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Optimal groundwater security management policies by control of inexact health risks under dual uncertainty in slope factors

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HIGHLIGHTS

- This study develops an integrated health risk groundwater remediation model.
- The model considers remediation cost, contamination and health risk distributions.
- Multiple uncertain properties in the process of health risk assessment are addressed.
- It could be simultaneously beneficial for public health and environmental protection.
- Optimal remediation strategies could be obtained according to specific requirements.

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ABSTRACT

Groundwater remediation is a complicated system with time-consuming and costly challenges, which should be carefully controlled by appropriate groundwater management. This study develops an integrated optimization method for groundwater remediation management regarding cost, contamination distribution and health risk under multiple uncertainties. The integration of health risk into groundwater remediation optimization management is capable of not only adequately considering the influence of health risk on optimal remediation strategies, but also simultaneously completing remediation optimization design and risk assessment. A fuzzy chance-constrained programming approach is presented to handle multiple uncertain properties in the process of health risk assessment. The capabilities and effectiveness of the developed method are illustrated through an application of a naphthalene contaminated case in Anhui, China. Results indicate that (a) the pump-and-treat remediation system leads to a low naphthalene contamination but high remediation cost for a short-time remediation, and natural attenuation significantly affects naphthalene removal from groundwater for a long-time remediation; (b) the weighting coefficients have significant influences on the remediation cost and the performances both for naphthalene concentrations and health risks; (c) an increased level of slope factor (*sf*) for naphthalene corresponds to more optimal strategies characterized by higher environmental benefits and lower economic sacrifice. The developed method could be simultaneously beneficial for public health and environmental protection. Decision makers could obtain the most appropriate remediation strategies according to their specific requirements with high flexibility of economic, environmental, and risk concerns.

1. Introduction

The intensification of human population growth, energy consumption, and technological development has led to an increase groundwater overuse and contamination (Andrade et al., 2017). Groundwater contamination, especially by petroleum hydrocarbons, has become a difficult problem worldwide (Minetti et al.,

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2017). Petroleum contaminated groundwater can pose a major environmental threat for ecosystems and public health (de Barros and Fiori, 2014; Moolla et al., 2015; Khodaei et al., 2017; He et al., 2017a; Chen et al., 2017). In the past decades, remediation technologies have been widely developed to remove of dissolved petroleum hydrocarbons from contaminated groundwater (Careghini et al., 2013; McHugh et al., 2014; Fonkwe and Trapp, 2016; Zanjani et al., 2016; He et al., 2017b). However, groundwater remediation is a complicated system with time-consuming and costly challenges, which should be carefully controlled by appropriate groundwater management approaches (Ritzel et al., 1994; Mayer et al., 2002; Baú and Mayer, 2006; Freidman et al., 2016; Libera et al., 2017).

In the past decades, numerous groundwater management methods and their uncertain property have already been proposed (Amiri et al., 2016; Hou et al., 2016; Chutia and Datta, 2017; Lu et al., 2017). For example, Dhar and Patil (2012) proposed a multi-objective design for a groundwater quality monitoring networks considering spatiotemporal pollutant concentrations as fuzzy numbers. Spatiotemporal concentration values were considered as fuzzy numbers by using triangular fuzzy membership function, which assumes a maximum value of 1 and minimum value zero. But the stochastic uncertainties of values were not taken into consideration. de Barros et al. (2013) provided a stochastic evaluation of the rebound concentration in a pimp-and-treat system conducive to estimating the probability that the rebound concentration will exceed some regulatory critical value. The risk was the rebound concentration exceeding a critical concentration value, and considered as uncertainty with randomness. Majority of researches for groundwater management focus generally on parameter with single uncertain property. In addition, multi-objective programming is one of the widely-used methods to deal with the tradeoffs between decision makers who represent different perspectives and have inconsistent decision goals. For example, Farhadi et al. (2016) developed an agent-based-nash modeling framework for groundwater management. The multi-objective optimization model found a Pareto optimal front among the three stakeholders (farmers, the government executive sector, and the environmental protection institutes, whose interests are reducing water deficit, increasing equity in water allocation, and reducing groundwater drawdown, respectively.) Results of case study demonstrated that the simulation-optimization model could lead to 58.3% less water extraction and approximately 3 m water level uplift.

However, there are two major challenges in the extensive studies for emphasis on groundwater remediation optimization. The first one is to systemically combine uncertain health-risk-assessment information into the groundwater remediation management (Bertone et al., 2016; Thakur and Mondal, 2016; Li et al., 2017). Majority of previous researches either only developed optimal remediation strategies without consideration of health risk affects or only instantly calculated health risk before or after the remediation implement (Shin et al., 2016; Mumford et al., 2016; Henri et al., 2016; Kumar et al., 2017). Seldom emphasizes the combination between remediation optimization design and health risk assessment. Integrating health risk assessment into groundwater remediation optimization management system is capable of not only adequately considering the influence of health risk on optimal remediation strategies but also simultaneously completing remediation optimization design and health risk assessment. Secondly, multiple uncertainties, especially presented as fuzzy and stochastic properties, extensively exist in the decision-making process of groundwater remediation in a real-word engineering (Zarlenga et al., 2016; Marchant et al., 2016; Sreekanth et al., 2016; Chen et al., 2016). For better understanding the performance of the optimization model in supporting groundwater decision-making, stochastic and fuzzy methods are two widely-used tools, which aim to examine the effects of parameters on optimal decisions (Joodavi et al., 2015; Vadiati et al., 2016; Boso and Tartakovsky, 2016). Fuzzy set theory could address uncertainties with unknown precisely coefficients. Chance-constrained programming advanced from stochastic mathematical program has been proved as an effective approach in addressing stochastic coefficients (Singh et al., 2010; Morankar et al., 2016; Lu et al., 2016; Chen et al., 2018). Nevertheless, some difficulties frequently occur when a coefficient has dual or multiple uncertain properties. It is thus necessary to propose a fuzzy chance-constrained programming approach to handle dual or multiple uncertainties (Lu et al., 2008; He et al., 2008; Tartakovsky, 2013; Wood, 2017). Despite numerous researches on uncertainties in groundwater mathematical modeling, they hardly founded the influence of multiple uncertainties of health risk assessment on a groundwater remediation management system.

Therefore, this study aims to fill this gap by developing an integrated health-risk-based groundwater remediation management programming, where two-fold uncertainties in the process of health risk are taken into consideration. Health risk assessment is presented as one of major constraints to make the optimal remediation performance satisfy both environmental and health-risk standards. A crucial coefficient with dual uncertainties is treated as stochastic-fuzzy number, whose influences on optimal strategies, remediation performance, and health risk assessment have been evaluated by a fuzzy chance-constrained programming approach. The capabilities and effectiveness of the developed method are illustrated by an application of a naphthalene contaminated case in Anhui, China. The following tasks are conducted in the study: 1) developing an integrated health risk groundwater remediation optimization programming with economic and environmental decision-making interests; 2) identifying dual uncertain coefficient as stochastic-fuzzy numbers and addressing uncertainties through a fuzzy chance-constrained programming approach; 3) applying the developed programming model to solve a real-word naphthalene-contaminated groundwater remediation management problem; and 4) discussing cost control, remediation performance, and health risk under different scenarios and detecting uncertainty influence on optimal strategies to support decision making for groundwater remediation management.

2. Methodology

2.1. Overview of the groundwater management problem in this study

The site is an aquifer in a power plant contaminated by oil, which has an area of $2400 \times 2000\ ft^2$ and is located in Anhui, China (Fig. 1). Table 1 lists the potential levels of slope factors based on fuzzy chance-constrained programming method. The other details of the application are shown in S1 of the Supplementary Material.

2.2. Health risk constrained groundwater remediation optimization programming

For government executive sectors, the primary objective of groundwater remediation management is minimizing the remediation cost required by cleaning contaminated sites. The total remediation costs are generally the sum of construction and operating costs. For environmental protection institutes, the significant objective of the groundwater remediation management is minimizing the degree of contamination, which can be reflected by the contamination concentration at monitoring wells. Therefore,