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Optimal Design of Groundwater Remediation Systems with Treatment Plant Considerations

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Abstract

The Outer Approximation method is extended to accomodate the solution of groundwater remediation problems including treatment-plant design. The corresponding objective function is piecewise linear, monotonically increasing, and suitable for use with the Outer Approximation method. Optimal pumping well locations and corresponding pumping rates as well as optimal configuration of the treatment plant are obtained. The plant consists of units of air-stripping and granular activated carbon. The associated costs are determined using RACER, a commercially available software package for cost estimation. The proposed methodology is applied to a hypothetical case scenario.

1 Introduction

Optimal designs for pump-and-treat remediation systems traditionally define well locations and pumping rates. The treatment part of the process is consequently and subsequently designed according to the proposed optimal well configuration. In recent years there has been an attempt to examine the influence of the treatment plant configuration on the optimal remedial design.

Lefkoff and Gorelick [1986] studied the impact of high and low assumed treatment costs on the optimal design solutions under a rapid aquifer restoration scenario. It was demonstrated that high treatment costs lead to designs where treatment is the major design variable. Chang et al. [1992] used control theory to obtain a remediation design which implicitly included the treatment configuration through pumping capacity constraints. Direct consideration of treatment design components that use granular activated carbon was introduced by Huang and Mayer [1995]. They used a Genetic Algorithm and a formulation that explicitly included a nonlinear term for the treatment part of the process. They concluded that treatment considerations do not influence significantly the optimal pumping scheme. McKinney and Lin [1996] considered air-stripping technology as the treatment component. They used a nonlinear programming algorithm and showed that the treatment process for the particular example problem they considered has a significant impact on the remedial design by reducing the pumping cost by employing fewer wells and higher pumping rates. Similar conclusions were drawn by Culver and Shoemaker [1997] who extended their dynamic optimal control algorithm to include the treatment process. Their solutions demonstrate the impact of incorporating the treatment capital costs, but only when the management periods are short. Building on this work, Culver and Shenk [1998] formulated a new objective function and explicitly considered granular activated carbon for the treatment process. It was demonstrated that dynamic policies are superior to steady-state policies. However, it was also indicated that the dynamic algorithm is not efficient for large-scale problems with realistic, non-convex cost functions.

In the work presented herein, an activated carbon treatment plant design is incorporated into a groundwater management formulation that is based on the Outer Approximation (OA) method, as presented by Karatzas and Pinder [1993 and 1996]. The values of the objective function are obtained using RACER [1993], a commercial software package that provides realistic calculations based on market values. The resulting design is applied to a hypothetical aquifer remediation scenario.

2 The Method

The Outer Approximation method was modified for the implementation of the treatment plant design. The optimization problem is

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formulated as

$$min \sum_{i \in I} f(q_i, c_i) \tag{1}$$

$$such\ that$$

$$c_j \leq c_j^* \quad j \in J \tag{2}$$

$$0 \leq q_i \leq q_i^* \tag{3}$$

where:

$f(q_i, c_i)$: cost function;
q_i : pumping rate of well i;
c_i : concentration at well i;
c_j : concentration at node j;
c_j^* : cutoff concentration at node j;
q_i^* : pumping capacity for well i;

In this formulation, the objective function includes installation and operation costs for pumping and treatment, assuming air-stripping and granular activated carbon (GAC) single units for treatment. The information obtained from RACER includes unit sizes and corresponding costs for the treatment components, amount of GAC in each unit and operation and installation costs for the pumping wells. The additional information necessary for a complete design includes the amount of GAC necessary for treatment of the concentration levels in the influent water. This is estimated based on the following equations [Calgon Corporation, personal communication]:

$$\begin{aligned} (GAC) &= (0.083 \times (TOC) + 0.63 \times \log(CHC) + 0.565) \\ &\quad \times Q_{tot} \times 1.44 \times (T) \end{aligned} \tag{4}$$

where:

GAC : Granular Activated Carbon [lb/day];
TOC : Total Organic Compounds [mg/l];
CHC : Chlorinated Hydro Carbons [mg/l];
Q : influent water volume [gpm];
T : Time [hrs of daily operation/24 hrs];

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The complete calculation procedure of the objective function is the following:

- for the total amount of pumped water the corresponding necessary size of the treatment plant is determined.
- the influent concentration at the plant is calculated.
- the amount of carbon necessary for treatment of this concentration level is calculated.
- if the selected size includes the required amount of GAC, the corresponding cost is computed based on this size. If not, a larger size is determined based on the amount of GAC necessary for treatment.

3 Application of the Method

The remediation design methodology that incorporates both the well field and a treatment plant is demonstrated based on a hypothetical aquifer [Karatzas and Pinder, 1993 and 1996]. Figure 1 shows the initial contaminant plume, the locations of the pumping and observation wells for two remediation scenarios, and the boundary conditions for flow and transport.

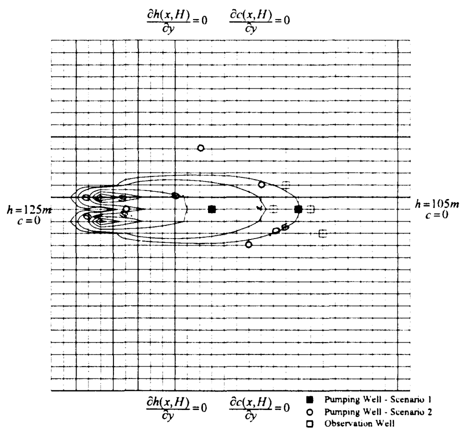

Figure 1: Hypothetical Aquifer Setting

A two-dimensional analysis showed that the objective function is piecewise linear in two dimensions and monotonically increasing.

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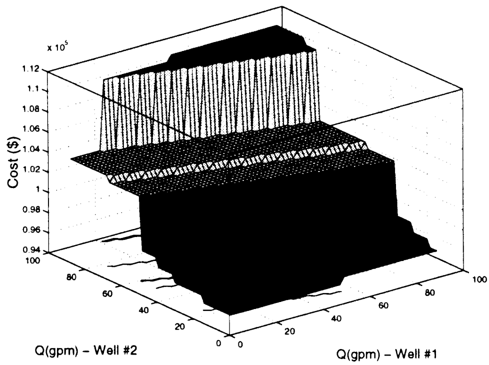

Figure 2: Objective Function

Due to these properties, application of the OA method guarantees global optimality.

Two contaminant concentration scenarios were considered to study the effects of the concentration level on the decision making process, one with a high and one with a low concentration (Figure 3).

The results for the two design cases of pumping and pumping with treatment are shown in Figure 4. When the low-concentration plume is considered, the design focusses on the optimal well locations and the corresponding pumping rates. The treatment plant components are selected based on the total volume of influent pumped water at the plant. The amount of GAC in the selected units is sufficient for the treatment of the contaminant at those low concentration levels. In the case where the design includes only pumping, the pumping rates are the same as when pumping and treatment designs are considered together. The cost of pumping is the same in both designs. However, there is an additional cost for the treatment components in the second design.

The opposite occurs when high-concentration levels exist in the aquifer. In that case the sizes of the treatment plant components are selected primarily so that enough GAC is present for treatment of the contaminant. This affects the pumping scheme too, with different pumping rates assigned in the two design cases of pumping costs and pumping with treatment costs. The cost for treatment in the second design corresponds to larger sized treatment units when compared to

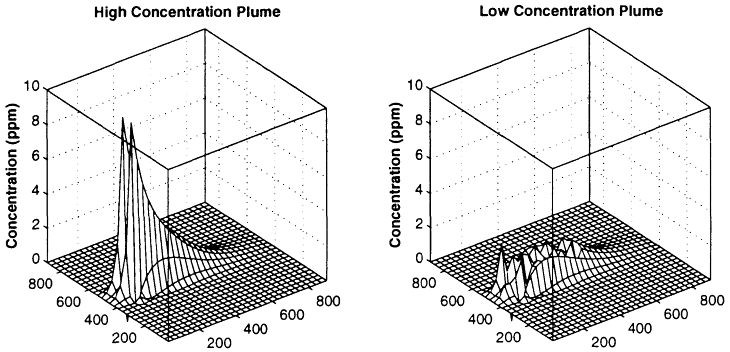

Figure 3: High and Low Concentration Plumes

that determined by the volume of pumped water alone. This reflects the requirement for a larger amount of GAC for the contaminant treatment.

The second remediation scenario includes four candidate pumping wells, as shown in Figure 1. The same contaminant plumes of high and low concentration levels are implemented. When low concentration levels exist, the pumping rates for the two designs are similar and the remedial design is driven by the pumping demand (Figure 5). The pumping rates are the same in the case of high concentration levels in the aquifer, unlike what was observed in the two-well scenario. This can be attributed to the the placement of the wells that allows significant reduction of the contaminant concentrations at the observation wells without pumping water at high concentration level.

4 Conclusions

Treatment plant units have been successfully included in an optimal aquifer remediation design using the Outer Approximation method. The solutions obtained include pumping well locations and corresponding pumping rates as well as sizes for the treatment plant components. Implementation of RACER as the tool for cost estimation provides treatment plant designs that consider the costs of both the

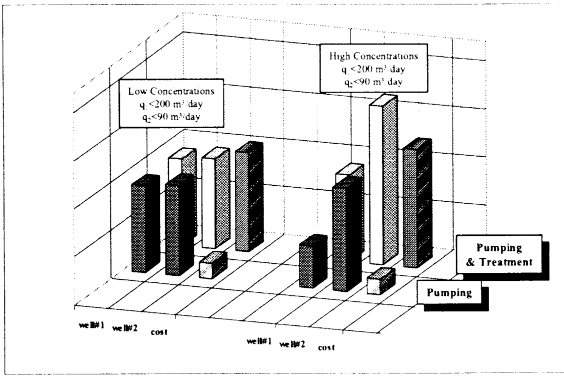

Figure 4: Scenario 1 - Pumping Rates and Remediation Costs

volume of pumped water and the contaminant concentrations. Estimation of the remediation costs using RACER results in an objective function formulation that is piecewise linear.

When a treatment plant is included in the design it can influence the optimal solutions. This occurs when the concentration levels are high enough that the treatment part of the process significantly impacts the design. However, the treatment plant design can have insignificant effect on the solutions in cases when the location of the pumping wells is such that mass removal is realized at no extra cost.
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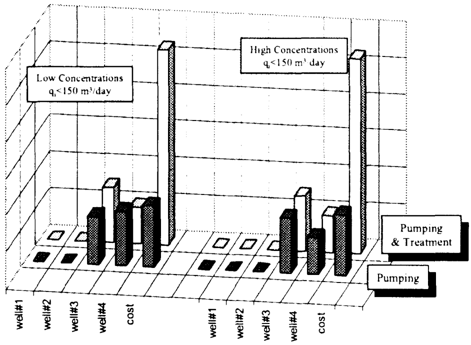

Figure 5: Scenario 2 - Pumping Rates and Remediation Costs

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