

A Multi-objective Optimal Model for Groundwater Remediation under Health Risk Assessment in a Petroleum contaminated site

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Abstract. This study proposes a multi-objective model (i.e. MOHRA) for groundwater remediation in a petroleum-contaminated site under health risk assessment. The optimization system is designed based on the pump and treat technology considering both cost and human health risk, which can provide reliable groundwater remediation strategies.

1. Introduction

Groundwater contaminated by petroleum products poses significant threats to human health and natural environment. Pump-and-treat (i.e. PAT) is one of the most widely used technologies in the petroleum polluted groundwater remediation process [1]. However, remediation of such contaminants involves large expenditure and time [2]. Therefore, simulation/optimization models have been used for determining optimal remediation strategies [3-7]. The simulation models are used to simulate contaminants whereabouts under various conditions, while, the optimization models are used to enhance design of management actions [8].

Challenge may emerge because any remediation decision can hardly ensure the constraints to be satisfied in health risk and the minimization of remediation costs. Multiple objectives optimization method may be applied to address this problem[9]. Thus, under this consideration, a multi-objective optimal model under health risk assessment (i.e. MOHRA) is developed in this study for optimal remediation design in western Canada. In the approach, the contaminant transport processes under remediation operations will be simulated and subsequently is replaced with a regression model. A multi-objective programming model considering health risk will be formulated to seek the optimal remedial design strategies.

2. Methods and materials

2.1. Optimization Objective

The optimization objective of a PAT system includes the system fixed cost, operation costs,



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contaminant environmental standards and human health risk. In the PAT system, the costs of one-time drilling and installation are significant less when comparing with operation costs. Hence, the optimization function can be described as follow:

$$\begin{aligned} \text{Min} \quad f_1 &= \sum_{i=1}^I q_i^{\text{In}} + \sum_{j=1}^J q_j^{\text{Ex}} \\ f_2 &= \left(\sum_{k=1}^K ELCK_k \right) / K \end{aligned} \quad (1)$$

where f_1 is total pumping rate at all injection and extraction wells, m³/hr; I, J are numbers of injection, extraction wells respectively; q_i^{In} is pumping rate for the i^{th} injection well, m³/hr; q_j^{Ex} is pumping rate for the j^{th} extraction well, m³/hr.

2.2. Constraints of the PAT Optimization Model

In addition to human health risk, PAT system may be impacted by engineering techniques and hydrogeological factors. Hence, the constraints for the PAT optimization model can be described as follow:

$$c_k(q_i^{\text{In}}, q_j^{\text{Ex}}) \leq c_{\max} \quad k=1,2, \dots, K \quad (2)$$

$$0 \leq q_i^{\text{In}} \leq q_{\max}^{\text{In}} \quad i=1,2, \dots, I \quad (3)$$

$$0 \leq q_j^{\text{Ex}} \leq q_{\max}^{\text{Ex}} \quad j=1,2, \dots, J \quad (4)$$

$$\sum_{i=1}^I q_i^{\text{In}} = \sum_{j=1}^J q_j^{\text{Ex}} \quad i=1,2, \dots, I; \quad j=1,2, \dots, J \quad (5)$$

$$ELCR_k \leq ELCR_{\max} \quad k=1,2, \dots, K \quad (6)$$

$$ELCR_k = SF \times CDI_k \quad (7)$$

$$CDI_k = CW_k / 1000 \times IR \times EF \times ED / (AT \times BW) \quad (8)$$

$$c_k = a_{0,k} + \sum_{i=1}^n a_{i,k} q_i + \sum_{i=1}^n \sum_{j=1}^n a_{ij,k} q_i q_j (i \neq j) + \sum_{i=1}^n a_{ii,k} q_i^2 + e_k \quad (9)$$

where q_{\max}^{Ex} for the i^{th} injection well and q_{\max}^{In} for the j^{th} extraction well, are maximum pumping rates, m³/hr; k is the number of monitoring wells; c_k is contaminant concentration of the k^{th} monitoring well which has been remediated, µg/L, and by a inference, a simulation, and the optimization method proposed by He et al. (2008)[10], the alternative of c_k would be obtained; c_{\max} is the maximum receivable contaminant concentration, µg/L; $ELCR_k$ is carcinogenic human health risk at k^{th} monitoring well, $ELCR_{\max}$ is the maximum acceptable carcinogenic human health risk value; SF is slope factor which is related to carcinogenic health risk, (mg/kg·day)⁻¹; CDI_k is daily intake of given contaminant at exposure location k , mg/kg·day; CW_k is concentration of exposed contaminant at exposure location k , µg/L; IR is ingestion rate, L/d; EF is exposure frequency, d/year; ED is exposure

duration, year; AT is average time, d; BW is body weight, Kg; $a_{0,k}$ is an intercept term of surrogate k ;

$\sum_{i=1}^n a_{i,k} q_i$ are linear terms of surrogate k ; $\sum_{i=1}^n \sum_{j=1}^n a_{ij,k} q_i q_j (i \neq j)$ are interaction terms of surrogate

k ; $\sum_{i=1}^n a_{ii,k} q_i^2$ are quadratic terms of surrogate k ; e_k is the error of surrogate k ; n is the number of explanatory variables.

2.3. Model solution

In order to solve the multi-objective problem, the liner weighting method may be adopted. Each single objective's weight can be obtained by the following steps: 1) normalize the objective functions; 2) find the pseudo nadir f_i^+ and anchor point f_i^- , for each single objective; 3) calculate each objective's weight by using the following formulas[11]:

$$\alpha_1 = \frac{f_2^+ - f_2^-}{f_2^+ - f_2^- + f_1^+ - f_1^-} \quad (10)$$

$$\alpha_2 = \frac{f_1^+ - f_1^-}{f_2^+ - f_2^- + f_1^+ - f_1^-} \quad (11)$$

And then, the multi-objective model can be transformed into the single objective, which can be solved through MATLAB.

$$\text{Min} \quad U(q) = \frac{(f_1^+ - f_1^-)f_2(q) + (f_2^+ - f_2^-)f_1(q)}{f_2^+ - f_2^- + f_1^+ - f_1^-} \quad (12)$$

3. Case Study

In western Canada, the MOHRA model is applied to a petroleum-contaminated site. The aquifer has been remediated many years with dual phase vacuum extraction method[10]. Since contaminated plume still found in the monitoring well, a PAT system, is applied, with 2 injection and 4 extraction wells, in or around the contaminant plume. The simulation domain, with an area of $270 \times 225 \text{ m}^2$ and a depth of 10 m, is shown in Figure 1, which is composed of 9720 finite difference grids (in the directions of x, y, z, each grid has dimensions of 5, 5, and 2.5 m, respectively).

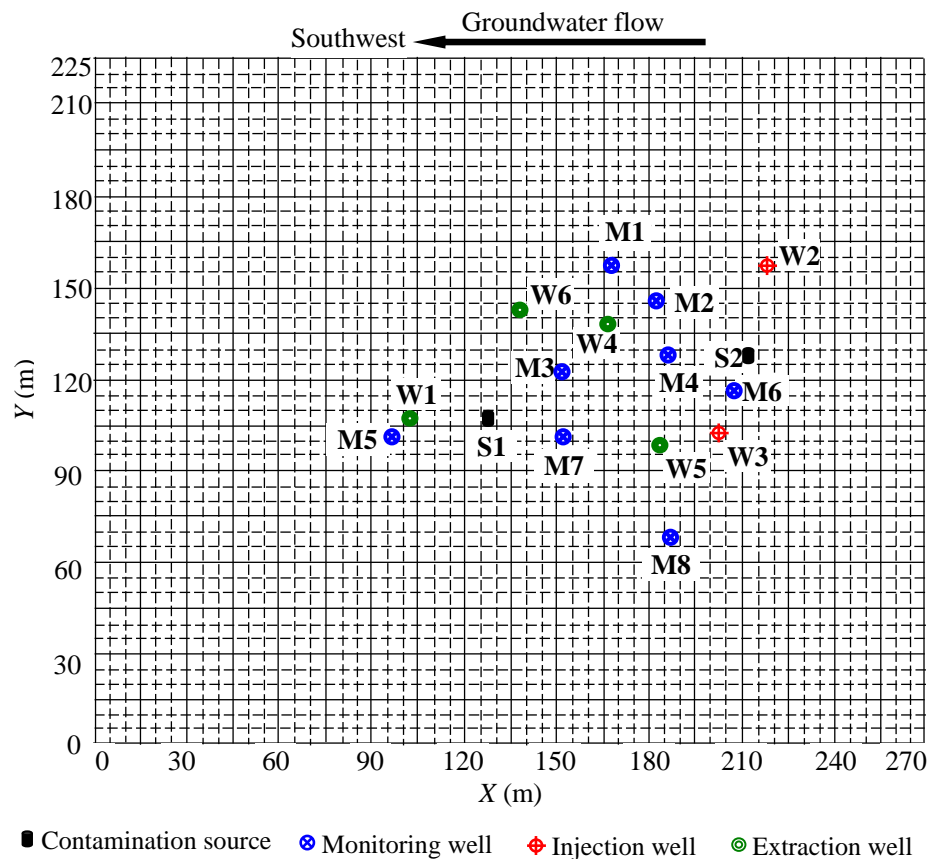


Figure 1. The simulation domain (He et al. 2008)

In this study, 5 years remediation duration is selected and benzene contaminant is considered as target contaminant in the optimization model. The acceptable carcinogenic health risk of benzene is 0.00002, AT is 10750 days and BW is 70Kg.

4. Results analysis

When the environmental standard is 150 $\mu\text{g/L}$ and the benzene carcinogenic health risk level is 0.00002, at six wells, the optimization pumping rates are 100, 89.4, 84.4, 0.0, 73.2, and 0.0 m^3/hr , respectively. It shows that at wells 4 and 6, the pumping rates are zero, which means that 4 wells are enough, and also leads to less cost through this optimization model.

Figure 2 shows the predicted benzene carcinogenic risk level under 5-year remediation durations. The risk level is higher in the center area compared with the boundary area, which may be impacted by the contamination sources. The peak health risk is 0.000019 (approximate to 0.00002). It means that, the contradiction between remediation cost and remediation effect is effectively solved by the multi-objective model.

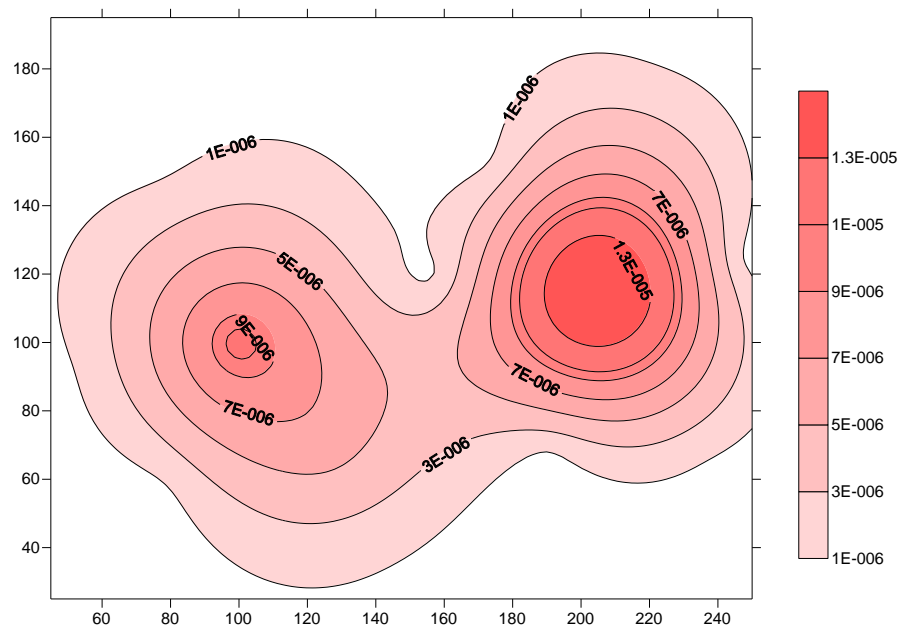


Figure 2. Predicted risk levels for 5-year remediation duration when environmental standard is $150\mu\text{g/L}$ and acceptable health risk level is 0.00002

5. Conclusions

In this study, a multi-objective model (i.e. MOHRA) was developed under health risk assessment for groundwater remediation in a petroleum-contaminated site. There are two advantages in comparison with other models: (1) the relationship between contaminant concentrations and pumping rates were obtained by a series of surrogate models; (2) both health risks and remediation cost were considered in the model. MOHRA can help systematically analyze interaction among contaminant transport, remediation technology, environment and health factors, and provide useful optimization information for decision makers.

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