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Optimal Remediation Design Considering Effects of Degradation Processes

: Pumping strategy with Enhanced Natural Attenuation

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ABSTRACT

We accomplished optimization for pump and treat (P&T) designs in consideration of degradation processes such as retardation and biodegradation, which are significant for contaminant fate in hydrogeology. For more desirable remediation, optimal pumping duration and minimum pumping rate constraint problems are studied. After a specific P&T duration, it replaces the P&T with the enhanced natural attenuation (ENA), which induces aerobic biodegradation by maintaining oxygen concentration. The design in this strategy carries out the optimization for the number and locations of oxygen injection wells.

Key word: remediation design, optimization, genetic algorithm, degradation processes, sorption, first-order decay, pump and treat, enhanced natural attenuation

1. Introduction

Degradation processes, such as retardation and biodegradation should be considered as important factors for optimal remediation design for P&T in aspect of that retardation imposes more pumping rates on more pumping wells in the remediation design and biodegradation reduce the pumping volume and the number of used pumping wells. If it can estimate the contaminant quantity removed by biodegradation in a given time, it is necessary to control the pumping duration for cost reduction. In a series of this optimization experiments, meanwhile, we recognized that minimum pumping rate constraint makes an effect on remediation design related to cost and feasibility.

For more effective remediation, this study presents a new remediation strategy, so-called ENA, which inducesaerobic biodegradation by maintaining oxygen concentration. To investigate the performance of ENA with respect to both cost and contaminant removal, three scenarios under a specific sorption condition are considered. The optimization of the number and locations of oxygen injection wells for the ENA application is conducted for each scenario.

2. Methodology

The simulation for groundwater flow, solute transport and solute reaction and the optimization for optimal solution are accomplished in MODFLOW, MT3D, RT3D, and GA, respectively. As a linked simulation-optimization model, they carry out the optimal remediation design for a contaminated aquifer with interchanging state variables and decision variables. GA has three basic operators: reproduction, crossover, and mutation. These operators make the optimum searching process for problems involved a non-convex objective function and complex constraints.

3. Synthetic Application for Theoretical Condition

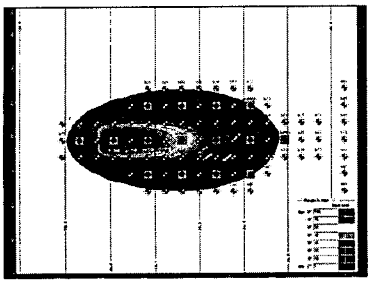

Fig 1. The distribution of a contaminant plume.

Parameter	Value
Hydraulic conductivity, K(m/sec)	3.0×10^{-5}
Effective porosity, n_e	0.25
Aquifer thickness, b(m)	30
Longitudinal dispersivity, α_L(m)	6.855
Transverse dispersivity, α_T(m)	1.371
Medium bulk density, ρ_b(kg/m^3)	1700
Specific yield, S_y	0.25

Table 1. The parameters for aquifer

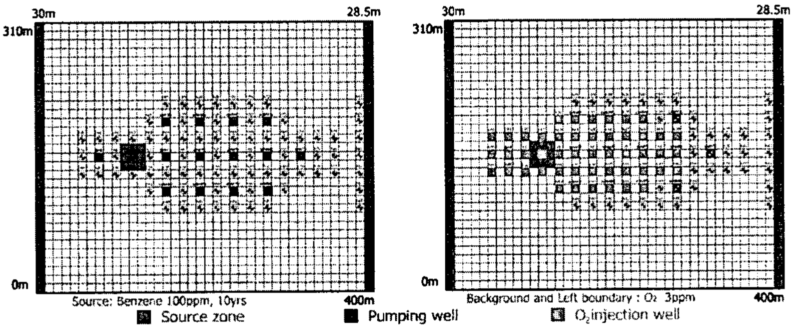

Fig 2. An aquifer domain involved P&T wells and ENA wells

3.1 Domain

For the numerical experiments, a homogeneous and isotropic aquifer system is assumed to a 400m×300m domain, and it is discretized into 40 by 31 finite-difference blocks. The distribution of a contaminant plume is in Fig. 1 and candidate wells for pumping and injecting oxygen are described with information about domain and others in Fig. 2. The properties of the aquifer are in Table 1.

3.2 Experimental settings

To evaluate the effects of pumping duration on remediation design, the optimization experiments under various degradation processes is carried out for several pumping durations in a given remediation time. We investigate effects of minimum pumping rates constraints by setting them to 30m^3/day and 60m^3/day, respectively. The optimization of the remediation design for ENA is executed with three scenarios under a specific sorption condition: (1) P&T (1.5yrs) and ENA (1yrs) (2) P&T (1.5yrs), ENA (0.5yrs) and NA (0.5yrs) (3) P&T (1.5yrs), two different ENA schemes (each 0.5yrs). We assume that the reaction of BTEX with oxygen is instantaneous aerobic reaction, and oxygen are injected in the form of oxygen released compound (ORC, 8ppm). The background oxygen concentration is set to 3ppm.

3.3 Objective function

The objective functions used for this study are given by:

$$\text{Minimization} \quad c_Q \sum Q + c_{well} N_{well} + P \quad \text{for the P\&T} \quad (1)$$

$$\text{Minimization} \quad c_{ORC} N_{ORC} + P \quad \text{for the ENA} \quad (2)$$

where Q is the total pumping volume (m3) ; c_Q, c_{well} and c_{ORC} are the cost for total pumping volume (cost/m3), an installed well (cost per a well), and an injected ORC (cost per a ORC), respectively ; P is the penalty value against violations (cost). Pumping rate, drawdown, and contaminant concentration for design constraints are allowed by 200m3/day, 10m, and 1ppm.

4. Results

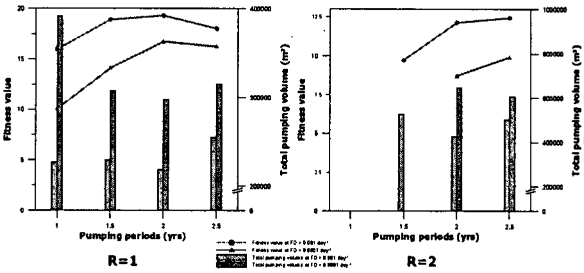

Fig 3. The optimization of the pumping duration

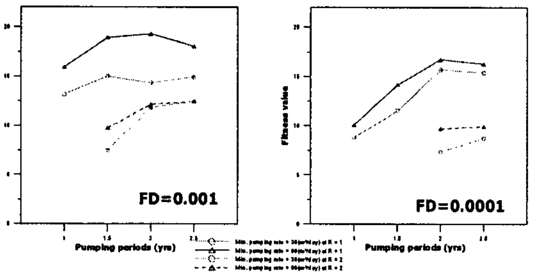

Fig 4. The minimum pumping rate constraint problem

Under the conditions of no retardation, 2 yrs pumping is superior to other pumping duration designs because pumping volume and the number of pumping well utilized in 2 yrs pumping design are required less than others. Short-duration pumping demands more pumping wells or too much pumping rates which can violate the drawdown and concentration constraints, while long-duration pumping makes excessive pumping volumes with long time. In the conditions that retardation factor is 2, the design for 2.5 yrs pumping period is suitable. This result shows that as retardation factor increases, more pumping duration is available because less pumping wells are required and, therefore, relatively expensive installation costs are reduced. But the pumping within fully 2.5 yrs is not efficient because the mass removal efficiency decreases with time.

Minimum pumping rate constraint problem is originated on setting a range of constraints for pumping rate. Too large minimum value may make the designs assess excessive pumping rate, but small value for minimum pumping rate constraint can impose extremely small pumping rates on new well, that is, this may require the unnecessary pumping well. In other words, the small minimum pumping rate constraint can yield less feasible designs than large minimum pumping rate constraint.

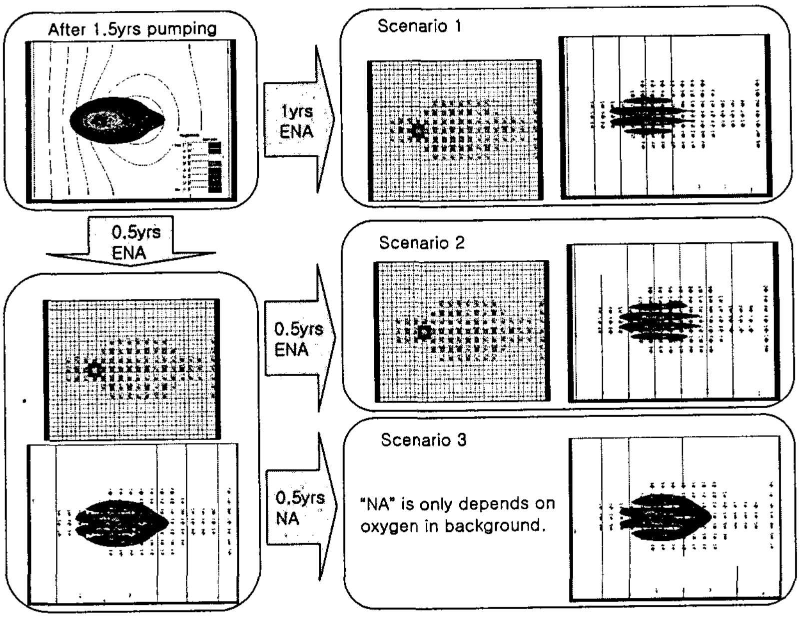

Fig 5. The applicaton of optimal design for ENA

Total remediation is 2.5yrs, and three scenarios begin from conditions after 1.5 yrs pumping. Through 1.5 yrs pumping, maximum concentration for BTEX in domain is about 10ppm. This indicates that pumping for 1.5 yrs sufficiently reduces concentration and then the application of ENA may be suitable with respect to cost. In the scenario 1 (1 yrs), 72 oxygen injections are required and their locations are on the vicinity of plume and at upgradient of groundwater flow. The concentrations in all observation wells satisfy the concentration constraints, however, maximum concentration in region not observed is about 6.5 ppm. In the first 0.5 yrs of scenario 2 and 3, concentration constraint is set to 3ppm for preventing from immoderate oxygen injection during short term. Maximum concentration in the not observed region is 7.7 ppm, and maximum concentration in observation is 2.7 ppm. The design is required 18 oxygen injections. In scenario 2, 40 oxygen injections are totally required. The concentrations in all observation wells satisfy the concentration constraints. Scenario 2 is more appropriate for costs than scenario 1. In the scenario 3 for natual attenuation (NA), the mass removal only depends on background oxygen. Maximum concentration in observation is 1.6 ppm, therefore this remediation design for scenario 3 is failure. Three scenarios are considered to examine the performance of ENA with respect to both cost and contaminant removal. Results show that the most cost-effective remediation design is scenario 2 although scenario 1 removes the most amount of contaminant in the aquifer and third scenario fails in remediation.

5. Acknowledgement

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