Optimization of pollution plume containment using management models

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Abstract The applicability of groundwater management modelling is evaluated using field data. The abandoned waste disposal site of a large chemical industrial plant was selected as a pilot study. Several strategies to optimize the containment/control of the groundwater contamination at the site were considered. This optimization was done using two different approaches. Due to specifically unfavourable local conditions it was found that conventional particle tracking gives better results than MODMAN optimization shell. The reason for this is the more restrictive interpretation of constraints in the MODMAN. The consequences for the waste disposal site are discussed leading to the special case of optimization under relaxed constraints. Additionally, the cost of each alternative was assessed and a ranking of suggested containment scenarios is presented.

INTRODUCTION

The important requirement of groundwater remediation and environmental protection is to comply with given criteria at minimum expense. In many cases, the lack of money prevents one to actually clean up the aquifer. What remains are temporal solutions which may stop the most urgent cases from getting worse (Hagemeyer et al., 1993; Johnson & Bowen, 1993). One of such studies is the subject of this article.

STUDY OBJECTIVE

A Waste Disposal Site (WDS) of a large chemical industrial plant in the Czech Republic was used for over 15 years for storing both solid and liquid wastes without protecting the shallow aquifer underneath. This resulted in heavy organic and inorganic pollution of subsoil and made a part of the aquifer unusable. The pollution plume evolution also endangered the surface water body nearby through the existing hydraulic contact between the groundwater and the river.

The following objective of this study has been formulated to avoid further spreading of the pollution plume: "By implementing a set of technical measures it is expected to
create a local groundwater flow system that will result in a containment/control of the contaminated groundwater. Several alternatives of the hydraulic isolation need to be analyzed. The extent of installation is to be optimized to guarantee the minimum total abstraction rate. The cost of the optimal solutions should be also evaluated.

SITE CHARACTERIZATION

The waste disposal site in question is situated on the right-hand bank of a river, in the area of a former sedimentation pool. From the geological point of view the area of interest is formed by heterogeneous fluvial sediments. They consist of clayey loam with a varying content of sand, sandy clay and locally clayey fine-grained sand. Their thickness varies between 2.5 and 8 m. Underlying marl and marlstone is assumed to be fairly impermeable. The saturated fluvial sediments host a phreatic aquifer with a comparatively good porous permeability ranging from 0.29 to 32.75 m day$^{-1}$. The direction of the groundwater flow is generally towards the southwest, however locally affected by seepage from the river with its water level elevated by a weir situated downstream. Groundwater system is also significantly influenced by the drainage pattern of the brook flowing through the old river bed along the southeastern edge of the WDS.

The groundwater is strongly contaminated with a wide spectrum of both organic and inorganic substances. The inorganic contamination is primarily due to extreme concentrations of chlorides, sulphates and bicarbonates (chloride concentrations up to about 8500 mg l$^{-1}$).

Aromatic chlorinated hydrocarbons are the most abundant organic contaminants with concentrations of thousands to tens of thousands of µg l$^{-1}$ (max. 48 700 µg l$^{-1}$). The dominant components are chlorobenzene, dichlorobenzene and trichlorobenzene. Other significant contaminants are benzene, toluene and naphthalene, however more priority pollutants were also identified in high to extreme concentrations.

In the surface water samples collected from the brook downstream of the WDS, increased levels of aromatic hydrocarbons have been confirmed.

SIMULATION OF THE GROUNDWATER FLOW SYSTEM

The groundwater system in the area is known to be rather complex. Therefore, prior to the optimization of the pollution control at the local scale, the regional groundwater flow system had to be simulated. A quasi-three-dimensional numerical model MODFLOW (McDonald & Harbaugh, 1984, 1988) has been implemented. A one-layered unconfined heterogeneous and isotropic aquifer was assumed. Among other features, the aquifer communication with a number of streams and canals in the area was taken into account in the model. The calibration was done with respect to hydraulic conductivity distribution in the area assuming average groundwater levels of June 1993.

On the local scale, the solution was expected to simulate considerable details. The general disadvantage of the finite difference codes is that local grid refinement affects the grid spacing along the total dimension of the model. This was avoided by adopting the telescopic approach. Artificial boundary conditions of the local model were derived from the regional solution. The aquifer was simulated as a three-layered domain to describe the groundwater flow better, especially in the close vicinity of streams, wells and trenches.
CONTAINMENT OPTIMIZATION

Two different approaches have been adopted in assessing the effect of the containment measures: Particle Tracking and MODMAN optimization. Particle Tracking approach is essentially a trial-and-error procedure based on the professional judgement contrary to the MODMAN solution when optimization software is used.

Particle tracking approach

In this method, an additional constraint was formulated: "Each particle that starts along the border of the containment area must be captured by the installation (well or trench) being considered".

The pathlines of the groundwater particles were computed with the MODPATH code (Pollock, 1989). The objective of the simulation was to find a scenario which would, under the given constraint, minimize the volume of groundwater to be abstracted from the system. Five alternatives of hydraulic isolation have been evaluated.

Alternative I assumes groundwater containment achieved by a set of pumping wells. In this case the constraint of maximum pumping rate of each well of 0.21 s\(^{-1}\) was added.

Alternative II represents a combination of active and passive means of the containment. A semi-open 1 meter thick slurry wall with the hydraulic conductivity of \(1 \times 10^{-9}\) m s\(^{-1}\) (8.64 \(\times 10^{-5}\) m day\(^{-1}\)) was designed along the northeastern, southeastern and southwestern sides of the WDS in order to isolate it from the nearby brook physically. The existence of this fully penetrating barrier resulted in a substantial decrease of the pumping rate required to satisfy given constraints.

Alternative III simulates the containment by a trench. The objective was to find the trench position (including length and depth) with the least groundwater discharge assuming a uniform slope of the trench. It has been further assumed that the trench is as efficient as possible, and therefore the hydraulic resistance of the trench bottom is equivalent to that of the aquifer material. However, if required, the trench clogging can be easily simulated provided the corresponding data are known.

Alternative IV uses the combination of an active (trench) and a passive (slurry wall) containment. The slurry wall has the same extent and permeability as in the case of Alternative II. Similarly to that scenario the slurry wall prevents unpolluted groundwater and water seeping from the brook to be discharged by the installation, allowing for smaller pumping rates.

Alternative V simulates the containment by a combination of a complete (closed) slurry wall and an interception well. The area of the waste disposal site isolated by the slurry wall is treated as a nonactive area in the model simulation assuming capping. The interception well situated northwest of the WDS is designed to capture the residual pollution in this part of the aquifer.

Containment optimization by MODMAN/LINDO software

The MODMAN (MODflow MANagement) shell is a Fortran code (GeoTrans, 1992) that adds optimization capability to groundwater flow model MODFLOW (McDonald & Harbaugh, 1984, 1988). MODMAN utilizes the Response Matrix technique (Gorelick
et al., 1993) to transform the groundwater management problem into a linear or mixed-integer programming problem. This substitution is essential for the MODMAN efficiency as every evaluation of the groundwater system response is reduced to simple matrix-vector multiplications as opposed to full simulation of the three-dimensional flow model needed in the Particle Tracking approach.

The solution of the management problem within the MODMAN shell is searched by the optimization code LINDO (Schrage, 1991a, b) that maximizes or minimizes a user-specified objective function (typically pumping rates or costs) subject to a set of user-defined constraints.

Formulation of the control problem

Two containment scenarios were considered: wells only (Alternative Ia) and their combination with the slurry wall (Alternative IIa). To fulfil the requirements of the mathematical programming techniques adopted in the optimization software, the following compliance line has been defined in the project: "the compliance line is a part of the outline of the WDS pollution plume along which groundwater velocity (in natural conditions) is not directed inwards."

Furthermore, in order to use a mathematically oriented optimization software like MODMAN, the qualitative objectives formulated earlier need to be expressed in the form of some scalar objective function. In the case of plume containment, the objective function is defined so as to minimize the total amount of groundwater abstracted from the set of managed wells. The pumping rates and locations of wells are the decision variables. There can be also some other physical or geometrical variables that have to be evaluated, e.g. the length and shape of the barrier (slurry) wall. They are however parameters and hence they cannot be optimized with the MODMAN shell. It should be noted that since the situation of the slurry wall in Alternative IIa was predefined and assumed to be the same as for the Particle Tracking method, the optimal solution of such a problem forms only a conditional minimum.

In both scenarios it was additionally assumed that the unmanaged situation is simply an unstressed groundwater head distribution prior to the introduction of any hydraulic control.

Optimization constraints

The direct consequence of the objective formulation is the following set of constraints:

(a) Head limits were defined in the locations of the candidate wells in order to avoid excessive drawdown. In Alternative IIa, such constraints were assigned also to the cells along the northwestern side of the slurry wall to prevent outward seepage through it.

(b) Head difference limits were specified in both alternatives along the compliance line.

(c) Gradient limits were used together with flow direction limits to define the allowed range of groundwater flow directions at a number of locations along the compliance line.

(d) Balance constraints were specified limiting the maximum possible pumping rates for each well to 16 m$^3$ day$^{-1}$ (Alternative Ia) and 6 m$^3$ day$^{-1}$ (Alternative IIa) respectively.
(e) The Integer constraint was used to choose \(x\) active wells among \(y\) candidate sites. Note that due to the local conditions only limited space was available for their allocation. In Alternative Ia five active wells from 13 candidates were chosen. For Alternative IIa, the constraint \(4\) of \(10\) was considered. In both cases an attempt to use a smaller number of active wells failed — the solution appeared to be unfeasible.

RESULTS

In Table 1, the results of the optimal solutions computed by the Particle Tracking method and using MODMAN/LINDO are summarized. The latter yielded significantly higher pumping rates and the number of active wells is also higher. The reason is that the criterion for the design of the effective plume containment by the Particle Tracking method allows contaminated water to leave a containment area if (and only if) it is finally captured by an installation. The constraints along the compliance line of the MODMAN solution are rather conservative and therefore more restrictive (Fig. 1). The final decision therefore depends on whether a so far unpolluted part of the aquifer is allowed to be contaminated, provided that the pollution is ultimately kept under control.

Table 1 Summary of the optimization solutions.

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Number of wells</th>
<th>Total pumping rate (m^3 \text{ day}^{-1})</th>
<th>Trench length (l \text{ s}^{-1})</th>
<th>Wall length (m)</th>
<th>Wall length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>4</td>
<td>25.92</td>
<td>0.30</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ia (MODMAN)</td>
<td>5</td>
<td>30.32</td>
<td>0.35</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>II</td>
<td>3</td>
<td>6.48</td>
<td>0.08</td>
<td>-</td>
<td>435</td>
</tr>
<tr>
<td>IIa (MODMAN)</td>
<td>4</td>
<td>7.50</td>
<td>0.09</td>
<td>-</td>
<td>435</td>
</tr>
<tr>
<td>III</td>
<td>-</td>
<td>20.46</td>
<td>0.24</td>
<td>320</td>
<td>-</td>
</tr>
<tr>
<td>IV</td>
<td>-</td>
<td>6.13</td>
<td>0.07</td>
<td>295</td>
<td>435</td>
</tr>
<tr>
<td>V</td>
<td>1</td>
<td>2.00</td>
<td>0.02</td>
<td>-</td>
<td>790</td>
</tr>
</tbody>
</table>

OPTIMIZATION UNDER RELAXED CONSTRAINTS

In order to evaluate the possible influence of the relaxation of the constraints on the optimal solution, a series of additional optimization runs was performed. The compliance line was gradually shifted away from the WDS along its northwestern section. This procedure was applied for both MODMAN/LINDO scenarios (pumping wells only (Alternative Ia)) and the combination of wells and slurry wall (Alternative IIa). However, only in the latter case it resulted in a decrease of the optimized total pumping rate. The price to pay for this improvement is an increase in size of additionally contaminated but still controlled area (Fig. 2).

In the case of pumping wells only, the existence of the stream in the close downgradient vicinity of the WDS resulted in enhanced binding of the constraints
Fig. 1 Schematized criterion of effectiveness of the groundwater pollution control in the case of (a) particle tracking approach, and (b) MODMAN/LINDO solution.

Fig. 2 Changes in optimized pumping rates and corresponding increase of contaminated area as a result of gradual constraints relaxation.

situated nearby. Consequently the relaxation of the other constraints at the northwest did not lead to any significant changes in the optimized solution.

ECONOMIC ASSESSMENT

Individual alternatives as optimized by Particle Tracking approach have been evaluated according to the present worth as well as the annual worth of their total costs (White et al., 1989). Economic assessment is based on the combination of investment and operational costs (Nawalany et al., 1992). The results for the individual alternatives of the WDS hydraulic isolation are summarized in Table 2, assuming planning horizon of 10 years and interest rate equal to 10%. It can be concluded that the least costly is Alternative III (intercepting trench). However, this alternative is considered rather risky because of the possible flow of dense pollution below the trench. This installation is also viewed as highly sensitive to the groundwater as well as surface water fluctuations.
Table 2 Economic assessment of the optimal solutions. The currency units are Czech crowns.

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Investment costs per year</th>
<th>Operational costs per year</th>
<th>Present worth of total costs</th>
<th>Annual worth of total costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>I (wells)</td>
<td>40 000</td>
<td>730 000</td>
<td>5 255 530</td>
<td>855 314</td>
</tr>
<tr>
<td>II (wells+wall)</td>
<td>6 555 000</td>
<td>547 500</td>
<td>10 466 700</td>
<td>1 703 400</td>
</tr>
<tr>
<td>III (trench)</td>
<td>128 000</td>
<td>182 500</td>
<td>1 431 880</td>
<td>233 032</td>
</tr>
<tr>
<td>IV (trench+wall)</td>
<td>6 643 000</td>
<td>182 500</td>
<td>7 946 880</td>
<td>1 293 320</td>
</tr>
<tr>
<td>V (closed wall +well)</td>
<td>11 860 000</td>
<td>182 500</td>
<td>3 163 900</td>
<td>2 143 360</td>
</tr>
</tbody>
</table>

Therefore the next best alternatives are preferred: Alternative I (wells only) and Alternative IV (trench and the slurry wall). The latter is slightly more expensive but certainly more safe than Alternative I.

CONCLUSIONS

Based on the calibrated regional and local models of groundwater flow, the analyzed alternatives of hydraulic isolation of the WDS have proved to be feasible solutions for the problem in question. The application of the management model improved the understanding of the groundwater system and forms a sound base for its protection. Future work is oriented at the extension of the optimization techniques for remediation problems when simulation of contaminant transport is included.

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