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Optimal groundwater remediation design considering effects of natural attenuation processes: pumping strategy with enhanced-natural-attenuation

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ABSTRACT: A simulation-optimization model is proposed to investigate the effect of natural attenuation processes on pump-and-treat and to enhance the application efficiency of the remediation method. Numerical experiments under varying retardation and attenuation conditions demonstrate that the efficacy and the feasibility of pump-and treat are considerably sensitive to the retardation factor and the attenuation rates. The severe retarded condition and attenuation are, the more remediation costs are required and even success of the remediation can not be guaranteed. For these conditions, long pumping strategy or enhancement of biodegradability can be cost-effective and safe. These results indicate that optimal remediations with or without considering natural attenuation processes result in quite different pumping schedules and well locations, and this should be noticed in real practices of groundwater remediation design. The enhanced-natural-attenuation (ENA) optimization process developed to overcome some limitations of the pump-and-treat method determines the locations injecting oxygen to attenuate residual contaminants remained in the aquifer after applying the pump-and-treat. The performances of the ENA model with the cost and the contaminant removal are evaluated for three scenarios. Among these scenarios, second scenario designed for each 0.5 years was most suitable to efficiently remove a low concentration of contaminants remained in the aquifer. This optimization model will be helpful to improve the efficiency in contaminated sites applying the pump-and-treat system.

Key words: optimization, remediation design, pump-and-treat, enhanced-natural-attenuation, retardation

1. INTRODUCTION

Pump-and-treat is the most widely used remediation system. However, it has been shown to have a number of technical and practical limitations due to complex reactions between contaminants and aquifer system. In particular, it has been proved to be a very expensive process and require ongoing costs for many years while not being efficient enough to decrease the contaminant concentration below a specific level (Mackay and Cherry, 1989). This inefficiency problem of pump-and-treat often occurs because the contaminants sorbed on aquifer soil do not be extracted sufficiently through only pumping. Berglund (1995) also indicated that the efficiency of the pump-and-treat method decreased as time elapses due to sorption mechanisms. The time needed for removal of 50% of the initial mass was less than half of the time needed to remove the next 40%, and an increase of removal from 90% to 99% required even more than a doubling of the cleanup time. Biodegradation can be another approach to enhance the efficiency and success of the remediation because microorganisms full of vitality, bringing about a wide range of biochemical reactions, live throughout the aquifer. U.S. EPA (2004) has already reported that a pump-and-treat system with natural attenuation (NA) is a new trend in recent remediation strategies.

To improve the efficiency of the pump-and-treat, a lot of researches about remediation design have been studied with focusing on the factors influencing on the remediation system (Ahlfeld et al., 1986; Wagner and Gorelick, 1987; Latinopoulos et al., 1994; Ahlfeld and Hill, 1996; McKinney and Lin, 1996; Guan and Aral, 2004, 2005; Ko et al., 2005; Warner et al., 2006). Nevertheless, most of their interests center on only hydraulic conductivity, excluding other reactions such as sorption and biodegradation. Contaminants dissolved in groundwater can be sorbed onto the surface of the soil in the aquifer and, as a result, some solutes will move much more slowly than the groundwater that acts as the medium of transport (Fetter, 1999). This phenomenon resulting from sorption is called as retardation. The attenuation rates of a contaminant indicate how many contaminants are naturally degraded by biogeochemical reaction. For example, in the case of almost all BTEX plumes, intrinsic biodegradation is clearly one of the most important attenuation mechanisms contributing to a decrease in contaminant concentration and mass (Seagren and Becker, 2002). The attenuation rates can be often expressed as a formulation of first-order decay rates that are readily used in solute transport models. Suthersan (2002) referred the sorption and biodegradation as representative mechanisms of the natural attenuation processes.

From these reasons, it is important that reactions between the contaminant and the aquifer should be considered in the remediation design processes to achieve successful groundwater remediation. In this study, the effects of the retardation factor and the first-order decay rates will be examined

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on the operation of pump-and-treat in a hypothetically contaminated aquifer. In particular, this study intends to suggest remedial alternatives to solve the inefficiency problem of the pump-and-treat method by evaluating and utilizing the natural attenuation processes of the aquifer system, which arises from various biodegradation reactions in the aquifer system. For this purpose, an optimization model for operating an enhanced-natural-attenuation (ENA) after major removal by pump-and-treat is developed to improve the efficiency of the overall remediation operation processes and the model tests will be performed on assuming three remediation scenarios.

2. CONTAMINATED AQUIFER FOR NUMERICAL SIMULATIONS

The numerical experiments to determine optimal designs of the pump-and-treat and the ENA are conducted in a hypothetical aquifer. A two dimensional unconfined aquifer is considered to be a domain 400 m wide by 310 m long by 30 m thick, which is discretized into 40 by 31 finite-difference blocks. The aquifer is assumed to be homogeneous and isotropic, with a hydraulic conductivity of 3×10^{-5} m/s. Constant head boundaries are assigned on the left (h_L=30 m) and right (h_R=28.5 m) so that groundwater flows from left to right in the aquifer. No-flow boundaries are imposed on the upper and lower sides of the aquifer (Fig. 1). The contaminant properties are based on those of benzene, which is one of the common groundwater contaminant. Several laboratory and field tests showed that the retardation factors (R) for the BTEX are generally in the range of 1.1 to 2 in typical shallow aquifers (Hubbard et al., 1994; Zogorski et al., 1997) and the first-order decay rates (λ) for benzene are often in the range of 0.001 to 0.01 per a day (Rifai et al., 1995; Suarez and Rifai, 1999).

It is assumed that the contaminant source is found and removed after a leakage occurring over 5 years from an underground storage tank adjacent to P2. The resultant contaminant plume is used as an initial condition for the pump-and-treat designs (Fig. 1). The concentration of the outmost contour of the plume shown in Figure 1 is 1 mg/L, which is specified to the water quality standard in this study. Based on the groundwater flow direction and the distribution of the contaminant plume, 87 monitoring wells are installed and the locations of 15 potential pumping wells are suggested. The initial contaminant plume and the pre-specified well sites are symmetric along the centerline of the domain because the aquifer is assumed to be homogeneous and isotropic and thus the pumping strategies will also be symmetric. All the wells are assumed to be fully penetrated. It is suggested that the cleanup must be achieved within 2.5 years. Detailed information for the aquifer and contaminant properties is summarized in Table 1.

For the ENA design, part of the above setting is little modified. The left boundary is set to be a constant oxygen concentration boundary of 3 mg/L, which is assumed to create an inflow of uncontaminated groundwater into the domain. In addition to that, 48 potential oxygen-injection wells are located on the locations of the monitoring wells installed previously (Fig. 2).

Table 1. Paremeters of aquifer properties.

Parameter	Values
Hydraulic conductivity	3×10^{-5} m/s
Porosity/Effective porosity	0.3/0.25
Longitudinal dispersivity	6.88 m
Transverse dispersivity	2.06 m
Medium bulk density	1700 Kg/m^3
Specific yield	0.25

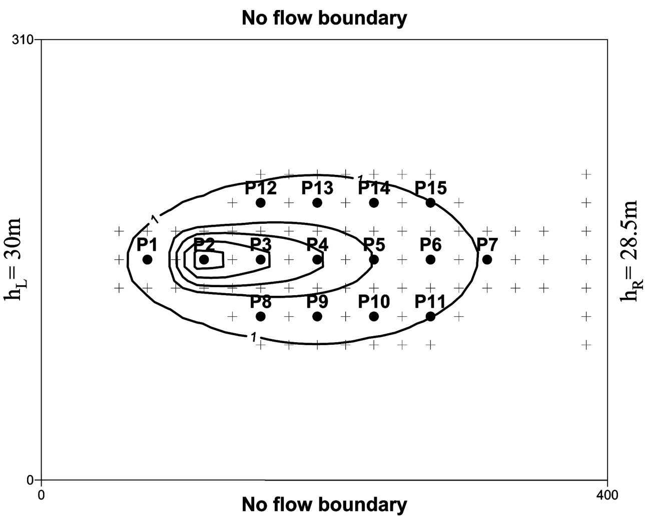

Fig. 1. Initial distribution of contaminant plume, locations of 15 candidate pumping wells (●) and 87 monitoring wells (+), and boundary conditions for the pump-and-treat design.

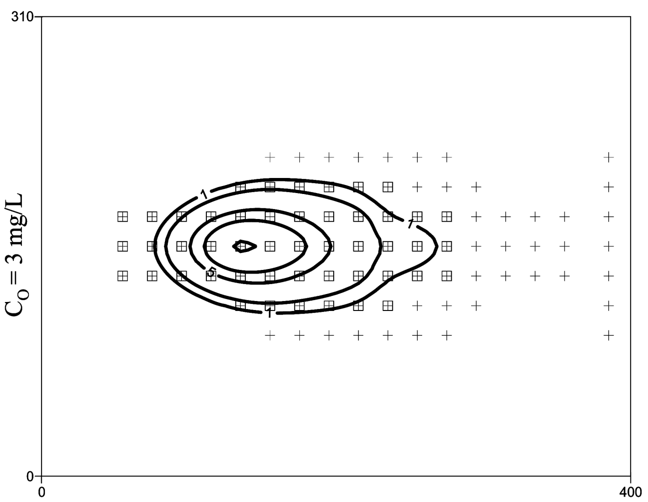

Fig. 2. Distribution of the contaminant plume after 1.5 years pumping and the 48 ORC injection wells (□) for the enhanced-natural-attenuation.

3. SIMULATION-OPTIMIZATION MODEL

In the simulation-optimization model, groundwater flow and solute transport simulation models are combined with an optimization model to obtain an effective remediation design (Gorelick et al., 1984; Guan and Aral, 2004, 2005; Ko et al., 2005). The simulation model computes state variables such as hydraulic head and concentrations for given initial design factors. Then, the optimization model updates the values of decision variables conditioned by some constraints. The updated decision variables will be used as subsequent design factors for the simulation models. In such a manner, the simulation-optimization model runs iteratively until it satisfies a stopping criterion or it reaches the maximum iteration number. In this study, for simulation-optimization approach, MODFLOW (Harbauch and McDonald, 1996) and MT3D (Zheng, 1990) coupled with a genetic algorithm (GA) (McKinney and Lin, 1994; Ritzel et al., 1994; Zheng and Wang, 2002; Ko et al., 2005) are used.

3.1. Simulation Model

In saturated unconfined aquifers, groundwater flow and reactive solute transport are governed by the following partial differential equations, respectively.

$$S_y\frac{\partial h}{\partial t} = \nabla\cdot(\mathbf{K}\cdot h\nabla h)+q_s \qquad (1)$$

$$R\frac{\partial C}{\partial t} = \nabla\cdot(\mathbf{D}\cdot\nabla C)-\nabla\cdot(vC)+\frac{q_s}{\theta}C_s+\left(\frac{\partial C}{\partial t}\right)_{rxn} \qquad (2)$$

where $\mathbf{K}$ is the hydraulic conductivity tensor [LT^{-1}]; h is the hydraulic head [L]; q_s is the source/sink term [T^{-1}]; S_s is the specific storage [dimensionless]; and t is the time [T]; R is the retardation factor [dimensionless]; $\mathbf{D}$ is the hydrodynamic dispersion tensor [L^2T^{-1}]; C is the solute concentration in the dissolved phase [ML^{-3}]; v is the average linear velocity [LT^{-1}]; θ is the porosity [dimensionless]; C_s is the concentration of the source/sink flux [ML^{-3}]; $\left(\frac{\partial C}{\partial t}\right)_{rxn}$ is the biological/chemical reaction term.

Because natural groundwater velocities tend to be small, equilibrium partitioning is often achieved. In particular, the linear sorption isotherm, which is a special form of Freundlich sorption isotherm, assumes that the sorbed phase and the dissolved phase have a linear relationship with a distribution coefficient. The relationship and the retardation factor in this isotherm are, respectively,

$$C^* = K_dC \qquad (3)$$

$$R_{lin} = 1+\frac{B_d}{\theta}K_d \qquad (4)$$

where C^* is the solute concentration in the sorbed phase [M/M]; K_d is the distribution coefficient [$M^{-1}L^3$]; R_{lin} is the retardation factor for linear sorption isotherm [dimensionless]; B_d is the bulk density of aquifer [ML^{-3}]. However, the linear sorption isotherm has the disadvantage that it is unable to consider the limitation of sorption sites in the soil. Weber et al. (1991) showed that nonlinear effects may have considerable impact on the assessment of solute transport at the field scale. The equilibrium isotherm that reflects the limitation and the non-linearity of the sorption is just a Langmuir sorption isotherm. At low concentrations, the Langmuir isotherm is consistent with the linear isotherm, while at high concentration, the sorption effect is negligible. The relationship and retardation factor for is written as;

$$C^* = \frac{\alpha\beta C}{1+\alpha C} \qquad (5)$$

$$R_{Lang} = 1+\frac{B_d}{\theta}\left(\frac{\alpha\beta}{(1+\alpha C)^2}\right) \qquad (6)$$

where α is the Langmuir sorption coefficient related to the bonding energy [$M^{-1}L^3$]; β is the sorption capacity (maximum absorbed solute amount), which is limiting sorption [M/M]; R_{Lang} is the retardation factor for Langmuir sorption isotherm [dimensionless]. Although R_{Lang} is calculated as a function of concentration in simulation-optimization model, in this paper (in particular, section 4.1.2 related with sorption isotherms), it is assumed to be a constant from combination of the Langmuir sorption coefficient and sorption capacity in keeping the consistency with linear sorption at low solute concentrations and then is compared with R_{lin} to investigate the effects of sorption isotherms on the pump-and-treat.

The biochemical attenuation reactions of contaminants in aquifer often assume the first-order decay reaction written as

$$\left(\frac{\partial C}{\partial t}\right)_{rxn} = -\lambda C \qquad (7)$$

where λ is first-order decay rates [T^{-1}], which can be an important tool for evaluating monitored-natural-attenuation at groundwater contamination sites (Newell et al., 2002).

3.2. Optimization Model

The GA coupled with both the MODFLOW and MT3D in this study searches the optimal decision variables by using three basic operators - reproduction (selection), crossover, and mutation - in order to achieve success in the groundwater remediation. The details of the global optimum searching process of GA can be found in Goldberg (1989) and Ko et al. (2005). The input parameters of the GA are given in Table 2.

3.2.1. Objective function for the optimal pump-and-treat system

To evaluate the properties of the aquifer and the contaminant, which can be affecting on the pump-and-treat designs,

Table 2. Parameters for the genetic algorithm.

Parameters	Values
String	50
Bit	33
Maximum generation number	300
Crossover probability	0.7
Mutation probability	0.1

numerical experiments under various conditions are carried out. The objective of the pump-and-treat design is to achieve the optimal decision variables, such as the pumping rates, the pumping periods, and the number and locations of pumping wells, to minimize the remediation costs with all the constraints satisfied.

$$\text{Minimization } F_{P\&T} = \sum_{i=1}^{N_P} q_i \cdot t_p + c_I \cdot N_P + P_{P\&T} \quad (8)$$

Subject to

$$q^*_{min} \le q_i \le q^*_{max} \quad i = 1, \ldots, M \quad (9)$$

$$s_j < s^* \; j = 1, \ldots, M \quad (10)$$

$$C_j < C^* \; j = 1, \ldots, N \quad (11)$$

$$C_k \le 0 \; k = 1, \ldots, O \quad (12)$$

where $F_{P\&T}$ is the objective function for the pump-and-treat; q_i is the pumping rates of the i-th well for the pumping period t_p; N_P is the number of the pumping wells operated; c_O and c_I are the coefficients for the operating and the installation costs, respectively; $P_{P\&T}$ is the penalty value for violation of the constraints; q^*_{min} and q^*_{max} are the minimum and maximum pumping rates, 60 and 200 m^3/day respectively; M is the number of pumping wells; s_j and C_j are the drawdown and concentration at a j-th observation point at the end of the cleanup time; s^* and C^* are the drawdown and the concentration constraints, 10 m and 1 mg/L respectively; N is the number of observation points; C_k is the concentration at k-th observation point installed to prevent the contaminant plume from going out of the right side of the domain that is assumed to be the compliance line; O is the number of observation points installed on the compliance line.

3.2.2. Objective function for the optimal ENA system

The application of ENA in this study is expected to increase the cost-efficiency of the remediation system by injecting a primary electron acceptor, such as oxygen in this study, that accelerates aerobic degradation of the contaminant. Several field works have suggested that although many hydrocarbons are rapidly degradable under the aerobic condition, lack of the oxygen limits the microbial degradation of hydrocarbons in the aquifer (Bedient et al., 1984; Lee and Ward, 1984). This fact has persuaded us to assume an instantaneous hydrogen-oxygen reaction and to inject oxygen by using an oxygen release compound (ORC) for enhancing biodegradation in this study. It is sufficiently valuable that a new optimization model using ENA will be introduced to remediate the contaminated aquifer described earlier by releasing ORCs and enhancing biodegradation.

ORCs are a unique material of magnesium peroxide that releases oxygen at a slow rate over a long period of time when hydrated. A study of ORC application (Koenigsberg, 2001) demonstrated that the technology is best applied to dissolved phase plumes and moderate levels of residual NAPL after the majority of the source is removed by more mechanically intensive means. It also showed that the treatment using ORC is economical because it requires only 1/4 of the cost by the pump-and-treat system. And it referred that the average lifetime for an ORC application in the field is six months. Based on these reports, the ORCs are assumed to maintain the vicinity of injection wells under sufficiently aerobic conditions for 6 months and they are inputted as the constant concentration boundary of oxygen in the MT3D in this study.

The objective of the ENA design is to determine the locations where the oxygen concentration should be kept to 8 mg/L among the 48 potential locations shown in Figure 2.

$$\text{Minimization } F_{ENA} = c_{ORC} \cdot N_{ORC} + P_{ENA} \quad (13)$$

where F_{ENA} is the objective function for the ENA; c_{ORC} is the cost per ORC; N_{ORC} is the number of the injected ORCs; P_{ENA} is the penalty value for the ENA.

4. RESULTS AND DISCUSSION

4.1. Case of Pump-and-Treat

In this section, the effects of the retardation factor under linear sorption isotherm (section 4.1.1) and first-order decay rates (section 4.1.3) used generally in reactive solute transport simulation model are evaluated on the pump-and-treat operation including the pumping rates, the pumping schedule (section 4.1.4) the number and locations of pumping wells. And numerical experiments to examine the effects the sorption isotherm on the application of the pump-and-treat is also carried out by comparing each result under the linear and Langmuir sorption isotherms (section 4.1.2).

4.1.1. Effects of the retardation factor in linear sorption isotherm on pump-and-treat

Varying the retardation factors in the linear isotherm had some significant effects on the pump-and-treat design, as shown in Figure 3. The results demonstrate that the pumping wells P3, P4, and P5 placed on the downgradient of the contaminant plume were used with increasing pumping rates within the range of the retardation factor of benzene (R=1.1~2). However, high retardation conditions, above a

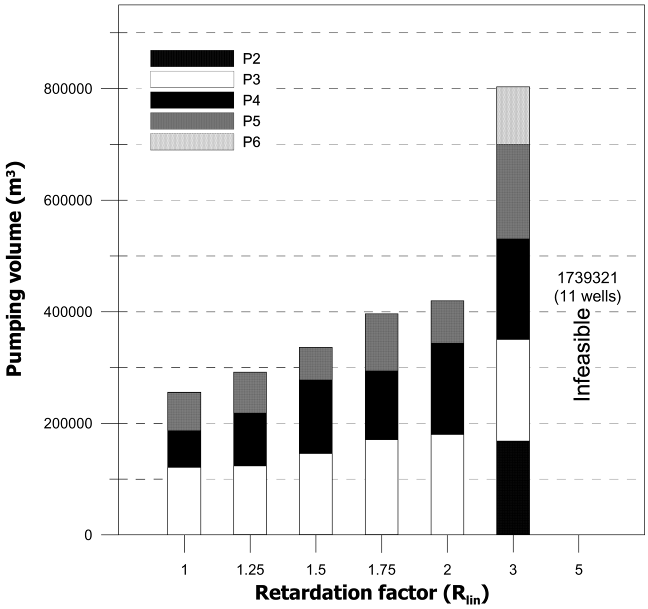

Fig. 3. Plot of optimal pump-and-treat designs with retardation factors (R_{lin}=1~5) in the linear sorption isotherm for λ=0.001.

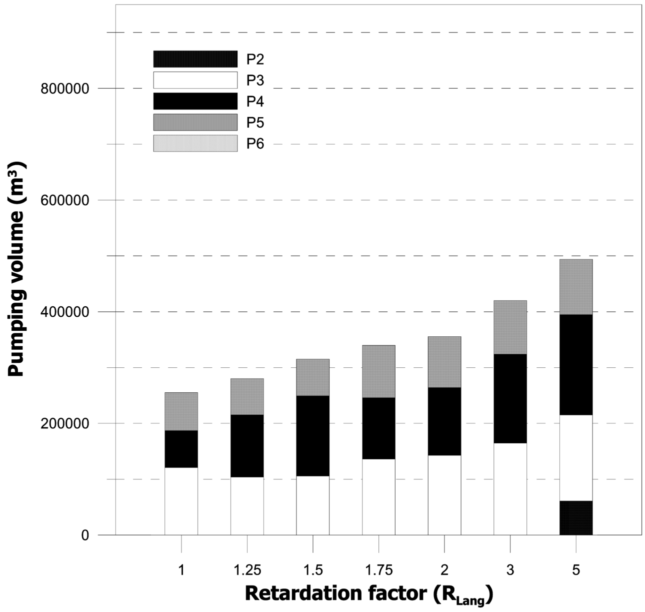

Fig. 4. Plot of optimal pump-and-treat designs with retardation factors (R_{Lang}=1~5) in the Langmuir sorption isotherm for λ=0.001.

R_{lin} of 2, brought about critical changes on the pump-and-treat designs by hindering the transport of contaminants into the pumping wells. Figure 3 shows that increments of R_{lin} from 2 to 3 dramatically increased the total pumping volumes and required two additional pumping wells for clean-ups. This means that the operation and installation costs greatly increased with the sorption resulting in the retardation. In addition, for R_{lin}=5, no design was feasible because they did not only cause excessive drawdown by immoderate pumping but also failed to lower the contaminant concentration to the target. From the perspective that the retardation directly disturbs the advection of the contaminant, this effect of the retardation factor was consistent with Ko et al. (2005) who referred to the fact that low hydraulic conductivity makes pump-and-treat infeasible.

And these results can also give an insight into the potential cost-reduction of remediation by surfactant application in order to reduce the retardation in the aquifer. For example, reducing R_{lin} from 3 to 2 through the injection of a surfactant was expected to result in about a 50% reduction in the remediation costs of the assumed groundwater contamination problem (Fig. 3).

4.1.2. Effects of the retardation factor in Langmuir sorption isotherm on pump-and-treat

In Figure 4, results under Langmuir isotherm conditions assuming sorption capacity (β) of 3 mg/Kg (Zheng and Wang, 1999) shows that the designs taking into account the Langmuir isotherm were less sensitive to variations in the retardation than those based on the linear isotherm. However, it is notable that a reduction of 14% on the total pumping volumes for the Langmuir isotherm design against that in the linear isotherm design for R=2 reached to 49% for R=3, and even the design for R_{Lang}=5 was found to be feasible. This result indicates that the choice of sorption isotherm can result in overdesign or underdesign and even determine the feasibility of the design. The differences between the designs are caused by the sorption capacity that limits the amount of solutes sorbing on the aquifer soil. And Figure 5 describes that a tenfold increase of sorption capacity increased total pumping volumes up to 13% for only R_{Lang}=2 and shows that the Langmuir isotherm design will eventually be analogous to the linear isotherm design as the sorption capacity increases. Because the sorption capacity will have much more effect on the pump-and-treat designs under strongly retarded conditions, as known from Figure 5 and a comparison Figure 3 and 4, and thus the differences between the designs based on the two isotherms will be greater as the retardation factor increases. Consequently, these problems associated with the retardation can increase the difficulty in deciding and performing the operational procedure of pump-and-treat.

4.1.3. Effects of first-order decay rates on pump-and-treat

Figure 6 shows that under conditions of R_{lin}=2 and pumping for 2.5 years, about 22% of the contaminant mass removed in the aquifer were attenuated by biodegradation of λ=0.001 day^{-1}. From this result, the potential benefits of enhancing biodegradation in the aquifer were evaluated by controlling the first-order decay rates in the simulation model. Figure 7 shows that if it can increase the λ of 0.001 day^{-1} by 0.0015 day^{-1} by injection of nutrients and/or electron acceptors into

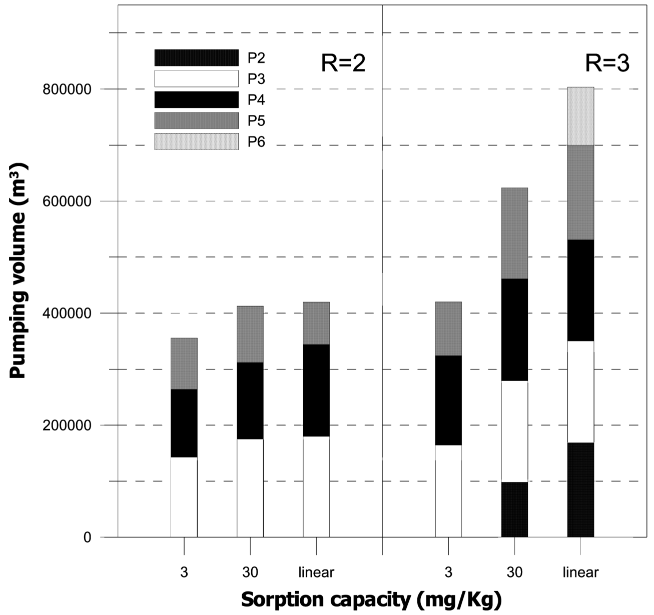

Fig. 5. Plot of optimal pump-and-treat designs with sorption capacities (β= 3 and 30 mg/Kg) for R_{Lang}=2 (left) and 3(right) and λ=0.001.

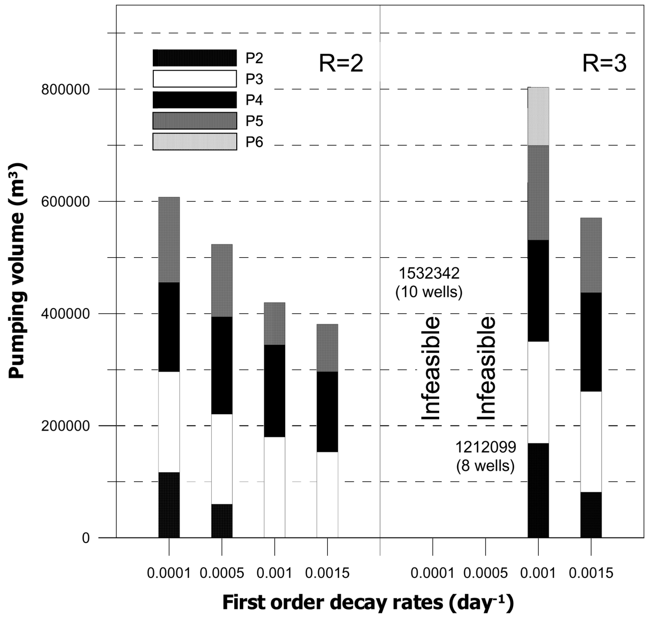

Fig. 7. Plot of optimal pump-and-treat designs with first-order decay rates (λ=0.0001~0.0015 day^{-1}) R_{lin}=2 (left) and 3 (right).

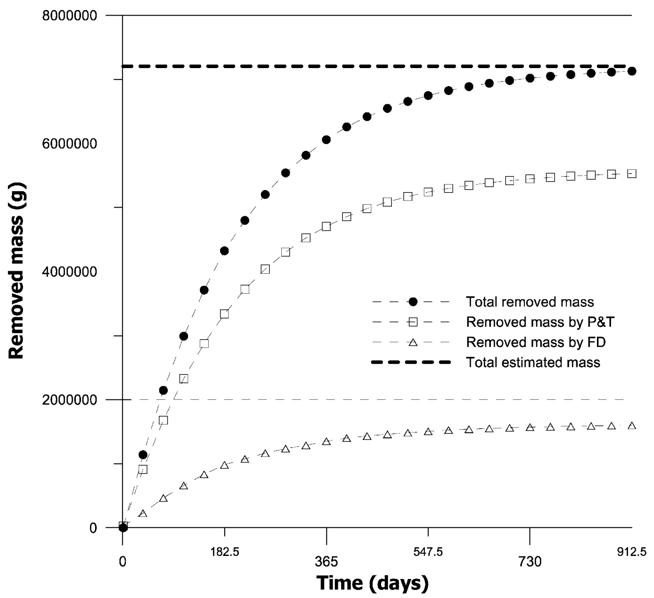

Fig. 6. Plot of total mass removed by pumping and first-order decay rates with time elapsed for R_{lin}=2 and λ=0.001 day^{-1}. About 22% of removed contaminant amount are attenuated but the mass removal efficiency by pumping decreases with time.

the assumed aquifer, the operation costs for R_{lin}=2 will be reduced by 10% and for R_{lin}=3 not only the total pumping volumes will be reduced up to 29% but also an additional pumping well will be unnecessary. Particularly, for the more severe retardation conditions under which the application of pump-and treat is not feasible, the enhancement of biodegradability can help the pump-and-treat to be able to remediate the contaminated groundwater successfully.

And a comparison between Figure 4 and Figure 7 also shows that only increments of 0.0005 day^{-1} of λ for R=2 considerably reduced the difference between the linear isotherm designs and Langmuir isotherm designs. This leads us to conclude that the enhancement of biodegradation will also be helpful in coming to a decision and application on the operation of pump-and-treat sensitive to the sorption isotherm assumption.

4.1.4. Pumping periods optimization with the retardation factor

The retardation also worked on the determination of optimal pumping periods significantly as shown in Table 3. (For comparison, in this section, it was assumed that λ=

Table 3. Optimal pumping period with retardation factor.

		Retardation factor, R_{lin}		
		1	2	3
	1	2.3 × 10^3 m^3 (4 wells)	Infeasible	Infeasible
Pumping	1.5	2.3 × 10^3 m^3 (3 wells)	5.3 × 10^3 m^3 (5 wells)	Infeasible
Periods, t_p (yrs)	2	2.2 × 10^3 m^3 (3 wells)*	4.2 × 10^3 m^3 (4 wells)	Infeasible
	2.5	2.6 × 10^3 m^3 (3 wells)	4.2 × 10^3 m^3 (3 wells)*	8.0 × 10^3 m^3 (5 wells)*

*Optimal design for each R_{lin}

0.001 day^{-1}) For no retardation (R=1), a pumping period of 2 years in a given remediation time, 2.5 years, was most appropriate among all the strategies. The reason why the short pumping strategy was suitable is that the contaminant mass was removed to a considerable extent by natural-attenuation as well as by the pumping. For R_{lin}=2, however, the most suitable design was to operate the pump-and-treat method for 2.5 years, which required fewer pumping wells than other designs. Moreover, for R_{lin}=3, only the pumping for 2.5 years could solve the remediation problem specified in this study. These results are because as the retardation factor increased the extraction of contaminants into pumping wells got into the difficulties and, thus, some short-term pumping strategies demanded more remediation costs, including additional pumping wells and greater pumping volumes, and even resulted in drawdown violation caused by excessive pumping in a limited pumping time. It can be noticeable that the strategy of short-term extraction can cause critical damage in terms of costs and safety under retarded transport conditions.

4.2. Case of Enhanced-Natural-Attenuation

Figure 6 shows that with R_{lin}=2 and λ=0.001 day^{-1}, the 2.5 yrs pumping strategy removed about 95% of the contaminant mass dissolved in the aquifer within only 1.5 years and that the mass removal efficiency decreases with time. And the results from section 4.1.3 also showed that improvement of biodegradation can be helpful in the pump-and-treat system applied under retarded conditions. These indicate that for a cost-effective and successful remediation, it is necessary to build an alternative to apply less expensive techniques such as natural-attenuation (NA) or enhanced-natural-attenuation (ENA) at a time when the efficiency decreases seriously. In this study, therefore, we have developed a new design model by means of ENA with the pump-and-treat method to improve the cost-efficiency of remediation operation processes. The model developed here is expected to overcome the inefficiency of a remediation system operating only a pump-and-treat method.

4.2.1. Performances of ENA design

To investigate the performance of the developed ENA model, the remediation designs were conducted considering three scenarios: (1) one stage of ENA for 1 year; (2) two stages of ENA each for 0.5 years; (3) one stage of ENA for 0.5 years and one stage of NA for 0.5 years. The NA was assumed that no action is done in contaminated aquifer, so that degradation of contaminant is only dependent on naturally inflowed oxygen at left boundary. All the scenarios began after solely pumping for 1.5 years with the aquifer condition of R_{lin}=2 and λ=0.001 day^{-1}.

In the design for the first scenario, a total of 56 ORCs for 1 year were required to inject into the vicinity upgradient of the contaminant plume so that the oxygen injected was transported into the plume along the groundwater flow

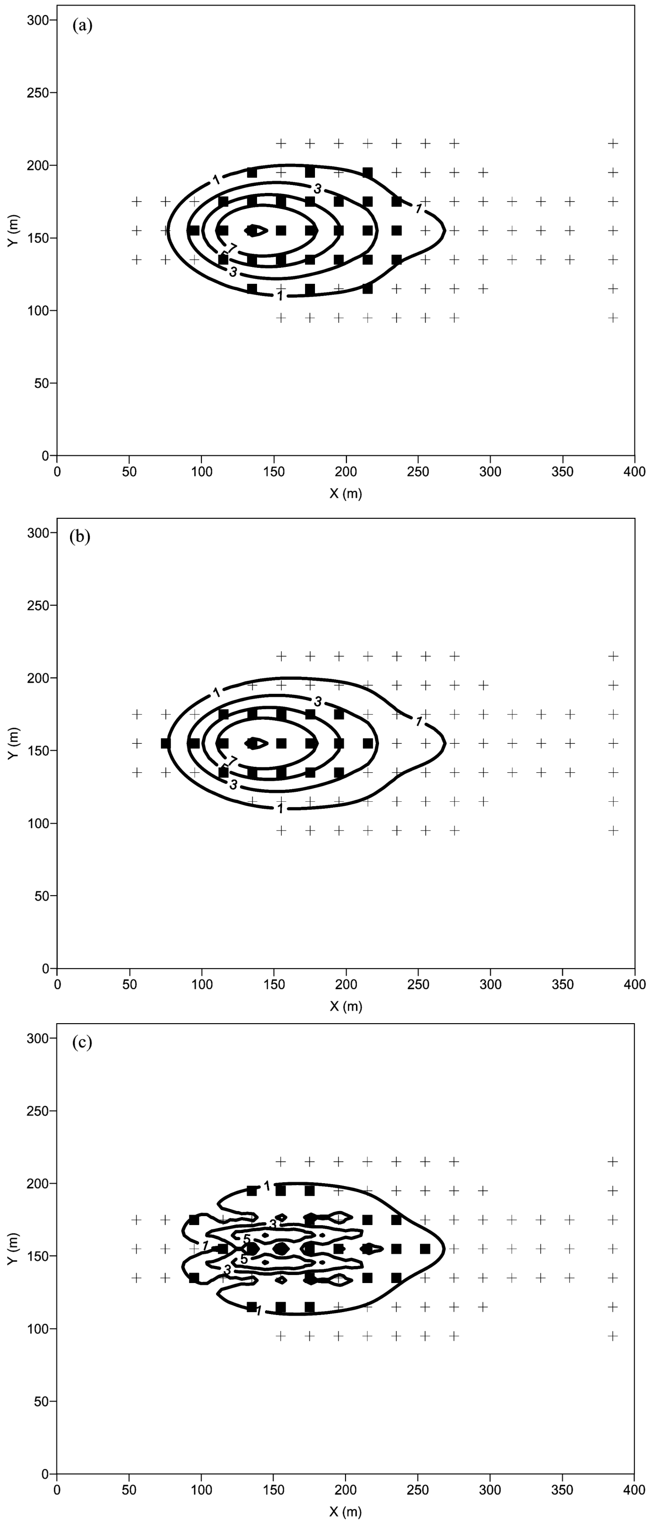

Fig. 8. Initial distributions of contaminant plume remained for each scenario and optimal ENA designs (locations injecting ORCs); (a) scenario 1; (b) first 0.5years for scenario 2 and 3; (c) last 0.5 years for scenario 2.

Table 4. Optimized results of enhanced-natural-attenuation.

	Number and distributions[a] of ORCs injected for 1 year		Total	Feasibility of design
	First 0.5 yrs	Second 0.5 yrs		
Scenario 1	28 (Figure 8(a))	28 (Figure 8(a))	56	Yes
Scenario 2	18 (Figure 8(b))	22 (Figure 8(c))	40	Yes (Optimal)
Scenario 3	18 (Figure 8(b))	0	18	No[b]

[a]The distributions of injected ORCs are shown in Figure 8.

[b]In scenario 3, the maximum concentration at observation points is estimated at 1.6 mg/L.

(Fig. 8(a)) and the concentrations estimated in all observation wells satisfied the concentration constraint specified in this study. For the first 0.5 years in the second and third scenarios, an ENA design was applied in both scenarios simultaneously because the initial contamination states in both scenarios are same. Figure 8(b) demonstrates the optimal injection locations of the 18 ORCs required for this first injection period. After the first ORC injection, the maximum concentration in the observation wells was found to be 2.7 mg/L. The ENA design for the next 0.5 years (the second half of scenario 2) suggested 22 ORCs to inject into the remaining plume shown in Figure 8(c), and therefore the second scenario required a total of 40 ORCs adding these 22 to the 18 ORCs for the first injection period. Finally, the third scenario applying the NA strategy, in which the mass removal depends on only background oxygen of 3 mg/L for the second 0.5 years, was found to be failure because the maximum concentration in the observation wells was measured at 1.6 mg/L. But it can also be a meaningful approach in the remediation efficiency because it was fairly close to the cleanup goal.

These numerical experiments conclude that the second scenario, injecting the ORCs depending on the variation of the plume distribution with time periods, was the most superior design with respects to costs (Table 4). However, all the successful designs have a drawback in that the concentrations in undetectable regions between the observation wells can be still above the cleanup goal. For an example, in the first scenario, maximum concentration in regions impossible to detect was confirmed to be about 6.5 mg/L in spite of not violating the concentration constraint in the observation wells. To overcome this drawback, it will be necessary to modify several settings, including the pre-specified injection locations and/or to intensify the concentration constraint that is often the typical standard specified in the literature or regulations at the design stage.

5. SUMMARY AND CONCLUSIONS

In this study, the importance of the natural attenuation processes, such as sorption and attenuation, as essential factors that should be considered on the design stage of pump-and-treat system was evaluated in a hypothetical aquifer. And we suggested enhanced-natural-attenuation system following the pump-and-treat as alternatives to improve the remediation efficiency in contaminated aquifer applying only the pump-and-treat system and developed the design model for the ENA. These are expected to provide a kind of guideline for the design of pump-and-treat system operated in an aquifer where the contaminants have a variety of natural and complex reactions.

Numerical experiments under varying retardation and attenuation conditions demonstrate that because the feasibility and the efficiency of the remediation system are highly sensitive to the retardation factor and attenuation rates of a contaminant, the pump-and-treat design without considering the natural attenuation processes can cause overdesign or underdesign. And they also indicate that before those considerations at the remediation design stage, needless to say, a better understanding about the fate and transport processes of contaminants in the aquifer through a careful site assessment ought to be involved first. The results show that strongly retarded transport prohibits short-term cleanup because it can not only increase the overall remediation costs but also cause serious drawdown violation by requiring excessive pumping rates. Under these severer retardation conditions, therefore, a longer pumping strategy should be adopted. In addition, it is significant that efforts to enhance biodegradability in aquifer system can be helpful to remediate the contaminant plume transporting under retarded condition.

The ENA optimization model determining the ORC injection locations was examined with respect to both cost efficiency and contaminant removal with considering three scenarios. Results show that the optimization model developed in this study is capable of obtaining the suitable designs to effectively attenuate residual contaminants remained after removing majority of contaminant plume using the pump-and-treat. Furthermore, if the pre-specified potential ORC injection locations are redistributed and/or the concentration constraint is intensified, this new ENA design model will be more useful to improve the efficiency of the remediation strategy including the pump-and-treat.

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