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Effect of constraint severity in optimal design of groundwater remediation

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ABSTRACT

Variation of decision variables for optimal remediation using the pump-and-treat method is examined to estimate the effect of the degree of concentration constraint. Simulation-optimization method using genetic algorithm is applied to minimize the total pumping volume. In total volume minimization strategy, the remediation time increases rapidly prior to significant increase in pumping rates. When the concentration constraint is set severer, the more wells are required and the well on the down-gradient direction from the plume hot-spot gives more efficient remediation performance than that on the hot-spot position. These results show that the more profitable strategy for remediation can be achieved by increasing the required remediation time than raising the pumping rate until the time reaches a certain limitation level. So, the remediation time has to be considered as one of the essential decision variables for optimal remediation design.

Key word: remediation design, optimization, genetic algorithm

1. Introduction

Pump and treat method may be the most conventional method for groundwater remediation. This method involves installing and operating a set of extraction wells so that the contaminated groundwater is hydraulically contained and can be pumped out for subsequent treatment. Recently, genetic algorithm (GA) that is one of the global optimum search methods is often used to design the system of optimal pump and treat method (Zheng and Wang, 2002).

In this study, the effect of remediation time is examined by comparing the changes of the remediation time with the change in constraint condition.

2. Simulation-Optimization Approach

In the design of pump-and-treat method, there are two sets of variables: decision and state variables.

Decision variables are basically pumping or injection rate for each well and the number of wells and their locations. State variables are the hydraulic head and drawdown, and the contaminant concentration. The simulation model updates the state variables by using given decision variables. Next, the optimization model evaluates them and selects the optimal decision variables according to the inherent optimum search algorithm with constraints for decision variables and/or state variables.

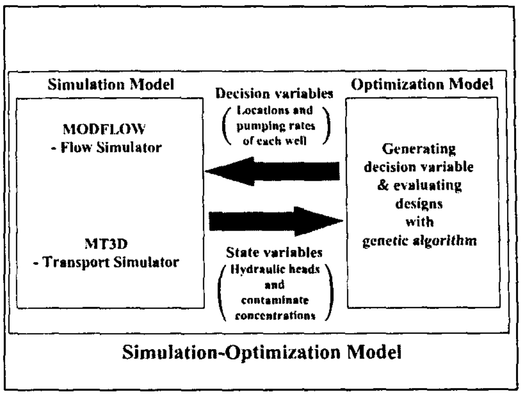

Figure 1. Simulation-optimization method

2.1 Simulation model

To evaluate the behavior of an aquifer system in response to pumping force, we used MODFLOW (Harbaugh and McDonald, 1996), a three-dimensional modular finite difference groundwater flow model, and MT3D (Zheng 1990), a three-dimensional solute transport model compatible with MODFLOW. The former solves the governing equation of three-dimensional groundwater flow:

$$\nabla \cdot (\mathrm{K} \nabla h) + q_s = S_s \frac{\partial h}{\partial t} \tag{1}$$

where K is the hydraulic conductivity tensor; h is the hydraulic head; q_s is the source/sink term; S_s is the specific storage; and t is time.

The three-dimensional solute transport governing equation in groundwater is:

$$\nabla \cdot (\mathrm{D} \nabla C) - \nabla (vC) + \frac{q_s}{\theta} = R \frac{\partial C}{\partial t} \tag{2}$$

where D is the hydrodynamic dispersion tensor; C is the solute concentration; C_s is the concentration of the source/sink flux; θ is the porosity; v is the average linear velocity; and R is the retardation factor. In this study, it is solved by the three-dimensional modular solute transport model, MT3D.

2.2 Optimization model

The optimization method in this study is GA. GA can identify the near-global optimum for problems with relatively complex objective function and constraints (Goldberg 1989). GA has three basic operators: reproduction, crossover, and mutation. These operators make the optimum searching process represented in the optimization model using genetic algorithm as they work on gene in cell. It is readily coupled with other simulation model like MODFLOW and MT3D (Figure 1) and so the domain with complicate boundary condition or initial condition for groundwater flow and contaminant transport can be applied easily (Askoy and Culver 2000; Zheng and Wang 2002).

3. Application for Theoretical Domain

3.1 Domain

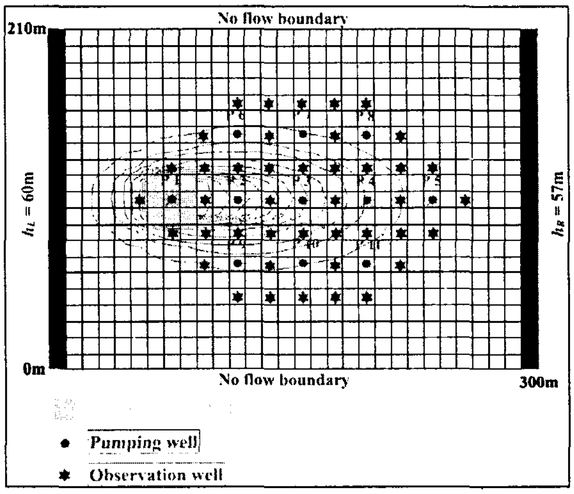

Figure 3. Contaminated domain for remediation

Table 1. parameters for aquifer and contaminant

Parameter	Value
Hydraulic conductivity, K(m/day)	0.864
Porosity, θ	0.25
Aquifer thickness, b(m)	30 (each 10)
Longitudinal dispersivity, α_L(m)	6.855
Transverse dispersivity, α_T(m)	1.371
Medium bulk density, ρ_b(kg/m^3)	1700
Distribution coefficient for linear sorption, Kd(L/mg)	1.58×10^{-7}

For the numerical experiments, a homogeneous aquifer system is generated. It is quasi-three dimensional and has three layers. Each layer is discretized into 30 by 21 finite-difference blocks (Figure 3). The leakage of contaminant for 10 years is assumed to make the initial condition for remediation. X1 is on hot-spot and the outmost contour of contamination is 1mg/L, and others are multiple of 10mg/L sequentially. Other information for aquifer and contaminant is in Table 1.

3.2 Objective function

The objective function used in this study is given by:

$$\textit{Minimization} \quad \sum_{j=1}^{m}\left\{\sum_{i=1}^{n} Q_{i,j}(q_{i,j},\ t_{i,j})\right\} + \omega(C^{\max},\ C^{*},\ t^{\max},\ s^{\max},\ s^{*}) \times P \qquad (3)$$

where $Q_{i,j}$ is the pumping volume of the i-th well for the j-th period (m3); $q_{i,j}$ is the pumping rate of the i-th well of the j-th period (m3/day, $0 \leq q_{i,j} \leq 120$); $t_{i,j}$ is the pumping duration of the i-th for j-th period (day); ω is the is the weighted factor for penalty value (dimensionless); $C^{\max}$, $t^{\max}$, and $s^{\max}$ are the maximum values of concentration, time, and drawdown at the end of remediation process (mg/L, day, m); C^{*}, t^{*} and s^{*} are the constraint values of concentration, time, and drawdown for the remediation system (mg/L, day, m, C^{*} is variable and t^{*} and s^{*} are fixed at 1825 days and 10m, respectively); P is the penalty value (dimensionless).

4. Results

As the constraint condition is set severer, the total pumping volume increases exponentially (Figure

4). The total pumping volume is calculated by multiplying the total pumping rate and duration time during operation. In Figure 5, the total pumping rate does not show any increasing or specific pattern from 10.0mg/L to 1.0mg/L of concentration constraint. It increases when the concentration constraint is set lower than 1.0mg/L. The required remediation time, however, sharply increases as the total pumping volume rises prior to the increase in the total pumping rate (Figure 6). In the case of minimizing total pumping volume, this plot shows that the remediation must be considered one of the decision variables for optimal pump and treat design.

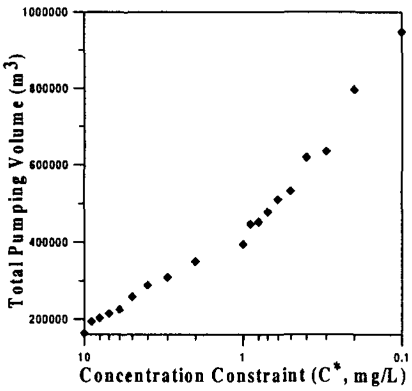

Figure 4. Total pumping volume vs. concentration constraint

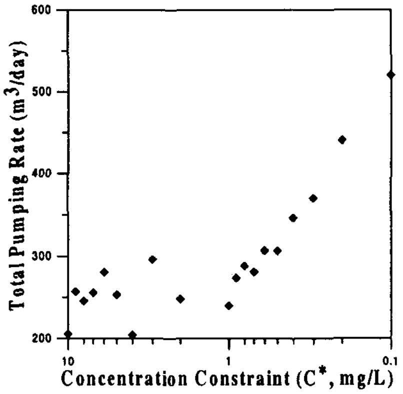

Figure 5. Total pumping rate vs. concentration constraint

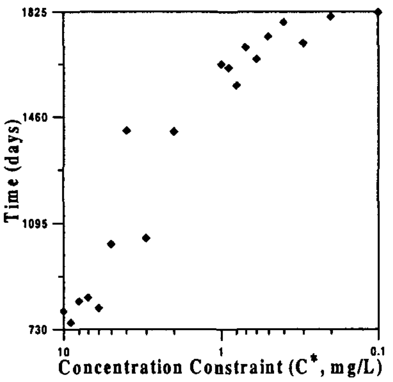

Figure 6. Remediation time vs. concentration constraint

The wells of P2 and P3 are mainly used for pumping and the well on hot-spot (P1) and the wells in down-gradient zone of groundwater flow and on centerline for contaminant distribution (P4, P5) also have relatively large portion of pumping rate (Figure 7). While the pumping rate of the well on the hot-spot (P1) is rarely changed, the wells on down-gradient zone such as P4 and P5 can be included in the group of main extraction wells for the severer constraint condition.

The mass of contaminant removal increases as the concentration constraint becomes severer (Figure 8). But, it hardly increases after a certain point (1.0 mg/L in here). This shows that the removal capacity of pump and treat system has an obvious limitation and other techniques are required in the severe constraint condition after a certain point of time.

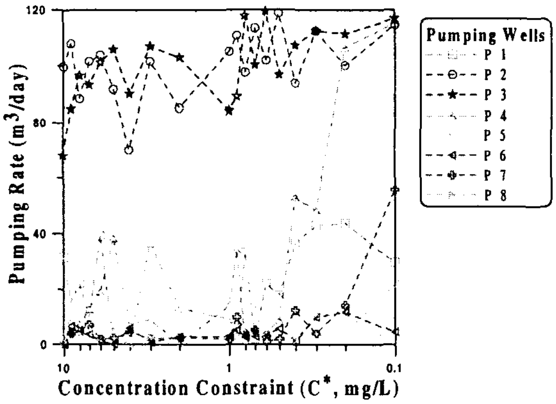

Figure 7. Pumping rate of each well vs. concentration constraint

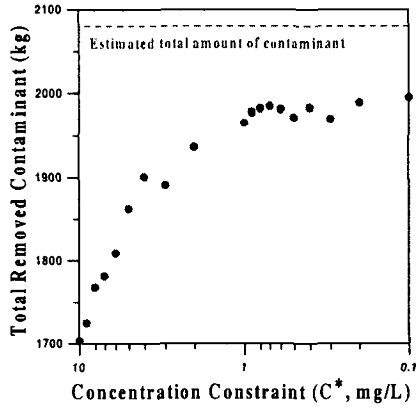

Figure 8. Total removal mass vs. concentration constraint

5. Summary and Conclusions

Simulation-optimization approach is applied to a hypothetical contamination problem for designing the optimal remediation design using the pump and treat method. As the constraint condition is set severer, the more total pumping volume is required. Also, the total pumping rate and required remediation time increase. But, the latter shows more rapid change and has more influence on the optimal remediation design than the former. The wells on the zone of down-gradient of groundwater flow are likely to be selected as additional extraction wells. On the respect of contaminant removal, the pump and treat method shows some limitations. It shows that other remediation techniques are required to raise the efficiency of remediation. From the results, it can be inferred that the remediation time must be considered as one of the decision variables in the optimal pump and treat design.

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