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Comparison of Continuous and Pulsed Pump-and-Treat for Mass Transfer-Limited Aquifers

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Abstract

Two different optimal design models are used to compare pulsed and continuous pumping remediation schemes for mass transfer-limited aquifers. All optimal design models couple a genetic algorithm with a flow and transport simulation model. The static pulsed pumping design model compares pulsed pumping with multiple management periods to continuous pumping for the same total remediation time. Results show that, depending on the initial mass of contaminant mass, it may be possible to cleanup the aquifer with costs similar to those of continuous pumping with less total pumping time. Although higher pumping rates are required for pulsed pumping, the total volume of water extracted decreases and the mass removal efficiency improves. The dynamic pulsed pumping design model compares pulsed and continuous pumping for the same pumping effort defined in terms of pumping days. By adjusting the total remediation time and using flexible management time lengths and pumping rates, considerable savings in both operating and capitals costs are achieved. Despite the longer remediation time, significantly less water is pumped out with increased mass removal efficiency.

Key words: Pulsed pump-and-treat, Genetic algorithms, Optimization, Aquifer remediation, Mass transfer-limitation.

Introduction

Part of the motivation for looking at ways to improve any remediation system is the enormous costs associated with cleanup as well as to increase the efficiency of cleanup. Over the next 30 years, it is estimated that the U.S. will spend between $ 400 billion and $ 1.7 trillion in remediating sites contaminated with hazardous wastes (Page, 1997). Therefore, even small improvements in the contaminant removal efficiency and reduction in remediation costs can be quantitatively significant.

Pulsed pumping has been suggested as a means of reducing high costs associated with ground water remediation (Keely, 1989; Sullivan, 1996). The application of pulsed pumping involves periodically turning on and off the pumps instead of pumping continuously. This may be especially useful for sites that are mass transfer-limited or with low hydraulic conductivity areas. Traditional pump-and-treat systems may initially remove a large mass of contaminants. However, for mass transfer-limited aquifers, the aqueous contaminant concentration will drop due to the slow kinetic desorption of the contaminant from the sorbed phase to the aqueous phase. Therefore, relatively clean water is extracted at the later stages of continuous pumping. This effect will lead to high remediation costs due to prolonged operating time. During the resting periods of pulsed pumping, concentration gradient driven desorption of the contaminant from the sorbed phase to the aqueous phase can be achieved. Furthermore, transfer of contaminants from the low conductivity areas to the relatively higher conductivity areas may occur. In a subsequent pumping period, the contaminant now in the aqueous phase can be readily removed. As a result, operating costs may be reduced during the resting periods when the pumping wells are turned off (Chan Hilton *et al.*, 2001).

Results of several earlier studies indicate that there is little, if any, improvement in the overall mass removal rate with pulsed pumping as compared to continuous pumping (Borden and Kao, 1992; Harvey *et al.*, 1994; Rabideau and Miller, 1994; Voudrias and Yeh, 1994; Gerhard *et al.*, 1998). However, as the modeling studies show, the advantage of using pulsed pumping over continuous pumping is the increased ratio of mass removed per volume of water pumped (Voudrias and Yeh, 1994; Gerhard *et al.*, 1998). Nevertheless, these studies do not focus on the optimal remediation design and costs of the pulsed pumping remediation schemes. Therefore, they do not support the claim of cost-effectiveness of pulsed pumping.

In this study, genetic algorithm (GA) optimization is used to analyze various pulsed pumping remediation schemes. GAs are probabilistic search methods that mimic the mechanics of natural selection and genetics (Holland, 1975). In contrast to the traditional search methods, they do not require derivative information and search from a population of policies. In addition, they can be applied to large-scale, complex problems, such as ground water remediation that might have non-linear, discontinuous and non-convex cost functions (Culver and Shoemaker, 1992; McKinney and Lin, 1995; Ahlfeld and Sprong, 1998). Due to their advantageous properties compared to traditional search methods, application of GAs to optimal ground water remediation design and management problems is increasing rapidly (Cieniawski *et al.*, 1994; McKinney and Lin, 1994; Ritzel *et al.*, 1994; Huang and Mayer, 1997; Wang and Zheng, 1997; Aksoy and Culver, 2000; Chan Hilton *et al.*, 2001; Aksoy and Culver, 2004).

This study explores the cost-effectiveness and the performance of pulsed pumping for mass transfer-limited and physically heterogeneous aquifers compared to traditional continuous pumping based on 2 different optimal design models. The first model, static pulsed pumping, compares pulsed and continuous pumping schemes for the same total remediation time. The second model, dynamic pulsed pumping, evaluates the pumping schemes that have the same total number of pumping days, but that can adjust the total remediation time for additional cost savings.

Methodology

In order to conduct the study, a ground water flow and contaminant transport model, BIO2D-KE (Culver, *et al.*, 1996), and a GA library, PGAPack (Levine, 1996), are linked together. The GA steps followed in this study start with the creation of the initial population of strings. Each string represents a set of decision variables, and therefore a potential solution, in binary encoding. The initial population of strings is randomly initialized and then evaluated with the objective function. Following the evaluation, each string is given a ranking fitness value. The selection process starts with the tournament selection method. In this method, 2 strings are selected randomly, and the one with the better ranking fitness value is copied into a temporary mating pool. This procedure is repeated until the number of strings in the temporary mating pool reaches the desired number of replacement strings. Since an elitist approach is utilized, a specified number of strings with the best fitness values are always copied to the new generation before the selection process starts. Following the selection process, information is exchanged between 2 strings using the crossover operator. Crossover is performed on each randomly picked pair with a certain probability, referred to as the crossover probability. Two-point crossover is applied where 2 locations are selected randomly and the material at the crossover sites is exchanged between the 2 selected strings. As a result, 2 new strings are created. Strings that do not undergo crossover become members of the next generation without modification unless they are subject to mutation. The mutation operator alters some of the bits on the strings in order to maintain the population diversity. Population diversity is sought in order to minimize premature convergence. Mutation is applied with a certain probability referred to as the mutation probability, which is generally low (1% to 4%). After the application of mutation, a new generation of strings is created. GA operations are repeated until a stopping criterion is met. In this study, the GA is terminated if no change is observed in the best solution after 50 successive generations.

The objective function used to evaluate the strings aims to minimize pulsed pumping remediation costs with no constraint violations. The magnitude of the constraint violations is determined using the response of the aquifer to a potential design (set of decision variables) encoded in a GA string. The response of the aquifer is quantified by BIO2D-KE, and given as head and concentration values at the end of the management time.

BIO2D-KE is a 2-dimensional depth-averaged finite element ground water flow contaminant transport simulation model. It can simulate the transport of contaminants that may undergo abiotic and/or biotic degradation and equilibrium and/or kinetic sorption. In this study biodegradation is assumed to be negligible with respect to advection, dispersion and sorption for the fate and removal of the contaminant. Although pumping rates and head values can change between pumping periods, it is assumed that the hydrological system responds quickly and that steady-state flow is achieved within pumping periods. Thus, within a pumping period, ground water flow is governed by the following equation for saturated flow:

$$\nabla \cdot (T\nabla h) + Q_w = 0 \tag{1}$$

where T is the transmissivity (L^2/T), h is the hydraulic head (L), and Q_w is the well flow rate (L^3/L^2T). BIO2D-KE simulates rate-limited contaminant sorption using the two-site equilibrium/kinetic sorption model that assumes 2 fractions controlled by 2 different sorption mechanisms. On one fraction (f) sorption is instantaneous and on the other (1-f) sorption is time dependent. As a result, the governing equation for solute transport undergoing rate-limited sorption is expressed as

$$b_s(n + \rho_b f K_d)(\partial C/\partial t) = \nabla \cdot (b_s D\nabla C) - b_s v \cdot \nabla C + (C_w - C)Q_w - b_s \alpha \rho_b[(1-f)K_d C - S_k] \tag{2}$$

where b_s is the saturated aquifer depth (L), C is the aqueous concentration of the contaminant (M/L^3), C_w is the contaminant concentration in the well water (M/L^3), D is the hydrodynamic dispersion coefficient (L^2/T), f is the fraction of sorption sites in equilibrium (-), K_d is the equilibrium partioning coefficient (L^3/M), n is the porosity (-), S_k is the mass of contaminant sorbed kinetically per unit mass of soil (M/M), t is the time (T), v is the linear velocity (L/T), ρ_b is the dry bulk density of the porous media (M/L^3), and α is the mass transfer coefficient (1/T).

All of the optimization models that will be discussed in later sections are applied to a homogeneous and confined aquifer depicted in Figure 1 (McKinney and Lin, 1994; McKinney and Lin, 1996; Aksoy and Culver, 2000). The dimensions of the confined aquifer are 244 m (east-west directional length) by 335 m (north-south directional length). The aquifer is discretized into 352 uniform rectangular elements with 391 grid points. Constant head boundaries of 35 m and 30.8 m on the west and east sides of the aquifer, respectively, create a flow in the easterly direction. No flow conditions exist at the north and south boundaries of the aquifer. Constant concentration boundaries (0 mg/l) are used on the east and west sides of the aquifer. Saturated thickness, porosity, and soil bulk density are 30.5 m, 0.2, and 1.81 g/cm^3, respectively. It is assumed that the aquifer is contaminated by an area source of tetrachloroethylene (PCE) for 15 years. PCE sorption parameters are 0.75, 0.0025 d^{-1}, and 0.36 cm^3/g for f, α, and K_d, respectively (Aksoy and Culver, 2000). The mass transfer rate used is within the range of rates reported for long-term contaminated soils (Koller *et al.*, 1996; Culver *et al.*, 1997).

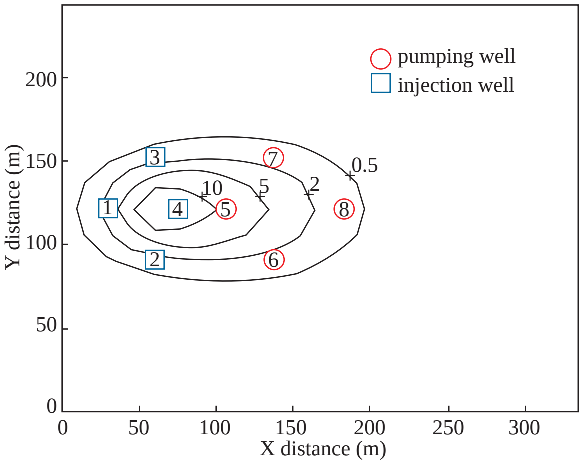

Figure 1. Initial PCE plume in total (aqueous plus solid) concentration (mg/l aquifer) and potential well locations.

General optimization model

The general optimization model is formulated as pulsed pump-and-treat ground water remediation systems with granulated activated carbon (GAC) treatment. The general objective of the optimization models is to minimize the operating and capital costs of continuous and pulsed pumping remediation schemes applied to mass transfer-limited aquifers. The cost functions incorporate the operating costs of treatment and pumping, and the capital GAC cost (McKinney and Lin, 1994; Culver and Shenk, 1998; Aksoy and Culver, 2000; Chan Hilton *et al.*, 2001). For GAC treatment, 100% contaminant removal efficiency is assumed. It is assumed that contaminated ground water is pumped out of the aquifer by continuous and pulsed pumping schemes, treated, and then re-injected back to the aquifer.

A pulsed pumping remediation scheme consists of multiple alternating periods of pumping and resting. During the resting period, pumps are turned off, and the treatment plant is not operated. Pumping and resting periods are represented by odd-numbered and even-numbered management periods, respectively. For example, a pulsed pumping remediation scheme with 5 management periods (MP = 5) consists of 3 pumping periods (management periods 1, 3 and 5) and 2 resting periods (management periods 2 and 4).

The general optimization model, with pumping rates as decision variables, can be mathematically expressed as

$$\begin{aligned}&\text{Minimize}[\sum_{m=1}^{MP} C_{\text{pump},m} + \sum_{t=1}^{ST} C_{\text{carbon},t} + \\ &\sum_{z=1}^{Z} C_{\text{capwell},z} + C_{\text{captreat}}]P_T\end{aligned} \tag{3}$$

where

$$C_{\text{pump},m} = 0.00038 t_m \sum_{e=1}^{E} [Q_{e,m}(60.96 - h_{e,m} + 10.5)] \tag{4}$$

$$C_{\text{carbon},t} = 0.42 t_s (C_t)^{0.48} Q_{tot,m} \tag{5}$$

$$C_{\text{capwell},z} = 5543 I_z (d_z)^{0.299} \tag{6}$$

$$C_{\text{captreat}} = 100,0000 n_{ads} \tag{7}$$

subject to:

$$0.0 \leq Q_{z,m} \leq 7.75 l/s \tag{8}$$

$$C_{aq\,\max} \leq C^*_{aq} = 1 mg/l \tag{9}$$

$$\begin{aligned}&C_{tot\,\max} \leq C^*_{tot} = C^*_{aq}(K_d \rho_b + n) = \\ &0.852 mg/(l \text{ aquifer})\end{aligned} \tag{10}$$

$$\sum_{e=1}^{E} Q_{e,m} = \sum_{i=1}^{I} Q_{i,m} \tag{11}$$

$$h_{\min} \geq 0 \tag{12}$$

$$h_{\max} \leq 60.96 m \tag{13}$$

where $C_{pump,m}$ is the pumping operational costs for management period m (\$), $C_{carbon,t}$ is the operational cost of the GAC treatment facility during simulation time step t (\$), $C_{capwell,z}$ is the capital and installation cost for well z (\$), $C_{captreat}$ is the capital cost of GAC adsorbers (\$), Z is the total number of potential wells (extraction + injection) (-), E is the total number of active extraction wells (-), MP is the total number of management periods (-), ST is the total number of simulation time steps (-), t_m is the length of the management period m (T), $Q_{e,m}$ is the volumetric extraction rate at extraction well e during management period m (L^3/T), $Q_{i,m}$ is the volumetric extraction rate at injection well e during management period m (L^3/T), $h_{e,m}$ is the hydraulic head, relative to the well depth, at the end of the management period m at potential extraction well e (L), t_s is the length of the simulation time step (T), d_z is the depth of well z (L), C_t is the weighted average influent concentration to the adsorbers for simulation time step t (T), $Q_{tot,m}$ is the total extraction rate during management period m (L^3/T), I_z is the flag (=0 if well z is never used, =1 if well z is ever operated) (-), n_{ads} is the number of adsorbers required for the treatment system (-), $Q_{z,m}$ is the volumetric pumping rate (injection or extraction) at a potential well during management period m (L^3/T), C_{aqmax} is the maximum aqueous concentration in the aquifer at the end of the remediation time (M/L^3), C$_{totmax}$ is the maximum total concentration in the aquifer at the end of the remediation time (M/L^3 aquifer), C$^*_{aq}$ is the aqueous concentration goal (M/L^3), C$^*_{tot}$ is the total concentration goal (M/L^3 aquifer), h$_{min}$ is the minimum head value in the aquifer at the end of the remediation time (L), h$_{max}$ is the maximum head value in the aquifer at the end of the remediation time (L), and P$_T$ is the penalty factor due to constraint violation(-).

The comparison of continuous and pulsed pump-and-treat schemes is evaluated based on 2 different optimal design models, namely; the static pulsed pumping model and the dynamic pulsed pumping model. These models are similar to the general optimization model with slight modifications in terms of the decision variables and constraint sets considered as discussed in the following sections.

Static pulsed pumping

The static pulsed pumping design model optimizes the pumping rates for specified management lengths and the total number of management periods. The decision variables for the static pulsed pumping design model are the extraction and injection rates at 4 potential extraction and 4 potential injection wells (Figure 1). It is assumed that the same wells are operated at the same pumping rates within every pumping period. Remediation schemes with 3, 5, and 7 management periods (MP = 3, MP = 5, and MP = 7, respectively) are considered. In addition to pulsed pumping schemes, a continuous pumping scheme (MP = 1) is computed in order to compare remediation designs and costs for pulsed pumping schemes to those for continuous pumping. It is assumed that all management time lengths (pumping and resting) within the total remediation time (1260 days) are equal. Therefore, the management time lengths are 1260, 420, 252, and 180 days for MP = 1, MP = 3, MP = 5, and MP = 7, respectively. As a result, actual pumping days decrease as the number of management periods increases. For example, actual pumping days for a continuous pumping scheme would be 1260 days. However, there are only 720 days for a pulsed pumping scheme with 7 management periods.

Remediation policies obtained using the static pulsed pumping design model are compared to continuous pumping for 2 different initial contaminant mass conditions. These are the small plume and the large plume cases. The initial contaminant plume for the small plume case is given in Figure 1. The peak aqueous concentration is 30 mg/l. For the large plume case, the initial aqueous and sorbed contaminant mass is doubled compared to the small plume case. All other features of the large plume case are the same as those of the small plume case.

Results for the static pulsed pumping runs

For the small plume case, the overall remediation costs (Table 1) are essentially constant regardless of the number of management periods. Optimum policies for pulsed pumping scenarios (MP = 1, MP = 3, MP = 5, and MP = 7) result in the selection of 1 injection well (well number 1) and 1 extraction well (well number 5). Only 1 GAC unit is selected. As a result, capital costs are the same. Pumping operational costs increase up to 15% as the number of management periods rises, due to increased pumping rates. However, this increase is compensated for by the decrease in treatment operating costs (down as much as 4%). As depicted in Figure 2, pumping rates required to cleanup the aquifer increase significantly (up to 63%) with the increasing number of management periods. This is expected, since for the same total remediation time the total pumping days must decrease with an increase in the number of pulsed pumping management periods (Figure 2). Thus, higher pumping rates are required to cleanup the aquifer in a shorter total pumping period. However, compared to continuous pumping (MP = 1), the total volume of water extracted to meet the water quality goals decreases with pulsed pumping despite the increase in pumping rates as shown in Figure 3. This decrease is more pronounced (up to 7%) with the increasing number of management periods for pulsed pumping scenarios. The contaminant removal efficiency, in terms of the mass of contaminant removed per volume of water extracted (PCE$_m$/V$_t$) generally increases by up to 5% with the increasing number of management periods (Figure 3). Results from these studies show that for the cases studied it is possible to meet the water quality goals with pulsed pumping using fewer pumping days and with similar total remediation costs as for continuous pumping.

Table 1. Remediation costs of the optimal pulsing policies given different total management periods.

Cost type	MP = 1	MP = 3	MP = 5	MP = 7
$\sum C_{\text{capwell}}$ ($)	38,000	38,000	38,000	38,000
C_{captreat} ($)	100,000	100,000	100,000	100,000
$\sum C_{\text{pump}}$ ($)	8700	10,000	9500	9500
$\sum C_{\text{carbon}}$ ($)	27,500	27,500	26,600	26,500
Total cost ($)	174,200	175,500	174,100	174,000

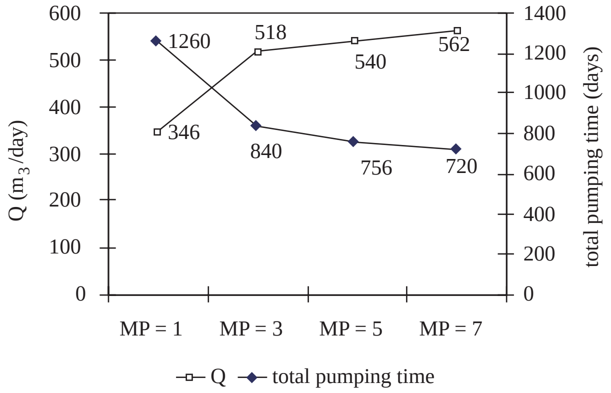

Figure 2. Extraction rates and the length of total pumping time for optimal static pulsing policies given different total management periods.

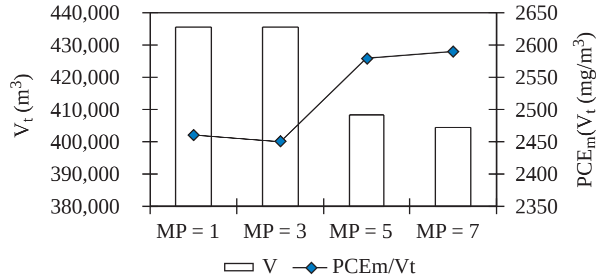

Figure 3. Total volume of water extraction (V_t) and mass of contaminant removed per volume extracted (PCE_m/V_t) for optimal static pulsing policies given different total management periods.

For the large plume case, none of the pulsed pumping scenarios result in a feasible policy that will meet the water quality constraints within the total management time of 1260 days. However, it is possible to find a feasible policy with the continuous pumping case. This policy costs $ 287,300. Two injection wells (well numbers 1 and 4) and 2 extraction wells (well numbers 6 and 7) are selected. Therefore, depending on the initial contaminant mass and pump capacity, pulsed pumping may necessitate a longer total remediation period (pumping and resting days) to meet the water quality goals.

Dynamic pulsed pumping design model

The dynamic pulsed pumping design model allows a longer remediation time for the pulsed pumping scheme compared to continuous pumping. However, the total number of pumping days is the same for both the pulsed and continuous pumping schemes. Both the pumping rates and the management period lengths are allowed to vary during the remediation period to obtain more cost-effective pulsed pumping schemes (Chan Hilton *et al.*, 2001). In a dynamic pulsed pumping scheme individual wells may pump at different rates, but all wells will use the same management period lengths. The constraint set used for the dynamic pulsed pumping design model is the same as that for the general optimization model. However, an additional constraint that limits the total pumping length is employed. This constraint sets the total pumping period length (t_{TP}) to 1260 days. Therefore, although total remediation time can be longer for the pulsed pumping remediation, the same effort, in terms of the total number of pumping days, is used for the continuous and pulsed schemes.

The dynamic pulsed pumping scheme is applied to the large plume case of the static pulsed pumping design model. Five management periods (MP = 5) are considered. The decision variables are the pumping rates at 4 potential injection and 4 potential extraction wells for each pumping period. Therefore, pumping rates and locations are allowed to change at every pumping period. All resting periods are assumed to be of equal length. Likewise, all pumping periods are of equal lengths with the exception of the first pumping period. This period is allowed to have unique length because the contaminant removal efficiency may be greatest for the initial pumping period. Therefore, 2 decision variables are used to control pumping and resting management period lengths. Assuming the total amount of pumping time (excluding resting periods) is fixed at 1260 days, the length of the first pumping period, t_1, is back-calculated from the value of the decision variable

Table 2. Optimal dynamic pulsed pumping policies given different management periods for the large plume case; Q_m= pumping rate during management period m, t_m= length of management period m, V_m= extraction volume during management period m.

	MP = 1			MP = 5		
Period m	Q_m (m^3/d)	t_m (d)	V_m (m^3)	Q_m (m^3/d)	t_m (d)	V_m (m^3)
1	1123*	1260	1,415,000	562	744	418,100
2				0	354	0
3				626	258	161,500
4				0	354	0
5				410	258	105,800
Total		1260	1,415,000		1968	685,400

*total of the rates at 2 active extraction wells

representing the length of the subsequent pumping periods, t_{sp}, as follows:

$$t_1 = 1260 - \left(\frac{MP-1}{2}\right) t_{sp} \qquad (14)$$

Results obtained for the dynamic pulsed pumping design with 5 management periods are compared to the optimum continuous pumping (MP = 1) policy obtained in the previous section for the large plume case.

Results for the dynamic pulsed pumping runs

Table 2 compares optimal designs for pulsed (MP = 5) and continuous (MP = 1) pumping. Results are given in total extraction rates (Q_m), length of the management periods (t_m), and the total volume of water extracted during management period m (V_m). Only 1 injection well (well number 1) and 1 extraction well (well number 5) are selected for the pulsed pumping scheme compared to 2 injection wells (well numbers 1 and 4) and 2 extraction wells (well numbers 6 and 7) for the continuous pumping scheme. Therefore, it is possible to meet the water quality standards with pulsed pumping using fewer active wells, although the time required for remediation increases by 56% . The total volume of water extracted for the dynamic pulsed pumping scheme is reduced by 52% compared to the continuous pumping scheme. Despite this decrease, contaminant removal efficiency (mass removed/volume extracted) is almost doubled for the pulsed pumping scheme. The figures are 1800 mg/m^3 and 3400 mg/m^3 for continuous and pulsed pumping, respectively.

Remediation costs for the optimal polices for continuous and dynamic pulsed pumping schemes are given in Table 3. Although treatment capital costs are the same, 50% , 55% and 34% savings are achieved in capital well costs, pumping operating costs, and treatment operating costs, respectively, for the dynamic pulsed pumping scheme compared to continuous pumping. Therefore, in addition to significant savings in the operating costs, savings in the capital costs are possible with dynamic pulsed pumping. These savings resulted in a 29% reduction in the overall remediation costs compared to continuous pumping.

Table 3. Remediation costs of the optimal policies for continuous (MP = 1) and dynamic (MP = 5) pulsed pumping schemes.

Cost type	MP = 1	MP = 5
$\sum C_{\text{capwell}}$ (\$)	76,200	38,000
C_{captreat} (\$)	100,000	100,000
$\sum C_{\text{pump}}$ (\$)	35,600	16,100
$\sum C_{\text{carbon}}$ (\$)	75,400	49,700
Total cost ($)	287,300	203,800

Conclusions

This study has analyzed various pulsed pumping remediation schemes with respect to continuous pumping for a mass transfer-limited aquifer. Results of the static pulsed pumping design problems show that depending on the initial mass of the contaminant, it may be possible to cleanup the aquifer with costs similar to those of continuous pumping with less total pumping time. Moreover, as indicated by the dynamic pulsed pumping design problems, significant savings both in operating and treatment costs can be attainable with pulsed pumping, if a longer remediation time compared to continuous pumping is permitted. The total remediation costs are reduced by 29% for the dynamic pulsed pumping scheme with flexible management time lengths and pumping rates. To put this in perspective, the reported capital costs for 21 sites that use pump-and-treat only as the remediation method range from \$ 310,000 to \$ 11,000,000, and the range of annual operating costs for these sites is \$ 91,000 to \$ 2,000,000 (EPA, 1999). Therefore, potential savings in remediation costs can make pulsed pumping appealing.

One of the major advantages of pulsed pumping over continuous pumping is the reduction of the total volume of water extracted. For all of the pulsed pumping remediation schemes evaluated, notably less (7% to 68%) water is pumped out. The volume of ground water extracted per year of operation at 21 pump-and-treat sites ranges from 6500 to $2.1x10^6$ m^3 per site (EPA, 1999). Therefore, reduction of water extracted may reduce the required treatment plant capacity. Additionally, mass removal efficiency per volume of water extracted has shown to be improved (5% to 3-folds) with the application of pulsed pumping schemes compared to continuous pumping. This outcome may be beneficial in increasing the contaminant removal efficiency in the treatment plant, in part due to higher inlet concentrations.

Nomenclature

b_s	saturated aquifer depth (L),
C	aqueous concentration of the contaminant (M/L^3),
C^*_{aq}	aqueous concentration goal (M/L^3),
C_{aqmax}	maximum aqueous concentration in the aquifer at the end of the remediation time (M/L^3),
C^*_{tot}	total concentration goal (M/L^3 aquifer),
C_{totmax}	maximum total concentration in the aquifer at the end of the remediation time (M/L^3 aquifer),
C_t	weighted average influent concentration to the adsorbers for simulation time step t (T),
C_w	contaminant concentration in the well water (M/L^3),
$C_{carbon,t}$	operational cost of the GAC treatment facility during simulation time step t (\$),
$C_{capwell,z}$	capital and installation cost for well z (\$),
$C_{captreat}$	capital cost of GAC adsorbers (\$),
$C_{pump,m}$	pumping operational costs for management period m (\$),
D	hydrodynamic dispersion coefficient (L^2/T),
d_z	depth of well z (L),
E	total number of active extraction wells (-),
f	fraction of sorption sites in equilibrium (-),
GA	genetic algorithm,
h	hydraulic head (L),
$h_{e,m}$	hydraulic head, relative to the well depth, at the end of management period m at potential extraction well e (L),
h_{min}	minimum head value in the aquifer at the end of the remediation time (L),
h_{max}	maximum head value in the aquifer at the end of the remediation time (L),
I	total number of active injection wells (-),
I_z	flag (=0 if well z is never used, =1 if well z is ever operated) (-),
K_d	equilibrium partioning coefficient (L^3/M),
L	length
m	management period (-),
M	mass
MP	total number of management periods (-),
n	porosity (-),
n_{ads}	number of adsorbers required for the treatment system (-),
S_k	mass of contaminant sorbed kinetically per unit mass of soil (M/M),
ST	total number of simulation time steps (-),
PCE_m/V_t	mass of contaminant removed per volume extracted (M/L^3),
P_T	penalty factor due to constraint violation (-),
$Q_{e,m}$	volumetric extraction rate at extraction well e during management period m (L^3/T), $Q_{i,m}$: volumetric extraction rate at injection well e during management period m (L^3/T),

$Q_{z,m}$	volumetric pumping rate (injection or extraction) at a potential well during management period m (L^3/T),
$Q_{tot,m}$	total extraction rate during management period m (L^3/T),
Q_m	pumping rate during management period m (L^3/T),
Q_w	well flow rate (L^3/L^2T),
T	transmissivity (L^2/T),
t	time (T),
t_m	length of management period m (T),
t_s	length of the simulation time step (T),
t_{sp}	length of the subsequent pumping periods (T),
v	linear velocity (L/T),
V_m	extraction volume during management period m (L^3),
V_t	Total volume of water extraction (L^3),
Z	total number of potential wells (extraction + injection) (-),
ρ_b	dry bulk density of the porous media (M/L^3),
α	mass transfer coefficient (1/T).

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