Reliability of hydraulic performance and cost estimates of barrier-supported pump-and-treat systems in heterogeneous aquifers

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Abstract Addressing the need for cost-effective long-term groundwater remediation methods, pump-and-treat systems, supported by means of additional impermeable barriers, are proposed as a reasonable alternative to standard pump-and-treat systems. Compared to only pumping, the barriers yield a reduction of the pumping rate required to establish a certain capture zone. This paper presents the results of a comparative analysis of the hydraulic performance of both systems in heterogeneous aquifers and, based on that, an economic evaluation. Taking into account the fact that the description of heterogeneous aquifers is inevitably uncertain, the hydraulic analysis is based on Monte Carlo simulations which incorporate the reliability (probability of failure) of the specific pump-and-treat system. The reliability trade-offs obtained show that considerably less water has to be pumped (and treated) if an additional impermeable barrier is implemented. This joint economic evaluation reveals, however, that due to the additional costs for barrier installation, a barrier-supported pump-and-treat system is only advantageous if the unit costs for pumping and on-site treatment exceed a certain limit, which again depends on the degree of aquifer heterogeneity.

Key words advective control; capture zone; cost estimation; hydraulic barrier; pump-and-treat; reliability

INTRODUCTION

The ineffectiveness of pump-and-treat technologies for the removal of organic contaminants from groundwater within a reasonable period of time leads to a reconsideration of appropriate pump-and-treat applications. Consequently, at many sites the pumping of groundwater is now predominantly intended for the hydraulic containment of the polluted subsurface areas. At the same time, innovations and amendments to conventional pump-and-treat technologies have been proposed in order to reduce operation and maintenance costs (OMC), either by improvements to the treatment unit or by an optimal adaptation of the pumping system itself. In contrast to experience in the field, most of the theoretical studies presented so far assume that a complete contaminant removal is feasible using abstraction wells in or near the contaminant source area (e.g. Huang & Mayer, 1997; Mansfield & Shoemaker, 1999; Zheng & Wang, 1999). However, more realistic contamination scenarios also need to be considered, where residual non-aqueous phase liquids (NAPL) release contaminants into the groundwater over very long time periods. For these cases, where complete contaminant removal is not achievable by practical methods, the long-term hydraulic control of the contaminated area at minimum costs must be the major objective of a
pump-and-treat measure. The significant part of total remediation costs depends on operation costs for pumping and the on-site-treatment of the water extracted. Consequently, minimization of the pumping rate is the main challenge when searching for cost-effective designs for pump-and-treat systems.

In this paper, the potential of impermeable barriers to reduce the pumping rate necessary for complete plume capture \( Q_{\text{cap}} \) is investigated. The goal is that in the long run the additional investment costs for constructing an impermeable barrier will be balanced by the lower operation costs resulting from a reduction of the pumpage \( Q_{\text{cap}} \). In order to take into account the uncertainty of information at real sites, the economic comparison between a standard pump-and-treat system (SPT) and a barrier-supported pump-and-treat system (BPT) is achieved by means of a Monte Carlo simulation, considering an ensemble of equally probable theoretical site scenarios that represent the uncertainty of the subsurface heterogeneity.

### FRAMEWORK OF THE ANALYSIS

#### Methodology and tool set used

The framework for the comparative economic analysis of a SPT and a BPT comprises three modules: (a) a stochastic simulator to generate the ensemble of aquifer realizations (continuous random transmissivity fields by Sequential Gaussian Simulation; see Deutsch & Journel, 1992); (b) a modelling environment to quantify \( Q_{\text{cap}} \) for SPT and BPT within each realization; and (c) a cost model to determine total remediation costs as net present value. The pumpage \( Q_{\text{cap}} \) is quantified in a three-step procedure. First, the flow regime is computed using a finite-difference program (MODFLOW, McDonald & Harbaugh, 1988). Given the flow field, a particle-tracking runtime (MODPATH, Pollock, 1994) is used to verify whether all particles marking the contour of the contaminated area are captured by the pumping well. Depending on the result of the hydraulic control, an improved estimate of the pumping rate is determined through a bisection method (e.g. Press et al., 1990). These steps are repeated until the minimum \( Q_{\text{cap}} \) is found. With values of \( Q_{\text{cap}} \) for each realization, the Monte Carlo simulation yields a probability distribution of \( Q_{\text{cap}} \) that depends on the uncertainty associated with the aquifer heterogeneity instead of a definite value. As a consequence, total remediation costs (which depend on \( Q_{\text{cap}} \)), can be related to the robustness of the pump-and-treat system. Here the term robustness is used to describe the probability of capture of all the contaminated water under all given hydrogeological circumstances.

#### Pump-and-treat scenarios

The scenarios considered in this paper are shown in Fig. 1. For the sake of clarity we take a rather simple situation of one fully penetrating pumping well and one straight impermeable barrier, in order to work out the characteristic differences of the SPT and the BPT. However, the simulation tool sets described above can also be applied to any level of complexity encountered at real sites. Here, a confined aquifer of constant
Barrier-supported pump-and-treat systems

(a) 
- Direction of ground water flow
- Contaminated area
- Recharge well

(b) 
- Position of impermeable barrier analysed in this study
- Further barrier positions that have been analysed

**Fig. 1** Scenarios for (a) a standard and (b) a barrier-supported, pump-and-treat system with flow regime and pathlines (only the central part of the model region is shown).

thickness and a uniform regional hydraulic gradient is described by means of a two-dimensional flow field. We follow a common procedure in capture zone analysis under uncertainty (e.g. Franzetti & Guadagnini, 1996; van Leeuwen et al., 1998): unconditioned realizations of the spatial transmissivity distribution are produced based on statistical characteristics that reflect a heterogeneity level rather than picturing the reality completely. Thus the results of the study cannot be transferred directly to a real site, but they clarify the interplay of the system influencing parameters and consequently facilitate decision making.

As one of the possible options, a BPT with a barrier located in the centre of the contaminated area (source zone), perpendicular to the flow direction is analysed. Anticipating that a practitioner would place the barrier at the down- or upgradient edge of the contamination, these options have also been investigated in a preliminary study. However, the results show that the central variant considered here is approximately as effective as the others. It should be mentioned that a similar scenario was analysed by Ahlfeld et al. (1987). This study, however, addresses the use of hydraulic barriers to partly contain and partly decontaminate source zones in the aquifer.

Two aspects appeared to be most sensitive for the reduced pumpage $Q_{cap}$ in the three barrier options: (a) the cut-off of high permeability zones within the source zone that otherwise could divert the groundwater flow away from the pumping well, and (b) the convergence of groundwater flow which generally occurs downgradient of a physical barrier and focuses the flow direction towards the pumping well (Fig. 1(b)).

The well is placed downgradient of the contaminated area, which seems to be generally preferable for long-term pump-and-treat operations as the required pumping rate decreases with increasing distance to the edge of the contamination. This is
because the capture zone divide lines tend to align better on the right and left sides of the source zone with increasing distance from the pumping well. This relationship can be derived directly from the analytical solutions presented by Javandel & Tsang (1986) for the delineation of well capture zones in homogeneous media. This influence of the distance $x$ between the pumping well and contaminated area is illustrated in Fig. 2 for SPT. $Q_{cap}$ is expressed as dimensionless quantity $Q' = Q_{cap}/Q_0$ where $Q_0 = iTW$ (with hydraulic gradient $i$, aquifer transmissivity $T$, and width of the contamination $W$) is the groundwater flow rate through the contamination (denoted as the Darcy flow rate). The distance $x$ is also normalized as the ratio $x/W$. As shown in Fig. 2, $Q'$ increases if the well is moved towards the downgradient edge of the source ($x/W = 0$), where it takes a value twice the original Darcy flow rate to capture the source area. If the well is placed in the centre of the source area ($x/W = -0.5$), the required pumping rate is four times the Darcy flow rate through the contaminant area. For $x > 0$, $Q'$ decreases asymptotically to a value of 1 ($x \to \infty$). In the study presented here the pumping well is placed at $x/W = 0.5$.

![Fig. 2 Trade-off between pumping rate $Q'$ [-] and well position $x/W$ [-] relative to the contaminated area.](image)

Aquifer heterogeneity is simulated by 400 realizations of the spatial transmissivity distribution, assuming fluctuations of $T$ to be lognormally distributed with zero mean and variance $\sigma_T^2$. With $T_G$ as the geometric mean of $T$, the spatial correlation of $Y = \ln(TT_G^{-1})$ is specified by the integral scale $I_Y$, given by the two-point covariance function $C_Y(h) = \sigma_Y^2 \exp(-|h|/I_Y^{-1})$, where $h$ is the lag separation vector. In order to examine the influence of the extent of aquifer heterogeneity, realizations with the following values were considered: $I_Y/W = 0.5$ and 1.0, $\sigma_T^2 = 0, 0.1, 0.5, 1, 2, 3,$ and 4.5.

**RESULTS FROM THE HYDRAULIC ANALYSIS**

The reliability of a pump-and-treat system with respect to complete plume control is determined for any given pumping rate $Q$ as the percentage of realizations that yield a $Q'$ lower than $Q$. The results of the comparison of hydraulic performance of BPT and SPT are shown in Fig. 3. These are plotted as $Q'$-reliability curves by sorting the
calculated minimum pumping rates $Q'$ in ascending order (SPT: $Q_s'$, BPT: $Q_B'$). For a homogeneous aquifer ($\sigma_y^2 = 0$), the installation of an impermeable barrier leads to a remarkable reduction of the pumping rate from $Q_s' = 1.33$ to $Q_B' = 1.01$ (horizontal lines). Although this result cannot be transferred to heterogeneous aquifers, Fig. 3 depicts clearly that the BPT requires a lower pumping rate $Q_B'$ to achieve a certain robustness compared to $Q_s'$ for the SPT. This is true for all levels of heterogeneity considered. However, raising $\sigma_y^2$ and/or $I_Y/W$ yields an increase of $Q_s'$ and $Q_B'$. Ensemble mean values of $Q_s'$ and $Q_B'$ for a maximum degree of heterogeneity ($\sigma_y^2 = 4.5, I_Y/W = 1.0$) are approximately twice as high as those for the homogeneous case.

The variance of the $Q_s'$ and $Q_B'$ values obtained for each ensemble of realizations also rises with increasing degree of heterogeneity, especially with regard to the SPT. An enlargement of the integral scale of the aquifer patterns ($I_Y/W$) as well as an increase of the variance ($\sigma_y^2$) raises the probability of realizations with extreme transmissivity distributions that yield either very low or very high values of $Q_s'$ and $Q_B'$. Although it is not easily possible to predict whether a certain transmissivity distribution will yield low or high pumping rates, two main features that create relatively high $Q'$ values can be identified. These are: (a) high conductivity areas within or in the vicinity of the source zone that increase the local groundwater flow rate, and (b) preferential pathways, that point away from the downgradient well (see also Ranjithan et al. (1993), or Poeter & Townsend (1994)).

Alternatively, $Q'$ is relatively small if the local flow rate is low and the flow direction does not deviate from the well. In order to obtain better insight into the realization-specific performance of the BPT, the $Q_B'/Q_s'$-ratio for each single realiz-
ation is shown in Fig. 4, sorted in ascending order to express the probability that a certain ratio is achieved. It can be seen that pumping rates required for BPT are considerably lower compared to the SPT ($Q_B'/Q_S' < 1$) for nearly all realizations. An important feature is that, for the given framework, the diverging flow caused by the barrier does not lead to severe outliers by directing the contaminant flow into distant high conductivity channels. The converging flow downgradient of the barrier compensates this process. Thus given a value of $Q_S'$ the probability of failure by the installation of the barrier is nearly zero. We interpret these findings as a *blocking effect* by the hydraulic barrier, i.e. preferential pathways within the source area are intercepted leading to a flow rate reduction.

![Fig. 4 Probability of savings in pumping due to barrier installation.](image)

**ECONOMIC EVALUATION**

In order to focus on the impact of aquifer heterogeneity on total remediation costs for the pump-and-treat systems, we simplified the economic evaluation by assuming that pumping and on-site treatment are directly related to the pumping rate only (see Ahlfeld & Heidari, 1994). However, treatment costs depend particularly on a number of parameters, e.g. type of contaminant(s), treatment technique, contaminant concentration, etc., which we lumped together here using a unit cost approach. For an extensive discussion of the economic evaluation tool set the reader is referred to Bayer (1999).

Corresponding to the previous hydraulic investigation, an example site scenario was considered, with $W = 100$ m, $i = 2 \times 10^{-3}$, $T_G = 1 \times 10^{-2}$ m$^3$s$^{-1}$ and aquifer thickness $m = 20$ m. A comparison of total remediation costs of the SPT and the BPT assuming an operation time of 30 years and an expected performance reliability of 95%, is shown in Fig. 5. The considered discounted unit costs range between €0.05 m$^{-3}$ and €0.30 m$^{-3}$. They comprise expenses for planning, pumping, (pre-)treatment and the necessary manpower, for the whole operational period. Also the efficiency of the treatment technology to meet the clean-up standards has an important influence on unit costs. If, for example, air stripping has been chosen for the decontamination of groundwater, values of €0.05 m$^{-3}$ can be expected for low concentrations of adequately
sorbing chlorinated carbons, whereas high values result from more problematic contaminants at high concentrations. In some cases additional costs may have to be considered, e.g. for site-specific waste-water costs, that directly heighten the unit price per volume of water. For the BPT in this example, the price for the installation of a slurry wall is assumed to be €80 m\(^{-2}\) plus an initial investment of €35 000 for site installation.

At unit costs of €0.05 m\(^{-2}\) no remarkable difference between the BPT and the SPT can be observed. In this case, the cost savings resulting from the lower pumping rates \(Q_b'\) comprising the BPT are compensated by the additional cost for the barrier installation. However, if unit operational costs were in the range of €0.30 m\(^{-2}\) or more, the BPT becomes the cheaper alternative (as the expenses for the barrier remain constant).

In general, total costs increase with increasing \(\sigma_y^2\). This is due to the increased spread of the associated \(Q'\)-reliability curve (Fig. 3) and, thus, higher pumping rates for a given (high) reliability level. However, it should be noted that the BPT is less sensitive to \(\sigma_y^2\), which is reflected through the only small extra costs at high \(\sigma_y^2\) values (Fig. 5(b)). Consequently, the potential cost savings that can be achieved with the BPT depend on both the unit operation costs and the aquifer heterogeneity (Fig. 5(b)). The higher the value of \(\sigma_y^2\), and the higher the unit costs for pumping and on-site treatment, the higher the cost savings resulting from the installation of the impermeable barrier system.

**CONCLUSIONS**

In the numerical analysis presented, the hydraulic performance of a standard pump-and-treat system (SPT) and a barrier-supported pump-and-treat system (BPT) are
compared with respect to the control of a contaminated area. It is revealed that the installation of an additional barrier results in a considerable reduction of the pumping rate that is necessary to achieve hydraulic containment. Furthermore, the results show that incorporating the uncertainty concerning aquifer conductivity is an important means for assessing the reliability of pump-and-treat measures. The reduction of the required pumping rate, however, does not imply that the BPT generally is the better alternative. The economic analysis shows that the BPT is only advantageous if unit costs for pumping and on-site treatment surmount a certain limit, which depends on the degree of aquifer heterogeneity.

**Acknowledgements** Support for this work was provided by the German Department of Education, Science, Research and Technology (BMBF), Contract no. 02WT0019.

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