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Development and application of a novel method for regional assessment of groundwater contamination risk in the Songhua River Basin

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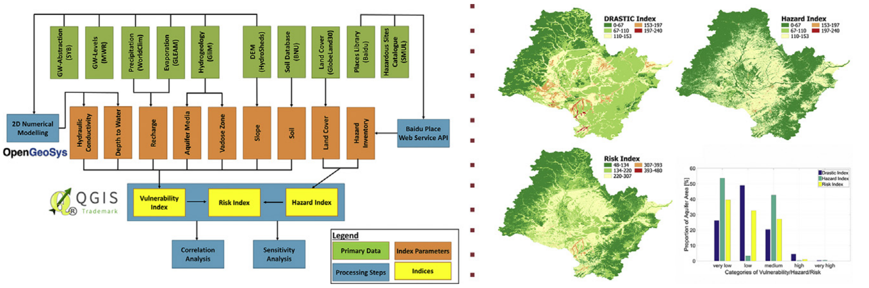
HIGHLIGHTS

- Integrate numerical modelling, public datasets and web mapping services into a groundwater risk assessment framework
- Evaluate various types of hazards from point and diffusive sources in a unified form
- Assess groundwater risk by index-overlay of groundwater vulnerability and hazard
- Generate maps for groundwater risk maps for the entire Songhua River Basin

GRAPHICAL ABSTRACT



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ABSTRACT

The main objective of this study is to quantify the groundwater contamination risk of Songhua River Basin by applying a novel approach of integrating public datasets, web services and numerical modelling techniques. To our knowledge, this study is the first to establish groundwater risk maps for the entire Songhua River Basin, one of the largest and most contamination-endangered river basins in China.

Index-based groundwater risk maps were created with GIS tools at a spatial resolution of 30 arc sec by combining the results of groundwater vulnerability and hazard assessment. Groundwater vulnerability was evaluated using the DRASTIC index method based on public datasets at the highest available resolution in combination with numerical groundwater modelling. As a novel approach to overcome data scarcity at large scales, a web mapping service based data query was applied to obtain an inventory for potential hazardous sites within the basin.

The groundwater risk assessment demonstrated that < 1% of Songhua River Basin is at high or very high contamination risk. These areas were mainly located in the vast plain areas with hotspots particularly in the Changchun metropolitan area. Moreover, groundwater levels and pollution point sources were found to play a significantly larger impact in assessing these areas than originally assumed by the index scheme. Moderate contamination risk was assigned to 27% of the aquifers, predominantly associated with less densely populated agricultural areas. However, the majority of aquifer area in the sparsely populated mountain ranges displayed low groundwater contamination risk.

Sensitivity analysis demonstrated that this novel method is valid for regional assessments of groundwater contamination risk. Despite limitations in resolution and input data consistency, the obtained groundwater contamination

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risk maps will be beneficial for regional and local decision-making processes with regard to groundwater protection measures, particularly if other data availability is limited.

1. Introduction

Since the 1950s, major advances in drilling technology and hydrogeological knowledge had facilitated a massive expansion in groundwater use across the developing world in order to satisfy the needs of irrigation, domestic purposes and industrial demand (Foster and Chilton, 2003). In China alone, >500 large cities rely on groundwater resource for their drinking water supply (Van der Gun, 2012). These excessive exploitation and inappropriate activities at the land surface lead to and foster degradation of groundwater resources in many areas (Jiang, 2009). Moreover, remediation of contaminated aquifers is cost intensive and time consuming and may not reach remedial objectives due to large storage, physical inaccessibility and retardation of contaminants (Travis and Doty, 1990). In this context, groundwater contamination risk assessment provides a useful tool to design and implement groundwater protection measures to prevent or reduce groundwater contamination (Zaporozec et al., 2002).

In a risk assessment, where risk is defined as hazard plus vulnerability, the combined rating of the potential harmfulness posed by a pollution source (hazard assessment) and the possibility of the spreading into and within the groundwater (vulnerability assessment) could be interpreted as the probability for groundwater contamination, both in quantitative or qualitative terms depending on the used method (Johansson, 1999; Varnes, 1984). Regarding the groundwater vulnerability assessment, existing methods are classified into three categories: Index methods, statistical methods (Erwin and Tesoriero, 1997; Li et al., 2015) and process-based methods (Sinkevich et al., 2005; Milnes, 2011). An overview about available methods is given by Zaporozec et al. (2002). Index methods, such as DRASTIC (Aller et al., 1987) or GOD (Foster, 1987), which focus on the key factors controlling the solute transport processes, are the most commonly used procedures for vulnerability mapping. They are relatively inexpensive, straightforward, adaptable on site-specific conditions (e.g. Guo et al., 2007; Lin et al., 2016), have a minimum demand of data and produce an end product embeddable into decision-making processes (Focazio et al., 2002). In consequence, index based methods such as DRASTIC were applied to evaluate groundwater vulnerability for basins with very diverse conditions in many regions of the world such as Europe (e.g. Albuquerque et al., 2013; Panagopoulos et al., 2006), the Middle East (e.g. Jamrah et al., 2008; Awawdeh and Jaradat, 2010), Nepal (Shrestha et al., 2017) and China (e.g. Huan et al., 2012; Wang et al., 2012; Ye et al., 2015).

However, the potential of standardized index methods based on a few key factors to predict groundwater vulnerability is questioned among researchers (Rupert, 2001). Gogu and Dassargues (2000) therefore emphasized the need to integrate process-based methods such as numerical models into widely used index methods to take into account the physical processes of water movement and the associated fate and transport of contaminants in the environment. There have been a very limited number of studies to quantify intrinsic vulnerability by including numerical modelling (Yu et al., 2010; Sophocleous and Ma, 1998; Connell and Van Den Daele, 2003). Process based methods need extensive field data, both for model setup and model calibration (Butscher and Huggenberger, 2008). Especially for the assessment of larger catchments, such data and information are scarce and unequally distributed (Ireson et al., 2006; Wu et al., 2011). Furthermore, a considerable amount of computational power is required to simulate process-based methods at larger scales, particularly if chemical and biological processes and unsaturated zone mechanisms are included in the simulation (Anane et al., 2013).

For a detailed assessment of potential hazards, information about the pollution sources and the characteristic of the pollutants should be taken under investigation. The difficulties in obtaining this specific data lead to the preference of an index based assessment system for hazards (Wang et al., 2012). An approach often applied for smaller catchments is to set up an inventory of potential hazard sources in combination with weighting and rating schemes (e.g. Kuisi et al., 2014; Aliewi and Al-Khatib, 2015). Alternatively, several previous studies used grid based data such as land cover or land use as a proxy parameter for describing potential anthropogenic pollution hazard from diffusive and point sources (Bartzas et al., 2015). The obtained data is either included in a modified groundwater vulnerability assessment (Gomezdelcampo and Dickerson, 2008; Fritch et al., 2000) or in a separate index based hazard assessment (Panagopoulos et al., 2006; Saidi et al., 2009).

The present study is concerned with the assessment of groundwater vulnerability, groundwater hazard and the resulting groundwater risk for Songhua River Basin, a large scale catchment providing water resources for more than 62 million people in North-East China (Yuhong et al., 2010). Although Songhua River Basin was one of the earliest urbanized centers in China since the 1950s, a series of developmental strategies by the government calling for a “revitalization of the Northeast's old industrial base” brought in new economic development and promoted rapid urbanization (Zhang, 2008). However, urbanization and industrialization adversely affected the surrounding ecosystems and environment (Fu et al., 2016). One of the environmental issues of aquifers in the study area is an increased pollution of the aquifer system by Nitrate from fertilizer overuse (e.g. Zhang et al., 1996; Gu et al., 2013). As North-East China is the old industrial heartland of China, discharges and leakages from industrial sources and brownfields put an additional potential pressure on groundwater resources (Nixdorf et al., 2015). Hence, assessing the groundwater environmental risk in the region is very necessary.

In view of the aforementioned limitations, we chose a combined approach using public datasets and web services, remote sensing as well as numerical groundwater flow modelling to generate input data for an index method based assessment of aquifer vulnerability, hazard and risk. Particularly the embedding of both a simplified 2D groundwater flow model and web-query data in the index based assessment methods aims to improve dealing with aforementioned problems of scarce field data on larger scales.

In this context the main objectives of this study are: Firstly, to develop a methodology to combine web-query data from web mapping services, numerical groundwater modelling and public datasets into a GIS-based groundwater risk assessment framework, secondly to apply the method to provide maps of groundwater vulnerability, groundwater hazard potential and groundwater contamination in the entire Songhua River Basin at the highest resolution available and thirdly, to identify the importance and interrelation of input parameters and obtained maps using sensitivity analysis methods.

2. Study area description

The Songhua River Basin is located in the northeastern region of China (119°52′ –132°31′ E and 41°42′–51°38′ N) and covers an area of >550,000 km^2 (Fig. 1). Its water drains to Songhua River, which is with a length of >2300 km the largest tributary of Amur River. Songhua River main tributaries are Nen River, which drains the Northern part of the basin and Second Songhua River coming from Jilin province in the Southern part of the catchment. The basin covers vast areas of the three Chinese provinces Heilongjiang, Jilin and Inner Mongolia as well