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Environmental- and health-risk-induced remediation design for benzene-contaminated groundwater under parameter uncertainty: A case study in Western Canada

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HIGHLIGHTS

- An environmental- and health-risk-induced groundwater remediation design is proposed.
- Flexible exposure frequency, intake rates and health risk thresholds are considered.
- A real petroleum-contaminated site is studied to measure performance of the approach.
- Health-risk concerns greatly increase operating costs for long-term remediation.
- Exposure frequency contributes more to health risk than intake rates.

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ABSTRACT

This study proposes an environmental- and health-risk-induced remediation design approach for benzene-contaminated groundwater. It involves exposure frequency and intake rates that are important but difficult to be exactly quantified as breakthrough point. Flexible health-risk control is considered in the simulation and optimization work. The proposed approach is then applied to a petroleum-contaminated site in western Canada. Different situations about remediation durations, public concerns, and satisfactory degrees are addressed by the approach. The relationship between environmental standards and health-risk limits is analyzed, in association with their effect on remediation costs. Insights of three uncertain factors (i.e. exposure frequency, intake rate and health-risk threshold) for the remediation system are also explored, on a basis of understanding their impacts on health risk as well as their importance order. The case study results show that (1) nature attenuation plays a more important role in long-term remediation scheme than the pump-and-treat system; (2) carcinogenic risks have greater impact on total pumping rates than environmental standards for long-term remediation; (3) intake rates are the second important factor affecting the remediation system's performance, followed by exposure frequency; (4) the 10-year remediation scheme is the most robust choice when environmental and health-risk concerns are not well quantified.

1. Introduction

Water quality is directly related to human health, especially when groundwater is used as drinking water in many regions (Ravindra and Garg, 2007; Azizullah et al., 2011). Water pollution is leading to the worldwide death and disease and adversely affects over one billion people every day in developing countries (WHO, 2012). A recent national report on USA water quality revealed that 45% of assessed stream miles, 47% of assessed lake acres, and 32% of assessed bays square miles were classified as polluted (USEPA, 2000; USEPA, 2006). Ground sources may be polluted due to industrial dumping, hydraulic fracking, and agricultural byproducts (Chae et al., 2004; Ravindra and Garg, 2007).While many contaminants are found that will not cause immediate discomforts or sicknesses, it is proven that low-level but overtime exposure to many contaminants will cause severe illness including liver damage, cancer, and other serious ailments. Organic pollutants as a major category of pollution are strictly monitored in North America, particularly some petroleum-related pollutants (Iturbe et al.,

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2005; Zhang et al., 2013). From 1987 to 1993, according to the Toxics Release Inventory in USA, over 2 million lbs of benzene, over 761 000 lbs of ethylbenzene, 4 million lbs of toluene, and nearly 4.8 billion lbs of xylene were released to water and land, and most of the pollutants were from petroleum industries. These contaminations may cause nervous systems disorder, immune systems depression and headache under short-term exposure, but liver and kidney damage and cancer under long-term exposure (Lopez et al., 2008; Kambhu et al., 2012; Peng et al., 2013).

Remediation of petroleum contaminated groundwater is thus urgently needed. In the United States, Congress passed the Safe Drinking Water Act in 1974. This law requires EPA to determine safe levels of chemicals in drinking water that do or may cause health problems, including benzene and other cancer-causing pollutants. As one of the most effective repair technologies, pump and treat (PAT) systems have been widely used in actual groundwater remediation sites (Dresel et al., 2011). Optimal design for PAT systems has thus attracted much attention of the related researcher. In the past several decades, many researches focused on parameter uncertainty in PAT remediation systems design (Janet et al., 1992; Kentel and Aral, 2007; He et al., 2011). Genetic algorithms and artificial neural networks were used to realize global optimization for remediation systems (Guan and Aral, 2005; Prasad and Mathur, 2007). Many simulation methods were also proposed for predicting the fate and transport of underground contaminants. For example, He et al. developed a simulation-based fuzzy chance-constrained programming (SFCCP) model based on possibility theory to handle simulation and optimization problems under uncertainty for a PAT system (He et al., 2008b). Lu et al. introduced interval parameters and interval-valued fuzzy parameters into the objective function and constraints to dealing with individual uncertainty and dual uncertainties existing in real-world cases (Lu et al., 2010). In general, the above mentioned efforts mainly considered environmental effects of groundwater contamination, and thus generated remediation plans for PAT systems.

However, health risks associated with groundwater contamination should also be concerned seriously. A critical procedure for decision-makers is risk assessment, in the course of regarding optimal remediation and management strategies for contaminated sites. It offers the bases for assessing and ranking the severity of site contamination (CCME, 1996). Due to the lack of sufficient information, uncertainty inherently exists in the process of groundwater transportation, transformation and remediation, resulting the risks also naturally coexisting with randomness (Chen and Ma, 2006; He et al., 2008a; Tartakovsky, 2013).Negligence of uncertainty in the assessment may result in adverse consequences, i.e. overdesign of systems (wasting capital and resources) or under estimation (threatening public health) (Li et al., 2007). Therefore, research work about risk assessment in groundwater remediation practices was also undertaken in the past decade. Chen and Ma developed a methodology combining the cost of reducing uncertainty with the selection of risk assessment models for remediation decision of site contamination (Chen and Ma, 2007). Baciocchi et al. proposed an alternative model which took source depletion into consideration for predicting the effective exposure duration of on-site receptors that exposed to contaminated groundwater (Baciocchi et al., 2010).

Among the existing researches, few literatures simultaneously took both environmental standards and health risks into the simulation and assessment account, under consideration of various uncertainties. In fact, taking various features (e.g. preference, life style, custom) from different communities into consideration would avoid waste of resources and inapplicable decisions for short-term but high-load projects, besides public health would be protected under long-term and low-operation remediation activities. This study considers exposure frequency and intake rates that are important for health risk assessment but difficult to be exactly quantified as the breakthrough point. Flexible health-risk control is incorporated in the simulation and optimization work under different remediation durations. Optimal remediation schemes can then be identified for decision-makers with various requirements, under an in-depth analysis of relationships between environmental standards and health-risk thresholds as well as their impacts on remediation costs. Insights of parameter uncertainty on the remediation system, and the impact of inexact exposure frequency and intake rates on health risk, can also be obtained simultaneously. The proposed environmental- and health-risk-induced remediation design approach will then be applied to a petroleum contaminated site in western Canada.

2. Methodology

2.1. Model objective

The minimization of total cost is usually selected as the objective of optimization models. The total cost for a usual PAT system includes operating costs that are tremendous high, and fixed costs that are usually neglected for being far less than the former (Minsker and Shoemaker, 1998). As the origin of operating costs, pumping rates may be determined as the objective of the optimization model instead of operating costs. As we known, the efficiency of remediation processes is closely connected with pumping rates, while the coefficients between remediation efficiency and operating costs are difficult to determine. There are also many conditions and technical constraints that could not be directly related to operating costs. Chosen the total pumping rate as the objective can solve the above problems. Consequently, the objective function in this study is set as the minimization of total pumping rate, including both injection and extraction rates. The function is described as follows:

$$\text{Minimize } TR = \sum_{i=1}^{I} Q_i^{In} + \sum_{j=1}^{J} Q_j^{Ex} \tag{1}$$

where TR is total pumping rate; I, J mean numbers of injection and extraction wells, respectively; Q_i^{In} and Q_j^{Ex} represent pumping rates for the ith injection well and the jth extraction well, respectively.

2.2. Model constraints

The objective is limited by numerous technical factors and the public concerns. Firstly, both injection and extraction wells have technical load limits. The limits restrict the upper bounds of pumping rates for all injection and extraction wells. Secondly, a stable hydraulic gradient should be maintained to assure groundwater flowing directly toward the plume interior; this is obtained through injecting an equal volume of clean water during a specified pumping period. The above technical constraints are described as follows:

$$0 \leqslant Q_i^{In} \leqslant Q_{i,\max}^{In} \tag{2a}$$

$$0 \leqslant Q_j^{Ex} \leqslant Q_{j,\max}^{Ex} \tag{2b}$$

$$\sum_{i=1}^{I} Q_i^{In} = \sum_{j=1}^{J} Q_j^{Ex} \tag{2c}$$

Another category of constraints is public concerns. In this study, they consist of two parts: environmental standards and human-health risk. For environmental standards, concentrations of contaminants (obtained from a 3-dimensional multiphase multi-