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Risk assessment of groundwater pollution using Monte Carlo approach in an agricultural region: An example from Kerman Plain, Iran

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ABSTRACT

In groundwater resource management, the risk assessment of groundwater pollution is an effective tool in arid and semi-arid regions, such as Kerman Plain, Iran. In addition to risk assessment, and the mapping of damage and pollution probability occurrence is considered as a fundamental phase of protective groundwater management in agricultural regions. To characterize risk index affecting the study area, a novel approach was developed by combining both damage map which was obtained by multiplying seven hydrogeological parameters of modified DRASTIC model with pollution and probability of pollution occurrence with consideration of uncertainty. The study area is located in an agricultural land; therefore, nitrate was used as a pollution parameter. The spatial distribution of nitrate concentration in the area was investigated by ordinary kriging. In addition, Monte Carlo simulation (MCS) and normal distribution function were used to evaluate the uncertainty of this parameter and the probability of pollution occurrence in the study area. Risk assessment parameters were constructed, classified, and integrated in a GIS environment. Groundwater movement induces the transport of pollutants underground. Thus, we proposed a new methodology combining damage map and Monte Carlo simulation for probability and parameters uncertainty. The proposed method can be used to monitor pollution damage on a regional scale and ensure effective groundwater resource management for reducing the amount of pollution for future. Damage index and risk classification were compared; results indicate a high degree of similarity. The regions with low and very low risks are located in the northeast, northwest, and central parts, where further studies could be conducted for the subsequent development and long-term design of protective measures.

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1. Introduction

Water reservoirs underground are important water resources. Groundwater is used for different purposes, such as drinking, irrigation, and industrial processes (Nampak, Pradhan, & Manap, 2014; Neshat, Pradhan, Pirasteh, & Shafri, 2013). As a convenient substitute, groundwater also provides additional water supply to compensate for insufficient surface water resources. As such, groundwater should be protected from contamination by implementing effective water resource planning and management. Antonakos and Lambrakis (2007) further indicated that a map of aquifer vulnerability can be effectively used to perform water quality assessment and management, thereby protecting groundwater. DRASTIC model is one of the most commonly used methods to assess aquifer vulnerability. DRASTIC includes several factors, such as topography, vadose zone impact, groundwater depth, soil media, aquifer media, hydraulic conductivity, and net recharge (US EPA, 1985). In central Japan, a GIS-based DRASTIC model is used to assess aquifer vulnerability (Babiker, Mohamed, Hiyama, & Kato, 2005). Assaf and Saadeh (2009) also used a DRASTIC model to explore potential nitrate-N-polluted groundwater zones. They also compared a DRASTIC vulnerability index with groundwater nitrate distributions mapped by geostatistical approaches. To study the risks and vulnerability of agricultural potential nitrogen pollution, Leone, Ripa, Uricchio, Deák, and Vargay (2009) also adopted this DRASTIC model. In another study, a DRASTIC vulnerability map is combined with kriging variance to formulate a nitrate monitoring network (Baalousha, 2010). Geostatistical techniques, such as indicator kriging (IK) and ordinary kriging (OK), are commonly applied in various applications, including iso-concentration maps showing groundwater contaminants (Stigter, Ribeiro, & Dill, 2006) and iso-probability maps revealing the

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concentration of a specific contaminant exceeding a particular threshold (Assaf & Saadeh, 2009; Chen, Jang, & Peng, 2013; Hu et al., 2005; Pulido-Leboeuf, Ribeiro, Pulido-Bosch, & Calvache, 2002; Ribeiro & Paralta, 2002; Stigter, Almeida, Carvalho Dill, & Ribeiro, 2005).

The properties of aquifer soil and dimensional distributions of hydrogeological settings vary with locations. However, only a small volume of data can be analyzed in field surveys because of time and cost limitations (Chen et al., 2013). Results derived from such inadequate data may be inaccurate and uncertain (Jang, Chen, & Ching-Chieh, 2008).

Freeze and Cherry (1979, pp. 413–416) revealed that nitrate contaminating groundwater is produced at the surface of agricultural fields and occurs in natural recharging zones. Antonakos and Lambrakis (2007), Assaf and Saadeh (2009), and Baalousha (2010) indicated that the concentration of nitrate-N can be used to estimate the amount of pollutants in a DRASTIC model. Groundwater pollution is one of the major environmental threats caused by human activities, such as the use of fertilizers in agricultural land. Agricultural activities have been developed from traditional methods to modern applications, resulting in an overuse of chemical fertilizers that increase the amount of pollutants, particularly when farmers are unaware of the adverse effects of fertilizer use. Some fertilizers, including nitrate, pollute water at a greater extent than other fertilizers. The frequent use of fertilizers in the agricultural land of Kerman Plain induces an increase in nitrate-N pollution in groundwater (Neshat, Pradhan, & Dadras, 2014). WHO (2008) guideline indicated that the ingestion of >50 mg/l nitrate in potable water can harm human health. To alleviate the effects of pollution in water resources, researchers should identify and assess the extent of pollution by constructing a risk map.

Efficient preventive programs, including risk management, should be implemented to monitor the risks of groundwater pollution. In many countries, vulnerability maps are used to prevent groundwater pollution. Inherent and natural characteristics are considered in traditional methods of vulnerability mapping. Other researchers also applied risk map in their studies. For instance, Ducci, De Masi, and Delli Priscoli (2008) explained that risks not only include the inherent vulnerability of an aquifer called static factor but also consider human activities as important dynamic factors. To prevent the drawbacks encountered in previous studies focusing on risk mapping, researchers should consider pollution occurrence probability factor in risk maps. Pusatli, Camur, and Yazicigil (2009) surveyed the risk of aquifer pollution in Küçük River in the western part of Turkey by combining vulnerability index and quality index. The DRASTIC model is also used to examine hydrochemical conditions under hydrogeological conditions and determine water quality classification. Both maps were combined and the risk of pollution index was obtained. Dixon (2005) added soil structure to the list of DRASTIC index parameters. This DRASTIC model is combined with three different methods, namely, fuzzy, fuzzy-applicable for lands/pesticides and herbicides, and fuzzy–soil structure to obtain a risk map for each of these methods. Among these methods, the DRASTIC method with a fuzzy–soil structure is the most effective and provides reliable qualitative data. Dimitriou et al. (2008) used a COP method to determine the vulnerability of karst Aquifer near Athens. Therefore, a pollution map used for industrial applications in the study area was combined with a vulnerability map. Ducci et al. (2008) investigated Alburni Karst Aquifer, which is the most important karst area in south Italy, to assess groundwater pollution by analyzing the risk map of this area. Saidi, Bouri, Ben Dhia, and Anselme (2011) also characterized the degree of risk affecting Souassi aquifer in Tunisian Sahel by using a DRASTIC method to combine hydrogeological parameters; hazard is also assessed by calculating the product of weighted hazard value (HI), ranking factor (QN), and reduction factor (Rf). Wang, He, and Chen (2012) further evaluated a risk map by applying intrinsic vulnerability, groundwater value, and integrate hazards. Chica-Olmo, Luque-Espinar, Rodriguez-Galiano, Pardo-Igúzquiza, and Chica-Rivas (2014) used an indicator kriging method to spatially assess a categorical variable associated with the quality of nitrate-polluted groundwater; Chica-Olmo et al. (2014) also considered the nitrate threshold values of the European nitrate normative.

Monte Carlo and Latin square are commonly used in simulation studies in which probability is considered (Haan, 2002). In this study, groundwater vulnerability, pollution, and probability of pollution considering uncertainty were combined to design a risk map. The vulnerability map was derived from a modified DRASTIC model (Neshat et al., 2013) which gave the highest correlation between nitrate concentration and various modifications, was selected as the optimal vulnerability result. Also, nitrate samples collected on May 2012 was used to obtain nitrate concentrations in the Kerman plain to create a pollution parameter for risk assessment. Monte Carlo simulation (MCS) approach was applied as a novel method to analyze model uncertainty with output stochastic sample numbers to assess the probability of groundwater pollution occurrence using SimLab software. The probability density function of each cell was then obtained from the achieved outputs. Results showed that this groundwater pollution occurrence probability map can be extracted by defining a degree of probability with a substantial level of damage. Groundwater pollution risk map was constructed to show possible damages but were not observed in groundwater. An occurrence probability map could also be designed to help extract a groundwater pollution risk map. Probability estimation provides a good perception of establishing the uncertainty level because of field data limitation. However, studies have not yet analyzed and characterized parameter uncertainty and parameter distributions of hydrogeological parameters because of damage and probability in any investigations based on DRASTIC model and Monte Carlo simulation.

2. Materials and methods

2.1. Description of study area

The study area is located in the Kerman Plain (Fig. 1), where arid and semi-arid regions are found in the southeast of Iran and cover an area of 978 km^2. The Kerman plain is saturated and unconfined aquifer and the average thickness of aquifer is about 80 m. This area is located at an altitude ranging from 1633 m to 1980 m above sea level and yielded 108.3 mm of rainfall in 2011. Summers are hot and dry, whereas winters are rainy. Autumn and spring are short. January and February are considered glacial months in terms of the water year. However, this phenomenon has not been observed as much in recent years because of climate change. Pistachio, which needs a lot of irrigation, is the main agricultural product of the area. It is mostly planted in arid and semi-arid regions. Thus, groundwater is very important for the economic survival of the area. Overusing of chemical fertilizers such as urea, ammonium sulfate and ammonium nitrate in the study area by farmers for over production of crops has led to excessive concentration of nitrate (Neshat, Pradhan, & Shafri, 2014).

Cretaceous and Eocene conglomerates (PC), along with Neogene or younger sediments and rocks (gp), as well as Eocene and Neogene volcanoes, constitute the geological characteristics of Kerman Plain.

The hydrogeological factors used in the risk map are listed in Table 1. In the Kerman Plain, the depth of groundwater table from the surface ranges from 15 m to >30 m. Hence, three classes of depth values have been established: 15–23 m; 23–30 m; and

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