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Monte Carlo-based interval transformation analysis for multi-criteria decision analysis of groundwater management strategies under uncertain naphthalene concentrations and health risks

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SUMMARY

A new Monte Carlo-based interval transformation analysis (MCITA) is used in this study for multi-criteria decision analysis (MCDA) of naphthalene-contaminated groundwater management strategies. The analysis can be conducted when input data such as total cost, contaminant concentration and health risk are represented as intervals. Compared to traditional MCDA methods, MCITA–MCDA has the advantages of (1) dealing with inexactness of input data represented as intervals, (2) mitigating computational time due to the introduction of Monte Carlo sampling method, (3) identifying the most desirable management strategies under data uncertainty. A real-world case study is employed to demonstrate the performance of this method. A set of inexact management alternatives are considered in each duration on the basis of four criteria. Results indicated that the most desirable management strategy lied in action 15 for the 5-year, action 8 for the 10-year, action 12 for the 15-year, and action 2 for the 20-year management.

1. Introduction

Because of the increasing water utilization for industrial, agricultural and domestic uses, as well as the inefficient and unsustainable resource exploitation, the quality and quantity of groundwater resources are deteriorating and shrinking at its weakest pace (Chang et al., 2007; Thiruvenkatachari et al., 2008; McKnight and Finkel, 2013; Mategaonkar and Eldho, 2014; Li et al., 2015). As one of important environmental problems, the management of contaminated groundwater has drawn great attention of the public since it is a time-consuming and costly challenge (Maqsood et al., 2005; Ko and Lee, 2010). A variety of techniques have been evaluated for groundwater cleanup from industrial and agricultural chemicals. Those methods are divided into biological (e.g., biodegradation and phytoremediation), chemical (e.g., fluid extraction, fenton, peroxide remediation and so on), and physical treatment techniques (e.g., landfilling, heat-adsorption, soil washing, pump and treat and so on) (Hamby, 1996; James et al., 2009; Lin et al., 2010; Huguenot et al., 2015; Iglesias et al., 2015). As a low-cost, highly efficient and widely used technology, the pump and treat method is identified as one of the most common groundwater management methods and has been used extensively in aquifer management compared to other technologies (Matott et al., 2006; Yang et al., 2013a,b).

At present, many inexact multi-objective decision analysis (MODA) and multi-criteria decision analysis (MCDA) are widely used to determine the most appropriate management strategy (He et al., 2009; Luo et al., 2012; Li et al., 2014). Mantoglou and Kourakos (2007) developed a modified multi-objective genetic algorithm for optimal management of groundwater aquifers under hydraulic conductivity uncertainty. Luo et al. (2014) developed a new probabilistic multi-objective fast harmony search algorithm for optimal design of groundwater management systems under uncertainty. Gaur et al. (2015) developed a multi-objective fuzzy optimization model considering three conflicting objectives by using particle Swarm optimization and analytic element method for obtaining a sustainable groundwater management policy. For real-world groundwater management problems, decision makers often need to simultaneously consider some competing criteria such as cleanup time, management cost, health risks and contaminant mass remaining in the aquifers with a variety of uncertainties. Compared with MODA, MCDA is more suitable in identify desirable alternatives when discrete multiple conflicting criteria are encountered (Adiat et al., 2012; Moglia et al., 2012). These application studies addressed the involved uncertainty

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information as extension of stochastic theory and fuzzy sets to integrate into MCDA management framework. Nasiri et al. (2007) introduced a decision support system for the prioritization of management plans based on their estimated compatibility index by using fuzzy sets theory to deal with system uncertainties. Qin et al. (2008) developed a stochastic multicriteria decision analysis method for optimizing petroleum-contaminated groundwater management systems. Yang et al. (2012b) developed a simulation-based fuzzy multi-criteria decision analysis method for supporting the selection of remediation strategies for petroleum contaminated sites.

Nevertheless, the abovementioned MODA and MCDA approaches were typically expressed uncertainty inputs in the form of a fuzzy distribution or a probability distribution. Moreover, the abovementioned studies seldom attempted to introduce health risk assessment in the decision making analysis under uncertainty. Because of the inherent natural heterogeneity and lack of complete knowledge of the physical, chemical, and biological processes, identification of a suitable groundwater management technology is a complex process and uncertainty in groundwater management problems often stems from uncertain geological or geoenvironmental parameters (e.g. intrinsic permeability, soil porosity, migration velocity, NAPL saturation and so on) (He et al., 2008; Fan et al., 2014; Gaur et al., 2015; Srivastava and Singh, 2015). In real-world groundwater management, many inexactness and imprecision parameters maybe discrete and irregularly distributed, thus traditional inexact MCDA approaches would fail to work (Warner et al., 2006; Yan and Minsker, 2011; Compernolle et al., 2014; Chitsazan and Tsai, 2015). Interval analysis has been demonstrated effective in dealing with inexact information, with its lower- and upper-bounds being known yet the specific distribution functions being unclear (Lu et al., 2011; Bhowmik et al., 2015; Pardo-Igúzquiza et al., 2015). Therefore, it is still desired that a new decision-making method need to be developed in support of groundwater remediation management, where a most-appropriated management strategy need to be identified under inexact input data.

Therefore, a Monte Carlo-based interval transformation analysis (MCITA) is proposed for multi-criteria decision analysis (MCDA) of groundwater management strategies under interval concentrations and health risks. In the method, Monte Carlo sampling technique will be used to generate a set of discrete realizations of the input information, with each one corresponding to one alternative management strategy. The realizations will then be input to an MCDA framework to output a complete ranking of the alternatives from the best to the worst. A real-world naphthalene-contaminated aquifer will be applied to demonstrate the performance of the method in generating the most desirable groundwater management strategy.

2. Monte Carlo-based Interval transformation analysis

2.1. Contaminant concentrations acquired though groundwater simulation

A two-dimensional, finite difference model is introduced for simulating degradation of contaminant in the groundwater. The mass transport equations are solved to calculate the spatial variation of the contaminant concentration. The model solves the transport equation to determine the fate and transport of the hydrocarbons and the electron acceptors/reaction by-products. The governing equations for the contaminant transport problem can be given as (Borden and Bedient, 1986; Yang et al., 2012a):

$$\frac{\partial(bH)}{\partial t} = \frac{1}{R_h}\left[\frac{\partial}{\partial x_i}\left(bD_{ij}\frac{\partial H}{\partial x_j}\right) - \frac{\partial(bHV_i)}{\partial x_i}\right] - \frac{H'W}{n} - \frac{Q}{n}\delta(x - x^{(r)})H \quad (1)$$

$$\frac{\partial Pb}{\partial t} = \left[\frac{\partial}{\partial x_i}\left(bD_{ij}\frac{\partial P}{\partial x_j}\right) - \frac{\partial(bPV_i)}{\partial x_i}\right] - \frac{P'W}{n} \quad (2)$$

$$\Delta H_{SO} = \frac{P}{F_O}, \quad P = 0 \quad \text{if} \quad H > \frac{P}{F_O} \quad (3)$$

$$\Delta P_{OS} = HF_O, \quad H = 0 \quad \text{if} \quad P > HF_O \quad (4)$$

$$H(x, y, t)|_{t=0} = H_0(x, y), \quad (x, y) \in \Omega, \ t = 0 \quad (5)$$

$$H(x, y, t)|_{t=\Gamma_1} = H_1(x, y, t), \quad (x, y) \in \Gamma_1, \ t \geqslant 0 \quad (6)$$

where H is the concentration of contaminant (mg/L); H' is the concentration of contaminant in the source or sink fluid; n is effective porosity; Q is the pumping rate; $\delta(x - x^{(r)})$ is the Dirac delta function evaluated at $(x - x^{(r)})$. P is the concentration of oxygen; P' is the concentration of oxygen in the source or sink fluid; ΔH_{SO} is the loss of contaminant concentration due to aerobic biodegradation (mg/L); F_O is the stoichiometric ratio for oxygen; ΔP_{OS} is the concentration loss of the electron acceptor (mg/L); Ω is the study domain; and Γ_1 is the first boundary condition. The simulated concentration at each monitoring well was firstly calculated under the variation of porosity from 0.25 to 0.35.

2.2. Interval transformation analysis

Because multiple occurrence of the interval-valued variable in the expression to be evaluated, the application of standard interval arithmetic usually overestimate the real results of a problem to a more or less large extent, which is well-known serious drawback for interval computations (Hanss, 2002). In this study, interval transformation analysis is introduced to reveal the potential inter-relationships among a variety of uncertain parameters.

In this study, total management cost (*TC*), average remaining naphthalene-contaminant concentration (*ARCC*) and maximum excess life time cancer risk (*MELCR*) are treat as interval data. For each action, interval parameters are divided as two levels (i.e. upper-bound and lower-bound) (Eqs. (2) and (3)). For overall n decision-making alternatives, 2^n various decision arrays (*DAs*) can be generated by transformation method (Eq. (4)) and these arrays will be used as inputs for simulation models. A 2^k arrays need require 2^k runs. The number of runs required for a complete design increases exponentially, resulting in a great computational burden.

$$AC_i^+ = (TPV, TC_i^+, ARCC_i^+, MELCR_i^+) \quad (7)$$

$$AC_i^- = (TPV, TC_i^-, ARCC_i^-, MELCR_i^-) \quad (8)$$

$$DAs = \underbrace{\left\{\underbrace{(AC_1^- \ldots AC_i^- \ldots AC_n^-)}_{1^{th}\text{ design}}, \ldots \underbrace{(AC_1^- \ldots AC_i^+ \ldots AC_n^+)}_{\lambda^{th}\text{ design}}, \ldots \underbrace{(AC_1^+ \ldots AC_i^+ \ldots AC_n^+)}_{2^{n\,th}\text{ design}}\right\}}_{2^n\text{ designs}} \quad (9)$$

2.3. Monte Carlo method

Monte Carlo (MC) method is used to generate a set of discrete realizations of the input information, with each one corresponding to one alternative management strategy. The realizations will then be input to an MCDA framework to output a complete ranking of the alternatives from the best to the worst. The key to Monte Carlo simulation is to generate the set of random inputs. A Monte Carlo