to forest and orchard (Table 1). The majority of the remaining area can be classified as cropland (21.17%), paddy fields (17.07%), urban area (6.11%), river (4.13%), and wasteland and aquaculture (1.91%).

In this study, the land use was reclassified into six categories according to the well surrounding environment:

- Cropland: Soybean, sugar cane, peanut, cassava, tea, vegetables, etc.
- Paddy field: Rice, lotus root, etc.
- Urban: Urban, residential areas, river, industrial areas
- Forest and orchard: Tea seed, Pine tree, Banyan tree, palm trees, banana, citrus, pineapple, litchi, etc.
- Landfill: Domestic waste and construction waste sites
- Wasteland and aquaculture: Wasteland, fish pond, other aquaculture sites

2.2. Socioeconomic data

In this study, the socioeconomic data (for 2008) for the nine metropolitan areas of the PRD region were cited from Guangdong Statistical Yearbook 2009 (GPBS, 2009). Data for these urban areas, including permanent populations (PP), population density (PD), urbanization, total volume of waste water discharged (TWD), the volume of living waste water discharged (LWD), the volume of industrial waste water discharged (IWD), gross domestic product (GDP), primary industry (farming, forestry, animal husbandry, aquaculture, etc.) GDP (PIGDP), secondary industry (processing industry)