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Impacts of urban land use on the spatial distribution of groundwater pollution, Harbin City, Northeast China

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ABSTRACT

Groundwater is the major available water resources in Harbin City, China, but rapid urbanization has adversely affected it in recent years and groundwater quality is deteriorating. In this study, the groundwater pollution indexes of groundwater monitoring wells were analyzed by using the projection pursuit dynamic clustering model and its spatial distribution was interpolated by using the modified local polynomial interpolation method. The “searchlight” shape model was used to extract the types of land use within the scope of each monitoring well in order to evaluate the relationship between the spatial distribution of groundwater pollution and land use. The correlation between the groundwater pollution indexes and land use was evaluated using Kendall's tau-b analysis. The groundwater pollution index is generally high. It has obvious spatial distribution characteristics and it mainly occurs in DaoW-NanG district and the eastern part of DongL-XiangF district. The results of Kendall's tau-b analysis show that the groundwater pollution indexes have a good correlation with land use. Residential and commercial areas, industrial area and agricultural area greatly influence the distribution of groundwater pollution. Moreover, the main impact indicators of groundwater pollution in the study area are NH_4^+, NO_3^- and $CaCO_3$.

1. Introduction

According to the United Nations (Bongaarts, 2014), urban population accounted for 54% of the world's total population in 2014. With the rapid spread of urbanization in the world, the issue of urban water supply has become the focus of attention (Parkinson and Tayler, 2003; Navarro and Carbonell, 2007). A continuous good quality water supply is a key factor in providing a good quality of life to urban dwellers and is also important for environmental sustainability and economic growth in urban centers, especially in most arid and semi-arid areas where groundwater is the major available water resource (Bailey et al., 2015).

Urbanization plays a very important role in the change of groundwater solute composition. New urban landscape may change the original surface conditions and thus the groundwater circulation system which affected the dilution and transport of groundwater to solute (Barron et al., 2013). Moreover, urbanization also adds new sources of pollution, which may penetrate into aquifers and then pollute the groundwater, thereby seriously limiting the development of a city (Rezvani et al., 2013; Zhang et al., 2015). Some studies have shown that in Shanghai of China and Baltimore of the United States, increased levels of nitrate 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 (Xue et al., 2009; Kaushal et al., 2011; Gu et al., 2012). At the same time, Punjab in Pakistan and Kharkiv city in the Eastern Ukraine are influenced by urban industrialization, sulfate, chloride and fluoride are obviously enriched in the shallow urban aquifer, seriously polluting groundwater which is widely used as drinking water source for the urban population (Farooqi et al., 2009; Vystavna et al., 2017). Therefore, the impact of urban land use on groundwater pollution has become a key issue of urban land use planning and urban water resource management and protection (Reddy et al., 2012; Chisala et al., 2007).

At present, many research projects have examined the relationship among specific land use patterns, corresponding pollutant emissions, and resultant groundwater quality (Kellner and Hubbart, 2016; Español et al., 2016; Koh et al., 2017). The selection of groundwater quality assessment methods is the primary problem (Sarukkalige, 2011). Traditional methods, such as the comprehensive pollution index method and the Nemero index method, can be calculated easily but ignore the

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weight factor (Zhang et al., 2000). Gray clustering and analytic hierarchy process can reflect uncertain characteristics but present a great subjectivity in determining the index (Yu et al., 2008). In recent years, the projection pursuit dynamic clustering (PPDC) has been widely used in water quality assessment because of its automatic classification and simple and intuitive results. It combines dynamic cluster rule with projection pursuit principle to modify the problem of parameters and projection index of the original projection pursuit clustering (PPC) model (Friedman and Tukey, 2006; Wang and Ni, 2008), and takes into account the numerical distribution characteristics of various water quality grades for various factors in groundwater quality standards. The optimal projection direction vector is obtained by the PPDC optimization, and the size of its components is determined by the characteristics of high-order data structure, which reflects the sensitivity of the groundwater environment to the change of the single index of each pollution factor (Wei et al., 2014). Although this method has been widely used in the field of water science such as regional water resources zoning (Wang and Ni, 2008), surface water quality (Zhao et al., 2012) and risk assessment (Zhao et al., 2014), it has not been applied in the study of groundwater quality assessment.

The effect of urbanization on water quality is a concern in Harbin City, the capital of Heilongjiang Province, China (Cai and Shang, 2009; Gong et al., 2015), which is the old industrial base of the typical heavy industry in the northeast city. In recent years, the rapid development of economy in Harbin City has increased the demand for water resources, thereby increasing groundwater production (Li et al., 2013). With the rapid economic development, the quantity and quality of the groundwater have been greatly affected by factories, waste landfills, groundwater exploitation, and other factors, which has seriously threatened the safety of groundwater supply (Zhang et al., 2008; Deng et al., 2011). Therefore, the more accurate description of the spatial distribution of groundwater pollution in urban and the analysis of the relationship between specific land use type and groundwater quality are essential for maintaining a suitable water supply for the city and achieving the sustainability of groundwater resources (Brink et al., 2008; Janniche et al., 2012).

The objectives of the paper are: (1) to establish the groundwater pollution index model by using the projection pursuit dynamic clustering (PPDC) model; (2) to determine the spatial distribution of groundwater pollution; (3) to evaluate the relationship between land use and groundwater pollution.

2. Study area

Harbin City is located in the southeast of Songnen Plain which is the largest political, economic and cultural center in the north of northeast China. Topographically, it is very high in the southeast, slightly higher in the south, west and northwest, lower in the middle and the east, with an elevation of 114–638 m (Li et al., 2013). This area presents a temperate continental monsoon climate with semi-humid and semi-arid characteristics. The average annual precipitation and evaporation are 503.2 mm and 1411.19 mm, respectively. The temperature is high in summer, cold in winter, and there is a large difference in temperature during the year. The average annual temperature is 3.4 °C (Deng et al., 2011). The main rivers in the area are the Songhua River, Ash River and Majiagou River, The Songhua River is the largest river system, as a firstorder stream, whereas the two remaining rivers are secondorder streams (Gong et al., 2015).

The study area is located in the urban area of Harbin City, covers an area of 592.72 km^2, and is situated at a latitude between 45° 38′ 17″ and 45° 51′ 50″ and a longitude between 126° 28′ 16″ and 126° 50′ 10″, occupying 27.18% of the total area of Harbin City. The study area is divided into four districts including SongBei district, DaoLi district, DaoW-NanG district, and DongL-XiangF district (Fig. 1). There are three types of confined aquifers in the high plain, confined aquifers in the first order terrace and aquifers in the floodplain in the area, of which the latter two types of aquifers are the main exploitation layers of groundwater in the city. The aquifers are alluvial sand, medium coarse sand and gravel layers of modern rivers, which contain large amounts of mud (Fig. 2) (Li et al., 2013). The groundwater recharge in the area mainly comes from underground runoff and atmospheric precipitation, agricultural irrigation water, domestic sewage, and industrial wastewater infiltration (Gong et al., 2015).

3. Materials and methods

3.1. Data collection

To reflect the impacts of land use on groundwater pollution accurately and comprehensively, the uniform distribution of sampling points was used as the main principle by considering the actual distribution of aquifers and the topography of geomorphology. Thus, a total 77 groundwater wells, with depths of 5.0–30.0 m, were monitored and sampled from July to August 2015 in the urban area of Harbin City (Fig. 1), including 48 wells of the Quaternary phreatic aquifer, 29 wells of the Quaternary confined aquifer, and 25 specialized monitoring wells, 52 civilian wells. The collected samples were tested in the Geology and Hydrogeology Environmental Laboratory Investigation Institute of Heilongjiang Province.

The results of water samples testing showed that nitrogen, salts and fluoride have a higher exceeding standard ratio, so eight indicators, such as sulfate, chloride, nitrate, nitrite, ammonia nitrogen, fluoride, total hardness, total dissolved solids, were selected as representative factors to reflect the water quality. These indicators can objectively reflect the situation of water pollution.

The urban land use data of Harbin City were provided by the Provincial Bureau of Surveying and Google Earth Mapping. The urban areas are divided into residential and commercial areas, industrial area, public facilities area, urban infrastructure facilities area, agricultural area, transportation facilities area, grass land and managed green areas, and water surface (Fig. 3). Table 1 shows the land use areas and their relative proportions.

3.2. Projection pursuit dynamic clustering

Projection pursuit, a statistical method, was developed to analyze high-dimensional data based on projection (Hall, 1989; Pires and Ribeiro, 2017). This paper describes an issue of linear projection. High-dimensional data are projected onto one-dimensional space and their characteristics are analyzed through the one-dimensional space (Ni et al., 2006; Zhao et al., 2014).

If *x0 ij* ($i = 1, \cdots, n$; $j = 1, \cdots, m$; n is the total number of samples; m is the number of cluster factors of the samples) is the initial value of the jth factor of the ith sample, the steps of developing the PPDC model are described as follows.

1) Data standardization

In order to eliminate the effect of different dimension and value range, the initial sample will be standardized. The standardization equation is

$$x_{ij} = \frac{x_{ij}^{0} - x_{jmin}^{0}}{x_{jmax}^{0} - x_{jmin}^{0}} \tag{1}$$

where ${x_{jmax}}^{0}$ is the initial maximum of the jth factor and ${x_{jmin}}^{0}$ is the initial minimum of the jth factor.

2) *Linear projection*

Linear projection is used to study the projection of high-dimensional data into one-dimensional linear space. If $\vec{a} = (a_1, a_2, \cdots, a_j, \cdots, a_m)^T$ is