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Impact of Well Locations on the Cost of Reclamation of Aquifers

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***Abstract*— This paper presents a study on the impact of potential well locations on the optimal groundwater remediation design by considering two possible groundwater remediation problems. The objective of each of the two problems is to minimize the total remediation cost conditioned by hydraulic head and contaminant concentration constraints. Flow and transport simulators MODFLOW 2000 and MT3DMS 5.0 are coupled with the genetic algorithm (GA) optimization toolbox of the Matlab to solve the two problems. Remediation time, pumping rates and number of pumping wells are the decision variables of the first problem, and for the second problem remediation time, pumping rates, number and locations of pumping wells are the decision variables. Discrete variables are introduced into the formulations by incorporating well installation costs. The results suggest that locations of pumping wells have definite impact on optimal groundwater remediation design.**

***Index Terms*— aquifer, groundwater, pump-and-treat, genetic algorithms, well location.**

I. Introduction

The cost reduction capability of optimization algorithms and the capability of simulation models to represent complex natural phenomena have motivated many researchers the use of these tools in combination to design several groundwater remediation systems. Major optimization approaches used for designing optimal groundwater remediation systems include linear programming [1]; non-linear programming [9]; dynamic programming [3], [7]; simulated annealing [4]; genetic algorithms [5], [8], [10], [11], [13]; Robust Optimization [12]; evolution strategies [2]. These works aim at achieving a single objective, such as; minimization of remediation cost, maximization of total cleanup, minimization of risk to health etc., and there exists a wealth of literature dealing with single objective optimization algorithms for optimal groundwater remediation design and management problems. These studies consider pumping rates, locations of extraction or injection wells as the decision variables. They are applied for designing optimal remediation systems for fixed or variable potential well locations. However, any work which explicitly studies the importance and impact of well locations is reported in the literature. The impact of well locations on the optimal design of a pump-and-treat remediation system is studied by solving two different types of groundwater remediation problems using a simulation-optimization model applied to a hypothetical site. The first problem is applied to an optimization problem in which the objective is to minimize the total remediation cost consisting of four cost components. The second problem demonstrates the impact of well locations on the optimal remediation design. The number of potential pumping wells in this case is increased form eighteen to thirty eight. The same formulations as in case of the first problem are used in this problem. This case yielded a much better result out of the two hypothetical scenarios.

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II. Simulation and Optimization Models

Development of a simulation-optimization model involves coupling of system simulators representing complex natural phenomena with an appropriate optimization algorithm.

A. Simulation Models

Groundwater flow and contaminant transport simulators are extensively used in groundwater remediation design and management problems to represent the complex natural phenomena. Many computer codes have been developed with various levels of sophistication for solving groundwater remediation problems. This work uses groundwater flow simulation model MODFLOW 2000 [6] and contaminant mass transport model MT3DMS 5.0 [14] to simulate a hypothetical two-dimensional contaminated aquifer. These two programs solve the governing equations of flow and mass transport equations respectively. They constitute the most widely used and versatile system simulators for groundwater remediation design problems. These simulation models are coupled to a Genetic Algorithms (GA) based optimization algorithm to obtain optimal remediation strategies.

B. Optimization Model

Genetic algorithm (GA) is a heuristic technique based on the biological concept of survival of the fittest. GA based algorithms mimic the evolutionary processes that have led to development of higher organisms in nature. Many previous studies which used GA have indicated that this technique is very effective at identifying high-quality solutions and it does not require continuity of the objective function or other assumptions such as convexity. The GA toolbox of Matlab R2008a coupled with both MODFLOW 2000 and MT3DMS 5.0 in this study searches for the optimal values of the decision variables by using the basic three operators –selection, crossover, and mutation – in order to provide an optimal design scenario of groundwater remediation.

III. Optimization Model Formulation

The objective of this optimization problem is to minimize the total remediation cost, which includes operational, treatment and capital costs by varying the extraction rates. The locations of the potential pumping wells and monitoring wells are shown in Fig. 2. The contaminant concentration at these wells must not be greater than 0.5 mg/L at the end of the remediation time. The objective function value is evaluated using the following equations:

$$\text{Minimize } Cost = \sum_{i=1}^{M} z_i (G_{pump,i} + G_{install,i}) + G_{carbon} + G_{capital} \quad (1)$$

subject to

$$C_i \le C_{goal1} \;\; \forall i = 1,2,\ldots,N \quad (2)$$

$$C_i \ge 0 \;\; \forall i = 1,2,\ldots,N \quad (3)$$

where

$$G_{pump,i} = A_{pump} \sum_{i=1}^{M} z_i \left[Q_i \left(H_0 - h_i + 0.7 P_a \right) \right] \quad (4)$$

$$G_{carbon} = \frac{S_c t_p}{d} \beta (C_T)^{\eta} (Q_T) \quad (5)$$

$$G_{capital} = A_{ads} n_{ads} \quad (6)$$

$$A_{pump} = \frac{0.002725 S_p t_p}{\varepsilon} \quad (7)$$

$$Q_T = \sum_{i=1}^{M} z_i Q_i \quad (8)$$

$$C_T = \frac{\sum_{i=1}^{M} z_i Q_i C_i}{Q_T} \quad (9)$$

$$n_{ads} = ceiling\left(\frac{Q_T CT}{V_a} \right) \quad (10)$$

$$G_{install,i} = \sum_{i=1}^{M} z_i \left(164 D_i + 5751 (\max[Q_i])^{0.453} \right) \quad (11)$$

where

$G_{pump,i}$ = pumping cost of well at i ($);

G_{carbon} = operational cost of the GAC (Granular Accelerated Carbon) treatment facility ($);

$G_{capital}$ = capital cost of GAC adsorbers ($);

$G_{install,i}$ = installation cost of monitoring and/or pumping well at i ($);

C_i = contaminant concentration at the end of the remediation time at well i (M/L^3);

C_{goal1} = target concentration level at the end of remediation time (M/L^3);

M = number of potential pumping wells installed;

Q_T = total extraction rate of contaminated water (m^3/day);

h_i = hydraulic head at the end of remediation time;

C_T = weighted average influent concentration to the adsorbers (mg/L);

n_{ads} = total number of adsorbers used in the treatment system.

Q_i = rate of extraction at well i (m^3/day);

Cost = total remediation cost ($);

z_i = flag indicating whether well i is active. If z_i = 0, well is not active and if z_i = 1, well is active;

Sp = energy cost coefficient ($/kWh);

t_p = remediation time (seconds);

N = total number of potential pumping and monitoring wells;

D_i= depth of well at i (m);

ε = Wire to water pump efficiency;

H_z = Depth to datum (m) = 10m;

P_a = Pressure required for adsorber (psi);

d = Fraction of carbon used at time of removal;

β = Freundlick isotherm coefficient;

η = Freundlick isotherm exponent;

S_c = Carbon cost coefficient ($/Kg.);

A_{ads} = Cost per adsorber unit ($/unit);

CT = Required contact time (minutes);

V_a = Pore volume of adsorber (m^3).

Extensive details on the derivation of the three cost components viz. G_{pump}, G_{carbon}, $G_{capital}$, and values of associated design parameters ε, β, η, P_a, d, S_c, A_{ads}, CT, *and* V_a may be found in Culver and Shenk (1998). The cost component in (11) is obtained from McKinney and Lin (1994).

IV. Case Study Applications

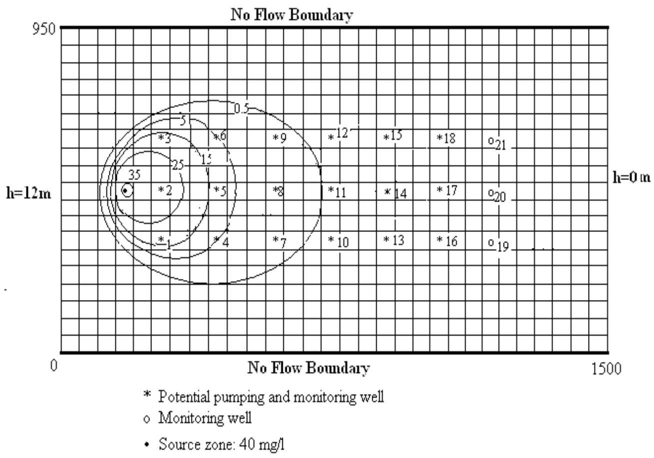

Fig. 1. Initial Distribution of Contaminant Plume and Potential Pumping and Monitoring Well Locations

Numerical experiments are conducted on a hypothetical aquifer to determine optimal strategies.The hypothetical aquifer is two-dimensional, homogeneous, isotropic, and confined. It is composed of 570 finite difference grids (each of size 50 m × 50 m), with overall dimensions of 1,500 m × 950 m. The hypothetical initial contaminant plume, which has a maximum concentration of 40 mg/L, is shown in Figure 1. A steady flow toward the right boundary is manitained with a constant hydraulic head of 12 m and contaminant

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Table 1: Details of Cost Components

Cost component	Scenario 1	2
	t_p^*=4.23 (years)	t_p^*=4.298 (years)
Pumping ($)$\times 10^4$	4.8636	3.3342
Treatment facility ($) $\times 10^5$	6.8328	5.43029
Capital cost ($) $\times 10^5$	3.0000	2.0000
Installation cost ($)$\times 10^5$	7.2623	4.64554
Remediation cost ($)$\times 10^6$	1.7581	1.2409

concentration of 0.0 mg/L on the left boundary, a constant hydraulic head of 0.0 m and contaminant concentration of 0.0 mg/L onthe right boundary and no flow at the top and bottom boundaries. The concentration at these wells must not be greater than 0.5 mg/L at the end of the remediation time. Relevant aquifer parameters are: hydraulic Conductivity *K* = 37.24 m/day; longitudinal dispersivity α_L = 70 m; transeverse dispersivity α_T =3 m; =10 m; distribution coefficient K_d = 0.245 cm^3/g.

A. . First Problem

The model is first applied to an optimization problem in which the objective is to minimize the total remediation cost consisting of pumping cost, operational cost of GAC treatment facility, installation cost of wells, and capital cost of GAC adsorbers. The formulation considers pumping rates at eighteen potential pumping wells, pumping locations, and remediation time as decision variables. The positions of the 18 potential wells are indicated in Fig. 1. Various cost components included in the objective function are, pumping cost, treatment cost, capital cost of GAC adsorbers, and cost of well installations. A binary variable is introduced into the formulation to decide whether or not a well would be installed at a particular location.

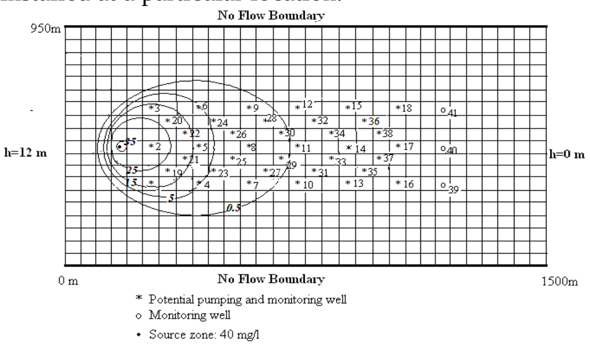

Fig. 2. Initial Distribution of Contaminant Plume and Potential Pumping and Thirty Eight Monitoring Well Locations

In this case the model identified only six pumping wells (viz. W7, W8, W9, W10, W11, and W12) out of the eighteen potential wells. The remediation cost of this scenario worked out to be 1.758×10^6 dollars. The optimal remediation time in this case is equal to 1,543 days.

The impact of well locations on the remediation cost was studied by making some modifications in the previous problem. Twenty new potential wells are introduced making a total of thirty-eight potential wells. There are a total of seventy seven decision variables in this problem. The positions of the newly introduced potential wells are indicated in Fig. 2.

B. Second Problem

Formulations of this problem remain the same as those of the first problem.

Interestingly, in this case, not only the remediation cost decreased significantly but also the number of pumping wells is reduced. Only four wells viz. W8, W11, W24, and W25 out of the thirty-eight potential locations are selected by the model and the remediation cost works out to be $1.240 × 10^6. The optimal remediation time in this case is equal to 1,569 days.

Table 2. Details of Extractions from the Selected Wells in Different Scenarios

Scenario 3 (t_p^*=4.23 years)		Scenario 4 (t_p^*=4.298 years)	
Wells selected	Extraction (*l/s*)	Wells selected	Extraction (*l/s*)
W7	2.460	W8	8.094
W8	8.059	W11	9.181
W9	2.472	W24	1.108
W10	7.221	W25	15.111
W11	15.063	-	-
W12	11.041	-	-
	46.316		**33.494**

The effect of well locations on the optimal design could clearly be understood from this study. Just by introducing twenty more potential pumping locations, the remediation cost could be reduced by a huge margin.

However, the optimal remediation time is 26 days more than that of the first scenario. This again implies that the length of optimal remediation time is influenced by the pumping locations. Details of these costs are listed in Table 1.

Details of extraction rates from the selected wells in different scenarios are shown in Table 2.

V. RESULTS AND DISCOSSIONS

In case of the first problem, six wells out of the eighteen potential locations are identified to represent the optimal strategy. The remediation cost corresponding to this strategy is $1.758 × 10^6. However, when the number of potential pumping wells are increased to thirty eight, the number wells selected by the model to represent the optimal strategy gets reduced to four and the remediation cost for this strategy is $$1.240\times 10^6$. This result provides an insight into the potential reduction in remediation cost by using sufficiently large number of potential pumping wells. Use of a large number of potential pumping wells ensures selection of wells at more appropriate locations. Results also show that by making appropriate selection of wells, it is possible to achieve reduction in remediation cost.

VI. Conclusion

Based on the findings of the present study, the following conclusions may be drawn:

(1) Well locations play a crucial role in the optimal design of a groundwater remediation system.

(2) Incorporation of remediation time as a decision variable ensures the use of optimal remediation time.

(3) Use of optimum number of pumping wells and optimum length of remediation time avoids wastage of time and money and reults in economic design of groundwater remediation systems.

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