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Optimal planning of a dynamic pump-treat-inject groundwater remediation system

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Summary This study integrates the genetic algorithm (GA) and constrained differential dynamic programming (CDDP) to design the pump-treat-inject system. The proposed model considers both the cost of installing wells (fixed cost) and the operating cost of pumping, injection and water treatment. To minimize the total cost while meeting the water quality constraints, the model can compute the optimal number and locations of wells, as well as the associated optimal pumping and injection schemes. Various numerical cases reveal that the requirement to balance the total volume between pumping and injection can significantly influence the final optimal design.

Introduction

Groundwater is a valuable natural resource. However, it is threatened by contaminants from industrial and waste disposal activities and the problem has become more serious in recent years. Contaminant removal to clean up the aquifer is very expensive and generally takes many years. Many approaches have been applied to this problem. The pump-and-treat (PAT) method is one of the most commonly applied methods of groundwater remediation. By pumping out contaminated groundwater, treating the water and injecting the clean water to confine the pollutant plume, the method is primary useful for decontaminating groundwater with highly soluble pollutants.

Effective design of a remediation system in groundwater requires consideration of more than just the effectiveness of the technological process involved. The first step necessary in planning is to define the goals of design. The most commonly used objective for the remediation design is to minimize costs associated with the remediation system. In recent years, optimization models have been developed to design a groundwater remediation system (Gorelick and Voss, 1984; Taghavi et al., 1994; Aly and Peralta, 1999; Culver and Shenk, 1998). Previously, the fundamental approach of an optimal design was concerned with how to operate only the pumping wells in the most contaminated area (Chang and Shoemaker, 1992; Huang and Mayer, 1997; Zheng and Wang, 1999; Chang and Hsiao, 2002). Chang

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and Shoemaker (1992) applied constrained differential dynamic programming (CDDP) to the optimal remediation design of time-varying pumping rates, while considering only the operation cost. Huang and Mayer (1997) used a genetic algorithm (GA) to find the optimal extraction wells and corresponding pumping rates in remediation design. Zheng and Wang (1999) used an integrated approach which used the tabu search (TS) to define well locations and linear programming for optimizing pumping rate. Although Huang and Mayer (1997) and Zheng and Wang (1999) examine both fixed cost and operation cost, they consider only a steady pumping rate. Chang and Hsiao (2002) integrated GA and CDDP to overcome the problem of simultaneously considering both the fixed costs of well installation and the operating costs of time-varying pumping rates.

The previously reviewed studies in optimization consider only the extraction wells. However, a cost-effective remediation system for soluble pollutants should include both the withdrawal and injection wells in general. The approach has the effectiveness of creating a capture area which contains and prevents the contamination from migrating (Cohen et al., 1994; Bear and Sun, 1998; Wang et al., 1999; Cunningham and Reinhard, 2002). Such a technique is referred to as pump-treat-inject (PTI), one of the PAT, in which the contaminated water is pumped then treated, and the treated water is re-injected into the aquifer (Bear and Sun, 1998). The PTI technique has the function of hydraulic control that extraction wells locate in the dissolved plume to capture the contaminated water, and treated water is re-injected by injection wells to create a pressure ridge along the axis of the plume (Cohen et al., 1994; Wang et al., 1999). Cunningham and Reinhard (2002) demonstrated that the flow of pumping and injection acts as a hydraulic barrier, protecting potential drawdown gradient from contamination, in much the same manner as a permeable reactive barriers. More than one optimization method for the design of a PTI system has been developed. McKinney and Lin (1995) used mixed-integer programming in creating an optimal design for the air-stripping treatment process. The objective is to minimize the total cost including fixed cost and operating costs of pumping and injection at five potential wells. Bear and Sun (1998) used the two-level hierarchical optimization model to optimize the PTI design. At the basic level, well locations and pumping/injection rates are defined to maximize removal of contaminants. At the upper level, the number of wells for pumping/injection is optimized, so as to minimize the cost, taking maximum contaminant level as a constraint. Their study neglects operating cost, however, which is a large part of remediation cost. Guan and Aral (1999) used a progressive genetic algorithm to optimize the remediation design. For a specified well number, their study defines the well locations and pumping or injection rates for each well. The proposed model considers only the operating cost of steady pumping and injection. Hilton and Culver (2000) used a genetic algorithm to solve the same example as McKinney and Lin (1995). The proposed model considers the fixed and operating cost of pumping and injection. Both studies consider pumping and injection rate equilibrium, i.e. total pumping volume equals total injection volume during the planning period. However, the pumping and injection rates for each well are steady in their studies. A few researchers have considered time-varying pumping and injection rates. Minsker and Shoemaker (1998) applied SALQR to design the in situ bioremediation, which involves determining time-varying pumping and injecting rates for the extraction and injection wells, respectively. The injection wells are used to stimulate the microbial population and accelerate degradation of pollutants by injecting electron accepters, nutrients, additional carbon or electron donor sources. However, the study considered only the operating cost not the fixed cost.

Total cost of a PTI system should include the installation and operation cost, and, to be cost-effective, the operation policy should be time-varying because the dynamic policies are allowed to change as the contaminant plume moves. However, optimal design for the PTI system is a highly complex problem and none of the previous works has examined this problem. Therefore, this study develops a hybrid algorithm by integrating the genetic algorithm (GA) and constrained differential dynamic programming (CDDP) to solve the dynamic PTI design problem. The optimal wells network and the optimal pumping or injection rates for each well are all computed by the proposed algorithm. The algorithm incorporates the time-varying policies of PTI system and also considers pumping and injection rate equilibrium for each time step.

Formulation of the planning model

The formulation to minimize both the fixed and operating costs of the system while determining the extraction or injection well network and pumping/injection rate is as follows:

$$\min_{\substack{W\subset\Omega\\ u_{t,j},j\in P\\ u_{t,i},i\in I\\ t=1,\dots,N}} J(W)=\left\{\sum_j a_1 y_j(P) + \sum_{t=1}^{N}\sum_j\left[a_2 u_{t,j}(P)[L_j(P)-h_{t+1,j}(P)]+a_3 u_{t,j}(P)\right]\right\} + \left\{\sum_i a_1 y_i(I)+\sum_{t=1}^{N}\sum_i[a_4 u_{t,i}(I)]\right\} \quad (1)$$

subject to

$$\{x_{t+1}\}=T(x_t,u_t(W),t,W),\quad t=1,2,\dots,N \quad (2)$$

$$c_{N,l}\leqslant c_{\max},\quad l\in\Phi \quad (3)$$

$$\sum_j u_{t,j}(P)\leqslant Tu_{\max},\quad t=1,2,\dots,N,\ j\in P,\ P\subset\Omega \quad (4)$$

$$u_{\min}^{(p)}\leqslant u_{t,j}(P)\leqslant u_{\max}^{(p)},\quad t=1,2,\dots,N,\ j\in P,\ P\subset\Omega \quad (5)$$

$$u_{\min}^{(in)}\leqslant u_{t,i}(I)\leqslant u_{\max}^{(in)},\quad t=1,2,\dots,N,\ i\in I,\ I\subset\Omega \quad (6)$$

$$h_{\min}\leqslant h_{t,i}\leqslant h_{\max},\quad t=1,2,\dots,N,\ i\in W \quad (7)$$

$$\sum_j u_{t,j}(P)=\sum_i u_{t,i}(I),\quad t=1,2,\dots,N,\ j\in P,\ P\subset\Omega,\ i\in I,\ I\subset\Omega \quad (8)$$

where Ω is an index set defining all of the candidate well locations in the aquifer; W is a network alternative, which is the union of the pumping network P and injection network I ($W=P\cup I, P\cap I=0$), and is the subset of candidate well locations ($W\subset\Omega$). W is represented by a chromosome in the GA described subsequently; $J(W)$ is total cost of W. $u_{t,j}$ is pumping rate at jth well in the pumping network P during time t. $u_{t,i}$ is injection rate at ith well in the injection network I during time t. $L_j(P)$ are the distance from the ground surface to the lower datum of the aquifer for well$j$; $h_{t+1,j}(P)$ denote hydraulic head for well j at time $t+1$; $y(\cdot)$ is the depth of well; a_1 is the well installation cost coefficient, a_2 is the cost coefficient for pumping the contaminated groundwater, a_3 is the cost coefficient for the pumped water treatment, and a_4 is the cost coefficient for injection water.

$T(x_t, u_t(W), t)$ represents the transition equation. $x_t = [h_t{:}c_t]^{\mathrm{T}}$ is the continuous state variable representing heads h_t and concentrations c_t, $u_t(W)$ represents the control vector whose length depends on W. $c_{\max}$ represents the maximum allowable concentration; Φ is the set of observation wells. $Tu_{\max}$ represents the maximum allowable total pumping rates from all extraction wells; $u^{(\mathrm{p})}_{\max}$ and $u^{(\mathrm{p})}_{\min}$ represent the maximum and minimum allowable pumping rate in the extraction well; $u^{(\mathrm{in})}_{\max}$ and $u^{(\mathrm{in})}_{\min}$ represent the maximum and minimum allowable injection rate in the injection well; $h_{\max}$ and $h_{\min}$ represents the upper and lower bounds of hydraulic head.

Eq. (1) is the total for the whole system including the installation and operation for pumping and injection. The first and second components in Eq. (1) are the costs of the pumping subsystem, involving installation and pumping operation cost. The pumping operation cost includes extraction and treatment costs. The third and fourth components in Eq. (1) are the costs of the injection subsystem, involving installation and injection operation costs. The fourth component in Eq. (1) assumed the cost to inject the water by gravity gradient is the minimal and can be neglected. Therefore, the operation cost for injection is only the cost to obtain the clean water. The transition equation in Eq. (2) is ISOQUAD (Pinder, 1978), an implicit finite element groundwater flow and transport model for a two-dimensional confined aquifer. The model computes changes in head and contaminant concentration due to pumping or injection. The mechanism of contaminant transport considered in the model includes advection, diffusion, dispersion, and linear equilibrium sorption. The constraint in Eq. (3) ensures the water quality standard will be met at the specified monitoring wells at the end of the planning period. The constraint in Eq. (4) specifies the capacity constraint for the treatment plants. The constraints in Eqs. (5) and (6) specify the capacity constraints for each pumping or injection well. The lower and upper bounds on the hydraulic head are listed in Eq. (7). The constraint in Eq. (8) is to maintain the volume equilibrium between pumping and injection during time t.

The algorithm of GCDDP: integration of a GA and CDDP

As previous stated, this investigation integrates GA and CDDP to solve the problem defined by Eqs. (1)–(8). The problem is a mixed-integer nonlinear time-varying problem and includes discontinuous variables (pumping/injection well locations) and continuous variables (time-varying pumping/injection rates), and cannot be solved by a single conventional optimization scheme. Therefore, this study further explores the problem structure and reformulates the problem into a two-level optimization problem to facilitate the application of GA and CDDP.

The main problem:

$$\min_{\substack{W\subset\Omega,\\ u_{t,j},j\in P\\ u_{t,i}i\in I\\ t=1,\ldots,N}} J(W)=\sum_j\left[a_1y_j(P)+J_2^*(P)\right]+\sum_i\left[a_1y_i(I)+J_3^*(I)\right] \tag{9}$$

The sub-problem:

$$J_2^*(P)=\min_{\substack{u_{t,j},j\in P\\ t=1,\ldots,N}}\left\{\sum_{t=1}^{N}[a_2u_{t,j}(P)[L_j(P)-h_{t+1,j}(P)]+a_3u_{t,j}(P)]\right\} \tag{10}$$

$$J_3^*(I)=\min_{\substack{u_{t,i},i\in I\\ t=1,\ldots,N}}\left\{\sum_{t=1}^{N}[a_4u_{t,i}(I)]\right\} \tag{11}$$

subject to Eqs. (2)–(8) (12)

Solving the two-level problem Eqs. (9)–(12) is equivalent to solving the original problem Eqs. (1)–(8). Firstly, the number of pumping and injection wells is obtained in Eq. (9).Then, the optimal pumping rate from Eqs. (10)–(12) is determined. However, by the two-level formulation, the discrete nature of the original problem is considered in the main problem and facilitates the application of other computational efficient algorithms to solve the sub-problem and thus reduce the computational burden. The main problem (Eq. (9)) is a discrete combinatorial problem and can be solved by GA. The decision variable for the main problem is network design W, that is a set of pumping (P) and extraction (I) wells, and is a discrete variable. The network design is encoded as a chromosome in GA and the total cost for the network design (chromosome) is the sum of the optimal operation costs ($J_2^*(P)$and$J_3^*(I)$) and its fixed costs. The optimal operating cost for a given network design is computed in the sub-problem using CDDP. The sub-problem represented by Eqs. (10)–(12) contains the operation cost and constraints and is a continuous nonlinear dynamic optimization problem. A CDDP algorithm (Chang and Shoemaker, 1992; Culver and Shoemaker, 1992, 1993; Mansfield et al., 1998; Mansfield and Shoemaker, 1999) is suitable to solve the sub-problem because the functions are separable in time. In principle, the sub-problem can also be calculated by GA but this will dramatically increase the required computational resources.

The GCDDP algorithm (Hsiao and Chang, 2001; Chang and Hsiao, 2002; Hsiao and Chang, 2002) shown in Fig. 1 is a GA with CDDP embedded to compute the optimal operation costs for each network design (a chromosome). Fig. 1 illustrates the procedure of the algorithm which including parameter encoding, the fitness calculation, and the evolution of the chromosomes through reproduction, crossover and mutation. Fig. 1 is further clarified by the following step-by-step description.

Step 0: initialization

The algorithm begins with a set of chromosomes (network designs) that are represented by binary strings. For all the cases, there are 100 chromosomes for each generation. First this study encodes the network design as chromosomes and randomly generates an initial population. A chromosome is a binary string to represent the status of the well installation

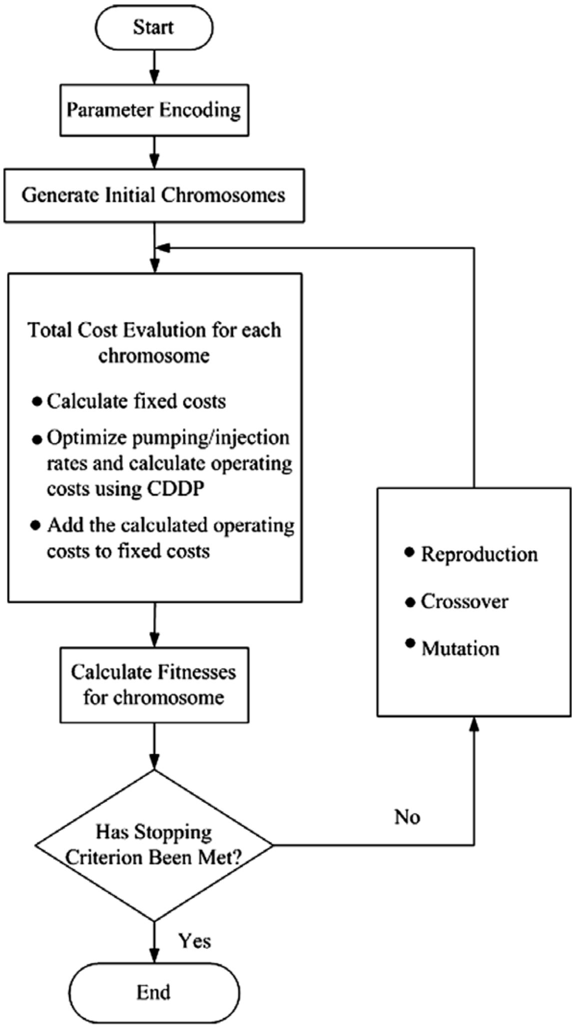


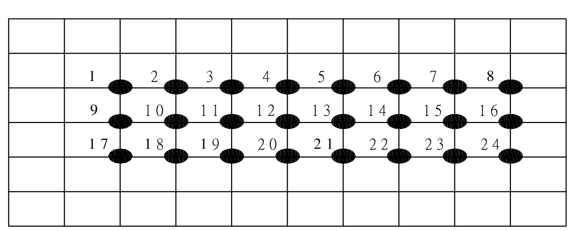
Figure 1 Flowchart of the GCDDP algorithm.

on a candidate site. The binary encoding is simple to code and manipulate. Well selection is binary, encoding and decoding is straightforward (Chang and Hsiao, 2002). In this study, the status of the well installation on a candidate site differs from what Chang and Hsiao (2002) propose, and have three situations: not installing a well; installing a pumping well; or installing an injection well. Fig. 2 is the example of encoding and decoding and there are 24 candidate sites to be encoded for each chromosome. Each candidate site requires 4-bit binary digits to indicate the status of the well installation. However, owing to the symmetrical condition of this study, only 16 wells need to be considered. Therefore, the bit numbers for a binary string (a chromosome) are 64. Decoding the binary digits, the genotype has 16 conditions and will be mapped to phenotype which has three situations, 0, 1, 2, to represent the status of well installation. This study assumes Phenotype 0 represents not installing a well, 1 represents installing a pumping well and 2 represents installing an injection well.

Step 1: evaluate the total cost and fitness value for each chromosome

The total cost for each chromosome, or network design, includes the fixed and associated operation costs. The fixed cost in Eq. (9) can be evaluated easily for each network design. For each chromosome, an embedded CDDP algorithm is applied to determine the optimal operating cost in Eqs. (10)—(12). The algorithm developed in this study is modified from that proposed by Chang and Hsiao (2002), with the modification for the derivatives of a transition equation. The modification is caused by considering the pump-treat-inject decontamination method.

The derivatives of the transition equation are adapted from Chang and Shoemaker (1992) with the modification with respect to u_t. The transition equation is expressed in matrix form as:



No of well	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Binary code	0000	0 001	0010	0011	0100	0101	0110	0111	1000	1001	1010	1011	1100	1101	1110	1111
Genotype	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Phenotype	0	0	0	0	0	1	1	1	1	1	1	2	2	2	2	2

Figure 2 The example of chromosome encoding and decoding to represent the status of well installation on a candidate site (Phenotype 0 represents not installing a well, 1 represents installing a pumping well, 2 represents installing a injection well).

$$([A] + [B]/\Delta t)\{h_{t+1}\} = \frac{[B]}{\Delta t}\{h_t\} - \{F_h\} + [L_h]\{u_t\} \tag{13}$$

$$([N(h_{t+1}, u_t)] + [M]/\Delta t)\{c_{t+1}\} = \frac{[M]}{\Delta t}\{c_t\} - \{F_c\} + [L_c(u_t)]\{c' - c_{t+1}\} \tag{14}$$

where the coefficients of the matrices and vectors are derived from the FEM flow and transport model.

Derivative of transition equation with respect to x_t, u_t is:

$$\left[\frac{\partial T}{\partial x_t}\right] = \left[\frac{\partial x_{t+1}}{\partial x_t}\right] = \begin{bmatrix} \frac{\partial h_{t+1}}{\partial h_t} & \frac{\partial h_{t+1}}{\partial c_t} \\ \frac{\partial c_{t+1}}{\partial h_t} & \frac{\partial c_{t+1}}{\partial c_t} \end{bmatrix} \tag{15}$$

$$\left[\frac{\partial T}{\partial u_t}\right] = \left[\frac{\partial x_{t+1}}{\partial u_t}\right] = \begin{bmatrix} \frac{\partial h_{t+1}}{\partial u_t} \\ \frac{\partial c_{t+1}}{\partial u_t} \end{bmatrix} \tag{16}$$

In Eq. (14), c' represents the concentration of the pumping water or injection water. This study assumes $c'_t = c_{t+1}$ for pumping water and $c'_t = 0$ for injection water, where c_{t+1} is the contaminant concentration of the groundwater in the aquifer.

Step 2: reproduce the best strings

Using tournament selection, GA selects parents from the string population based on the fitness of each string.

Step 3: perform crossover

Crossover involves randomly coupling the newly reproduced strings and each string pair partially exchanges information. Crossover aims to exchange gene information so as to produce new offspring strings that preserve the best material from two parent strings. In general, the crossover is performed with a certain probability (p_{cross}) so that it is performed on a majority of the population, where p_{cross} ranges from 0.8 to 1.0. The following cases use the crossover rate (p_{cross}) equals 0.8.

Step 4: implement the mutation

Mutation restores unexplored genetic material to the population to prevent the GA from prematurely converging to a local minimum. A mutation probability (p_{mutat}) is specified so that random mutations can be made to individual genes. The value of p_{mutat} normally ranges from 0.01 to 0.05 (Goldberg, 1989). A mutation probability (p_{mutat}) equals 0.01 in the following cases. Before implementing a mutation, a random number with uniform distribution is generated. If this number is smaller than the mutation probability, mutation is performed. Otherwise, it is skipped. Notably, mutation changes a specific gene ($0 \to 1$ or $1 \to 0$) according to the specific probability in the offspring strings that is produced by crossover operation.

Step 5: perform termination

After steps 1–4, a new population is formed. The new population requires evaluating the total cost such as in step 1. Total cost evaluation is used to calculate the fitness and assess the stopping criterion. The stopping criterion is based on the change of objective function value (total cost). If the best design does not improve over a pre-specified number of generations or the iterations equal the maximum number of generations, the algorithm terminates. Otherwise, it goes back to step 1 for another cycle (another generation). In the study, if the best design does not improve over ten generations or the generations number exceed thirty, the computation will terminate.

Results and discussion

This study presents the solutions obtained for a hypothetical, isotropic confined aquifer with dimensions of 600 m by 1200 m to demonstrate the performance of the algorithm described above. Fig. 3 indicates the finite element mesh which has 91 finite element nodes, along with 24 candidate well sites, and 17 observation wells. The boundary conditions on the north and south sides are no-flow boundaries for head and concentration. Constant-head boundaries with 22 and 10 m are located on the west and east sides individually, and constant-concentration boundaries with 0 mg/L are located on both west and east sides. The hydraulic head distribution prior to pumping is assumed to be steady and the initial peak concentration within the aquifer is 150 mg/L, and the water quality goal at the end of 5 years must be less than or equal to 0.5 mg/L (c_{max}) at all the observation wells. There are 20 management periods and each period (Δt) is 91.25 days. Aquifer properties are listed in Table 1. Table 2 presents the value of cost-related coefficients, a_1, a_2, a_3 and a_4 are explained in ''Formulation of the planning model'' section that adapted from Chang and Hsiao (2002) where the a_4 value depends on the case being analyzed.

The performance of the proposed model was evaluated in a number of scenarios as presented in Table 3. Case 1 considers the pumping strategy only, and the decision variables are pumping network and pumping rate. Other cases consider both pumping and injection strategies, and the decision variables are the network design and the rates of pumping and injection. For cases 1 and 2, the system is designed to dispose the treated pumping water into the river. Furthermore, case 2 also assumes that the system needs to import the clean water; as a result, the injection cost coefficients are much higher than those of cases 3 and 4. On the other hand, for cases 3 and 4, the system injects the treated water back into the aquifer. For case 3, the system is assumed to store temporally the treated water and then to inject it back to the aquifer. By contrast, for case 4, the rate of equilibrium between pumping and injecting as represented by Eq. (8) is employed to force the system to inject the treated water back into the aquifer simultaneously. The results of all scenarios are summarized in Table 4.

Effect of design concept on the optimal design and performance

Eqs. (1)–(8) are the formulation for the optimal design of groundwater remediation system in general, and an individual constraint in the formulation may relate to a design concept. As described in previous section, cases 1–4 make different design assumptions. This section will illustrate

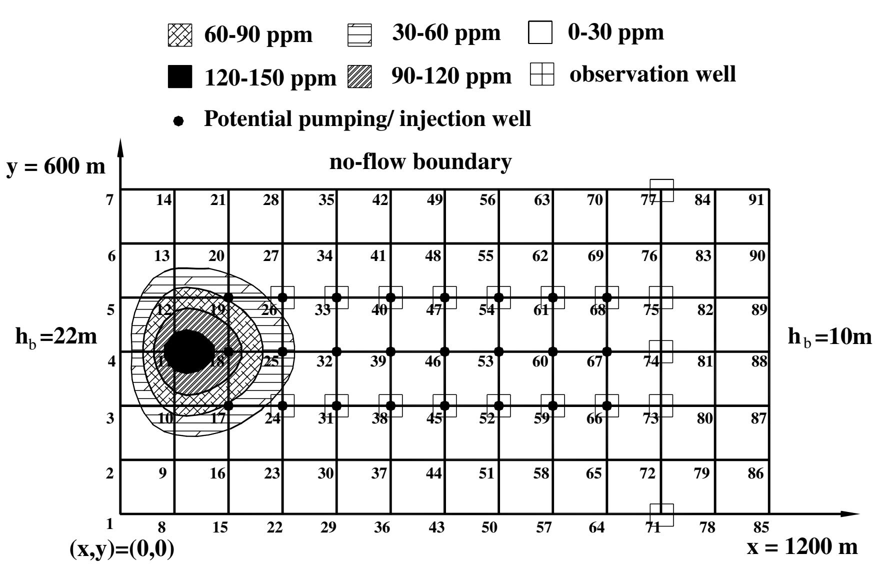


Figure 3 Finite element mesh, boundary conditions, initial plume, and locations of numbered observation and potential wells for all runs of the groundwater reclamation example.

Table 1 Aquifer properties of example application

Parameter	Value
Hydraulic conductivity	4.31×10^{-4} m/s
Longitudinal dispersivity	70 m
Transverse dispersivity	3 m
Diffusion coefficient	1×10^{-7} m^2/s
Storage coefficient	0.001
Porosity	0.2
Sorption partitioning coefficient	0.245 cm^3/g
Media bulk density	2.12 g/cm^3
Aquifer thickness	10 m
Ground elevation	120 m

Table 2 The value of cost coefficient in the cases and the values associated with the constraints

Coefficient	Value
a_1	\$12/m
a_2	\$1000/(m^3/s m Δt)
a_3	\$40,000/(m^3/s Δt)
a_4	\$1, or 2000/(m^3/s Δt)
Tu_{max}	2000 L/s
$u^{(p)}_{max}$, $u^{(in)}_{max}$	120 L/s
$u^{(p)}_{min}$, $u^{(in)}_{min}$	0 L/s
h_{max}	30 m
h_{min}	0 m

how to formulate a design concept by constraints, and examines the influence of each design concept on the total cost and the decontaminating performance by comparing the numerical results of each case. Table 3 indicates the scenarios for all cases; Table 4 summarizes the results; and Fig. 4 shows the pumping and injection rate at each time step for all the cases. Different colors in Fig. 4 are associated with the pumping and injection wells. The red is pumping; blue is injection. Case 1 considers the pumping system only and, as indicated in Table 4, and its optimal total cost is \$63,557. Although case 2 allows installing both pumping and injection wells, the optimal design uses injection wells only since the injection operation cost, cost to obtain the clean injection water, for case 2 is cheaper than the pumping operation cost which involved the pumping and treatment. Case 2 has the lowest cost among all the cases as indicated by Table 4. However, since injection well system can only dilute the contaminant concentration but cannot remove the pollutants from the aquifer, case 2 is not a good design although it has the lowest cost. The situation can be illustrated by Fig. 5, that shows the concentration distribution at the final time step for all the cases. As shown by Fig. 5b, the remediation system of case 2 only pushes the groundwater contaminants away from the observation wells to meet the pollutant constraints instead of removing the contaminants from the aquifer. To correct this problem, case 3 required the system using the pumping well by adding a constraint '$\mathrm{num}(P) > 0$', where $\mathrm{num}(P)$ is the number of pumping well. Case 3 also assumed the injected water came from the treated water so that the total injection cost was cheaper than in case 2. Table 4 shows that only one pumping well and two injection wells were installed and the fixed cost of case 3 is lower than that of case 2. However, since the total pumping cost of case 3 was much higher than that of case 2, the total cost of case 3 was still higher than that of case 2. However, unlike case 2, case 3 removed the pollutants from the aquifer, as indicated by Fig. 5c.

For cases 1—3, the system assumed all or part of the treated water was disposed to river and this may have another environmental impact that is not considered in the cost function. To avoid the potential environmental concern, one potential solution is to inject all the pumped and treated water back into the aquifer and design a closed water-circulation system to continuously wash the aquifer until the pollutant concentrations meet the water quality standard. There are several other measures such as the gra-

Table 3 The scenario summaries for each case

Case	Strategy	Injection cost coefficients	Pumping and injection rates equilibrium
1	Pump	Not considered	Not considered
2	Pump and inject	2000 ($m^3/s\ \Delta t$)	Not considered
3	Pump and inject	1 ($m^3/s\ \Delta t$)	Not considered
4	Pump and inject	1 ($m^3/s\ \Delta t$)	Considered

Table 4 The summaries of result for all cases

Case	Number of pumping well	Number of injection well	Total pumping cost		Total injection cost		Total cost
			Fixed cost	Operating cost	Fixed cost	Operating cost	
1	2	0	2880	60,677	0	0	63,557
2	0	5	0	0	7200	32,869	40,069
3	1	2	1440	62,782	2880	0	67,102
4	5	5	7200	104,766	7200	0	119,166

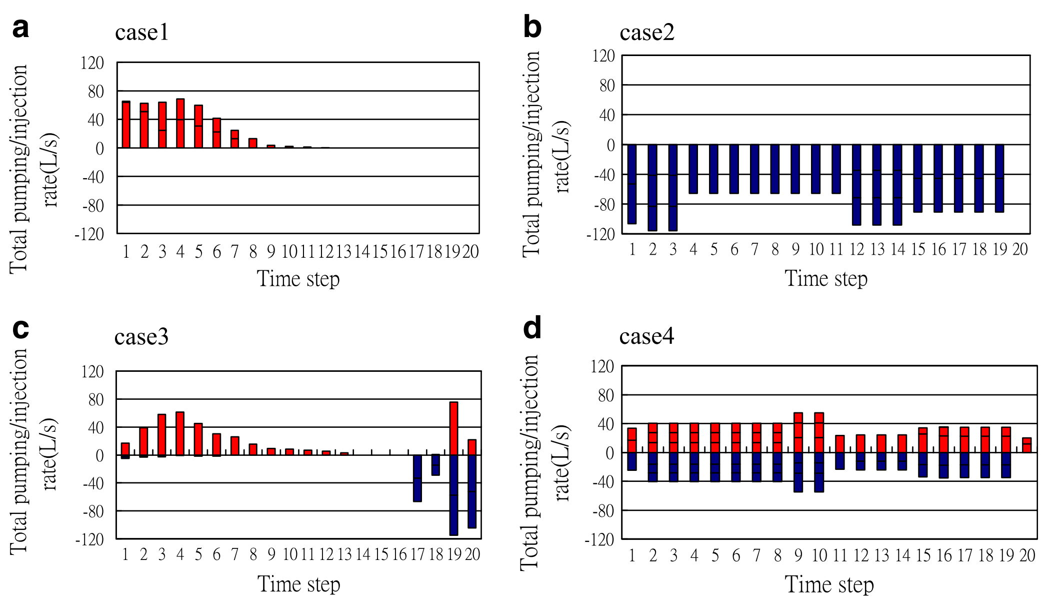


Figure 4 (a) Total pumping/injection rate at each period in case 1. (b) Total pumping/injection rate at each period in case 2. (c) Total pumping/injection rate at each period in case 3. (d) Total pumping/injection rate at each period in case 4.

dient control or the mass removal constraints to avoid the case 2 situation. But, all of them still have the problem of waste water disposal. Therefore, in case 4, a rate equilibrium condition is added to enforce that the injection rate equals the pumping rate for each time step, and there will be no treated water disposal. Table 4 shows that the number of pumping wells increases to five and both the fixed and operation costs are all increased. In fact, case 4 has the largest total cost among cases 1—4, and this is not surprising from the optimization aspect since case 4 has the tightest constraints. Fig. 4d shows the pumping and injection rates for all the time steps. Fig. 5d shows the concentration distribution at the final time step and it indicates that the designed system can remove the contaminants from the aquifer. Enforcing the rate equilibrium condition may have another advantage of reducing the groundwater drawdown during the remediation process. Fig. 6 shows the drawdown contour line of cases 1 and 4 at the period when the aquifer had maximum drawdown. Comparing the contour line, the maximum drawdown is 8 m in case 1 but is 3 m in case 4. Case 4 even increased the water level (a negative drawdown) in the east region. These results demonstrate the advantage of applying pumping and injection wells simultaneously to reduce the drawdown and decrease the risk of environmental impact, the land subsidence. The additional cost of case 4 can be viewed as the cost to eliminate the potential environmental concern.

The previous discussion shows that, to evaluate a design concept, one has to consider the system outcome in more detail besides only the direct fixed and operation costs. A practical pump-treat-inject system requires the pumping and injection wells be arranged in an appropriate manner.

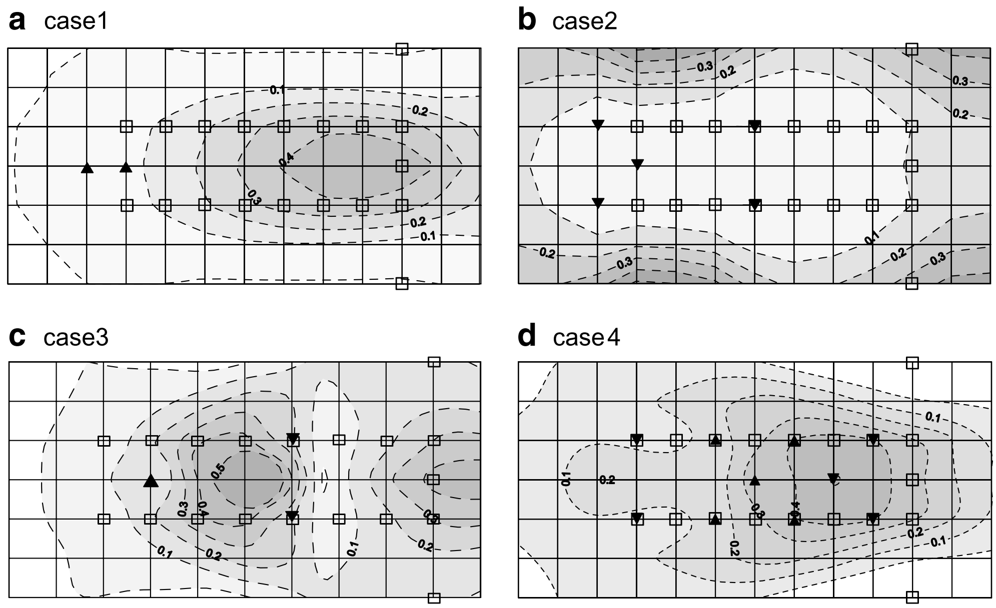


Figure 5 The optimal number of well and concentration distribution at the final period in cases 1—4 (unit: ppm) (▲: pumping well, ▼: injection well).

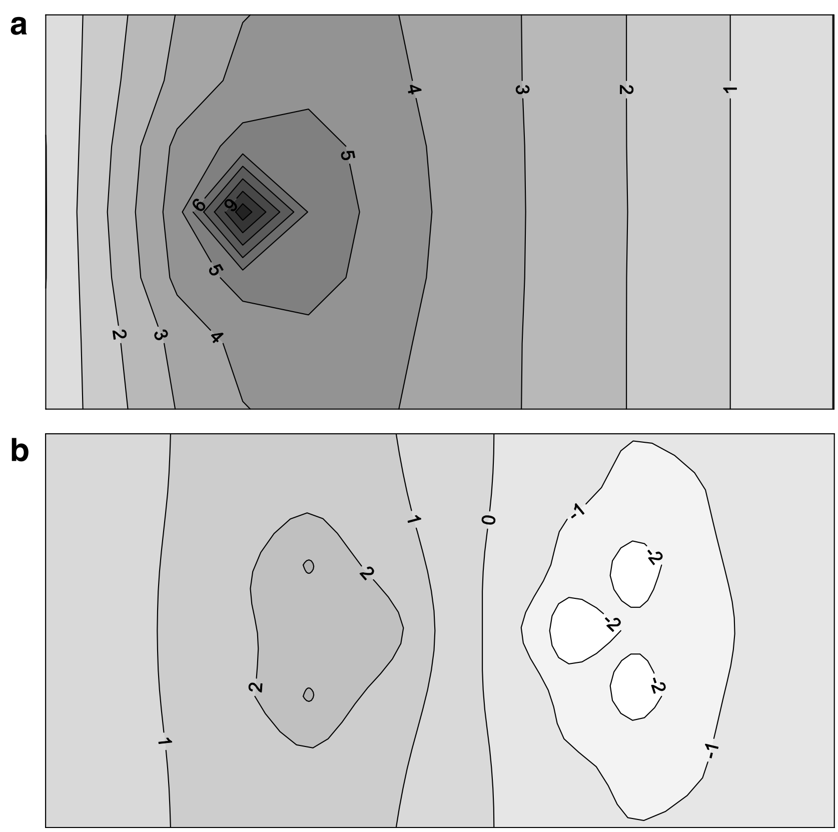


Figure 6 The maximum drawdown contours at the remediation period (unit: m).

Enforcing the rate equilibrium condition in the system design can potentially reduce environmental concerns caused by the decontamination process but increasing the total cost.

The required average CPU time for all the cases is 103,668 s (29 h) on AMD CPU (Athlon(tm) XP2000 + 1.54 GHz). The computation loading will increase as the problem scale (nodes number) increased. However, since the principle algorithm structure is GA for the proposed hybrid algorithm, the algorithm has great potential to reduce the computing time by parallel computing technology. Therefore, to apply the algorithm in a large field case in the future, a cluster machine may be the choice and this required more studies.

Conclusions

This study proposes an optimal planning model for groundwater remediation system based on the pump-treat-inject technique (PTI). The optimization model integrated CDDP and GA to design a pumping and injecting network system and the associated operation policy with a minimum total cost while simultaneously considering the fixed costs and time-varying operating costs. A PTI system using only injecting wells may have the lowest cost but is not a practical design, since an injection well can only dilute the contaminant concentration but can't remove the contaminants from the aquifer. This study has demonstrated how to define the optimal formulation to obtain a PTI design that is practical and cost-effective.

For groundwater remediation, the most environmentally friendly strategy is to recycle the treated water in the aquifer for the whole remediation process since the water recycling can reduce the potentially environmental concern caused by discharging the treated groundwater into surface water. By enforcing a rate equilibrium condition in the PTI design, the planning model can create a complete water recycling PTI system. However, a PTI system with the pumping and injecting equilibrium during the decontamination process has a higher total cost than a system without it.

Although this study has investigated several cases, the objective is to minimize the total cost. However, other considerations are still possible for a future study. Since a remediation project may last for years, the installation schedule for the pumping or injecting wells in principle should consider the movement of the plume. That is, the wells should be installed when they are needed to reduce the present value of the installation cost. The problem can be formulated as a capacity expansion (optimal scheduling) problem, and the kernel CDDP algorithm needs to be modified to solve it. Another possibility is to formulate the problem as to minimize the remediation time if time is the concern, and the objective function needs to be reformulated in this situation.

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