BRIDGING THE GAP BETWEEN CONVENTIONAL PUMP-AND-TREAT SYSTEMS AND PERMEABLE WALLS: HYDRAULIC AND ECONOMIC ASPECTS OF BARRIER SUPPORTED PUMP-AND-TREAT SYSTEMS

Peter Bayer, Michael Finkel, Georg Teutsch

Corresponding author: Peter Bayer
Center for Applied Geoscience
University of Tuebingen
Sigwartstrasse 10
72076 Tuebingen, Germany
Phone: ++49 7071-2973178, Fax: ++49 7071-5059
E-mail: peter.bayer@uni-tuebingen.de

Key words: hydraulic barriers, pump-and-treat, stochastic modelling, capture zone delineation, reliability, economic evaluation

ABSTRACT

Barrier supported pump-and-treat systems (BPT) are hybrid, partly active and partly passive groundwater remediation technologies. Similar to the active conventional 'pump-and-treat' method, they consist of pumping wells which continuously operate to hydraulically capture a contaminated aquifer zone. In order to reduce the extraction rate, vertical barriers are installed in the subsurface. They act like the 'funnels' of the PRB variant 'funnel-and-gate' and are applied to opportunely direct the groundwater flow. The objective is to reduce the extraction rate, which can be regarded as a surrogate of the total remediation cost. Especially regarding the expectedly long operation time of aquifer restoration, reducing the continuous expenditures on pumping and treatment seems to be a desirable goal. However, only few studies have addressed barrier supported pump-and-treat systems in a general way, and as a result little is known about the potential of this technology and an optimal system design. In the presented study we investigate the influences of uncertainty of aquifer heterogeneity and of the direction of the hydraulic gradient based on a coupled hydraulic modelling and Monte Carlo analysis. The performance of two BPT configurations is compared to a conventional pump-and-treat system. The performance criteria are minimum pumping rates and the reliability to capture a predefined aquifer contamination. Starting from this, characteristic hydraulic system sensitivities are revealed, which are an important support for a site-specific application. Additionally, a sophisticated economic toolset is adopted to enable the selection of a cost-efficient configuration of the technology. We illustrate that the interplay of several hydraulic and economic decision variables has to be considered, leading to an optimal system design, which is hard to prognosticate intuitively.

INTRODUCTION

Decision makers that set up remedial action plans for the management of contaminated aquifers generally have to deal with two major objectives: contaminant removal and containment of contaminated aquifer zones. In early stages, emphasis is placed upon the source zone, its identification, localisation and, if possible, the application of source zone remediation technologies. The objective is to reduce the risk for the groundwater and other receptors coming from contaminant centres, especially from non-aqueous phase liquids which act as long-term sources and continuously release pollutants to the passing groundwater. In many cases, however, expecting a complete remediation in a reasonable timeframe showed up to be a bold venture (e.g. MacDonald & Kavanaugh

1994). In fact, so far only a few sites are reported where complete aquifer restoration could be achieved. As a consequence, to control the subsurface contamination and eliminate its spreading, containment plays an important role during an expectedly long operation time (e.g. Cohen 1997).

Under certain circumstances, a complete encapsulation by installing impermeable walls around the critical aquifer zones might be a solution. For this a reliable sealing construction is necessary, based on artificial and, if existing, natural barriers such as low permeable layers. Usually the physical containment is supported by one or more pumping wells in the interior in order to create an inward pointing hydraulic gradient reducing the risk in case of leakage. Strictly speaking, this approach is not a remedial rather an isolation technique, since contaminant removal is only a side aspect. Aside from this, the required sealing is difficult to obtain in many cases, due to existing buildings at the site and the demanding technical construction. Furthermore, the detection of leakages often results in additional modifications and finally increasing expenditures. These drawbacks direct the interests to alternative technologies, ideally characterized by a higher flexibility, a wide experience and more accurately complying with the aquifer remediation issue.

The classic, and still most widely used, groundwater remediation method is 'pump-and-treat' (Reeves et al. 2001). Extraction (and in some cases injection) wells are installed in order to reach both hydraulic containment and contaminant recovery. The capture zone around pumping wells determines the boundary of the contained aquifer zones. The pumped water is treated on-site by specified clean-up technologies, depending on the prevalent contaminants. This simple concept is appealing and in many cases identified as the only feasible remediation option. Additionally, 'pump-and-treat' is highly flexible and several innovative technologies such as *surfactant flushing* have been developed to enhance to the performance of the classic (conventional) pump-and-treat approach (US EPA 2001a). Conventional pump-and-treat systems (CPTs) are characterized by low capital costs arising from well, treatment plant installation, and mobilisation. Oppositely, the permanent consumption of energy and treatment material adds up to relative high expenditures for the system operation and maintenance. Passive systems like permeable reactive walls (PRBs) are proposed as promising alternatives to active methods like CPT, where the operation time is believed to be long. PRBs are intended to clean up the contaminant plume in-situ by reactive zones installed in the subsurface downgradient of the pollution. Optionally, impermeable barriers can be arranged in so-called 'funnel-and-gate systems' to direct the contaminant flow to the treatment zones (Starr & Cherry 1994). The idea is that the high initial investment for constructing a PRB will be compensated in the long run by the lower operational costs of this passive technology compared to active pumping (US EPA 2001b). For PRBs, the capture zone is determined by the line that separates the streamlines through the treatment zone from the encompassing aquifer. Contrary to pump-and-treat, the static permeable (-impermeable) wall construction represents a relative inflexible technology for hydraulic containment. While CPT can be adapted to changes of natural hydrological or hydrogeochemical constraints, such as variations in groundwater flow or (local) contaminant depletion, for the installation of robust passive elements one has to consider the worst case which consequently yields a system over-designed to most conditions. Alternatively, if the performance is insufficient and off-site migration cannot be prevented by PRBs alone, passive systems can be supported by pumping wells. However, this mainly occurs if the technological capabilities have been overestimated or safety factors to deal with site variability have been set too low.

Barrier supported pump-and-treat systems (BPTs) are hybrid methods that bridge the gap between active and passive technologies. In addition to CPT, impermeable vertical walls are installed in the subsurface to facilitate the control of groundwater flow and contaminant capture. The idea is to reduce operational costs compared to CPT by reducing the pumping rate required to establish the wanted capture zone. Aside from this, the dynamic adaptability of pumping rates together with the fixed position of the barrier results in a semi-flexible system that is capable of being modified during its application.

PREVIOUS WORK

Though widely accepted as an efficient remediation technology (e.g. US EPA 1996) only few studies investigated BPTs in a general way in order to identify important performance criteria and sensitivities between design parameters and objectives. Bowen & Johnson (1993), Russell & Rabideau (2000) and Bayer et al. (2001) discussed the application of BPT in a technical-economic framework compared to competing methods for typical site scenarios. The findings show that the complex and site-specific interplay of various parameters and constraints determines the hierarchy of different remediation technologies. A general conclusion is that high treatment and low barrier costs tend to favour BPT over CPT. In the exemplary comparison by Bayer et al. (2001), BPT was shown to outperform a funnel-and-gate system for a broad range of different decision variable settings.

While the above mentioned work is based on a deterministic description of the aquifer assuming a complete knowledge of the hydraulic aquifer properties, this paper considers uncertainty aspects focusing on the system sensitivity of both CPT and BPT to aquifer heterogeneity and to the direction of the regional hydraulic gradient. It is a continuation of a preceding study (Bayer et al. 2002), where we examined the influence of various 'levels' of aquifer heterogeneity on the performance of a BPT. The setting considered consists of a barrier of fixed length placed in the centre of a quadratic contaminated area perpendicular to the direction of a uniform hydraulic gradient and completed by one downgradient pumping well. The hydraulic analysis was based on Monte Carlo simulations in order to obtain the reliability of capture, or vice versa the probability of system failure. For this, assuming a given statistical characteristic of the spatial hydraulic conductivity distribution, a number of equally probable realisations were generated. After the numerical calculation of the minimum pumping rate Q' for each realisation, the ensemble pumping rates were sorted in order to infer Q'-reliability trade-offs. These show that considerably less water has to be pumped (and treated) if an additional impermeable barrier is implemented. However, a simplified economic evaluation by means of a unit cost approach revealed that due to the additional costs for barrier installation, the BPT is only advantageous if unit costs for pumping and on-site treatment exceed a certain limit. This limit showed up to be dependent on the degree of aquifer heterogeneity.

In this paper, using a similar Monte Carlo simulation framework, a more sophisticated economic model as presented by Bayer (1999) and Bayer et al. (2003) applies. Two different BPT variants are compared with CPT. An additional hydraulic barrier is either positioned up- or downgradient of a predefined quadratic contaminated area (Fig. 1). In the following text we first give a brief explanation of the hydraulic model set-up, which is employed for the Monte Carlo analysis. Then, after selecting a constant statistical parameter setting of the spatial conductivity distribution, the influence of uncertainty in the hydraulic conductivity and the direction of the hydraulic gradient is discussed from a technical and economic point of view.

MODEL CONFIGURATION AND CALCULATION OF PUMPING RATES

The steady-state two-dimensional hydraulic model is based on the solution of the two-dimensional flow equation by finite differences. The quadratic model domain is subdivided into a regular grid of 300x300 cells of 2 m side length each. A confined aquifer, 10 m thick, is assumed. Sequential Gaussian simulation (Deutsch & Journel 1992) is used to generate stochastically 400 realisations of the spatial transmissivity (T) distribution. It is presumed that fluctuations of T are log-normally distributed with zero mean and variance σ_Y^2. With T_G as the geometric mean of T, the spatial correlation of $Y = \ln(T\ T_G^{-1})$ 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. A moderate spatial variability given by $\sigma_Y^2 = 1.0$ and $I_Y = 50$ m is selected. The mean hydraulic conductivity is set $k_f = 0.001$ m/s (T_G = 0.01 m²/s). A uniform hydraulic gradient *gradh* = 0.005 is accomplished by constant head boundaries at the model edges. The influence of a change of the flow direction is modelled by a rearrangement of these constant head boundaries. Starting from a reference set up, where the gradient is pointing from north to south ($\theta = 0°$), flow directions are varied up to $\theta = 30°$ to the SE direction (Fig. 1).

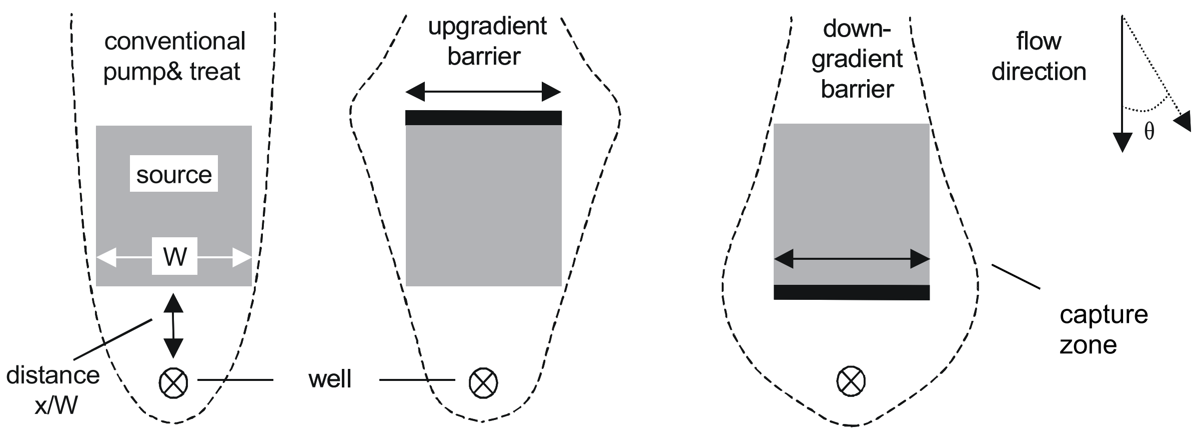

Fig. 1. CPT and BPT variants and direction of uniform groundwater flow. The depicted capture zones outline the results for a homogeneous aquifer under minimum pumping *Q'* to catch the contaminant source.

The reference site is characterized by a quadratic contaminated zone in the centre of the model area measuring W = 100 m. For a more general view, assuming linear scaling the model and site configuration can be described by normalized design parameters, e.g. I_Y/W = 0.5. To simplify matters the remediation strategy is based on only one central pumping well, positioned at a distance of x = 50 m (x/W = 0.5) downgradient of the contamination. The BPT variants are characterized by hydraulic barriers restricting a direct inflow of groundwater into the contaminated area (or outflow, respectively). The barrier length is B = 100 m (B/W=1).

The pumping rate Q' is calculated in a three-step procedure. First, the flow regime is computed using a finite-difference program (MODFLOW, McDonald & Harbaugh 1988). Then, given the flow field, a particle-tracking routine (MODPATH, Pollock 1994) is used to verify whether all particles marking the contour of the contaminated area are captured by the pumping well. Finally, according to the result of the hydraulic control, an improved estimate of the pumping rate is determined through a bisection method (Press et al. 1990). These steps are repeated until the minimum Q' guaranteeing complete capture is found. For each of the equally probable transmissivity realisations one value Q' is obtained. Sorting these values yields a probability distribution of Q' that depends on the uncertainty associated with the aquifer heterogeneity instead of a definite value. Note that Q' values are calculated as dimensionless values. That is, they are referred to the undisturbed Darcy flow through the contaminated zone under homogeneous conditions (σ_Y^2 = 0). Accordingly, Q' equals unity for the homogeneous reference case (Q' = 1).

RESULTS OF HYDRAULIC MODELLING

The uniform regional gradient direction is changed anti-clockwise starting from NS orientation (θ = 0°) at 5° steps up to a maximum deviation of θ = 30°. Fig. 2 shows the resulting trade-off between Q' and the probability of capture p_{cap}. For the unchanged hydraulic gradient direction the influence of aquifer heterogeneity finds expression in the calculated pumping rates that nearly quadruple from Q' = 0.8 to 3.2 at increasing p_{cap}. The typical sigmoid trend of the curves reflects the sensitivity of the system reliability to Q'. In particular if p_{cap} is exceeds 90% (p_{cap} > 0.9), a disproportional rise of Q' is needed to reach an increase of system reliability. Remarkably, the trade-off curves do not significantly change their shape for a deviated hydraulic gradient direction up to θ = 30°. However, the values of Q' increase and roughly double from θ = 0-30°. The change of Q' is minimal for θ = 0-5° and then nearly linearly rises with θ. The absolute rise can be identified a function of the given p_{cap}, being minimal for low p_{cap} and maximal for high p_{cap}.

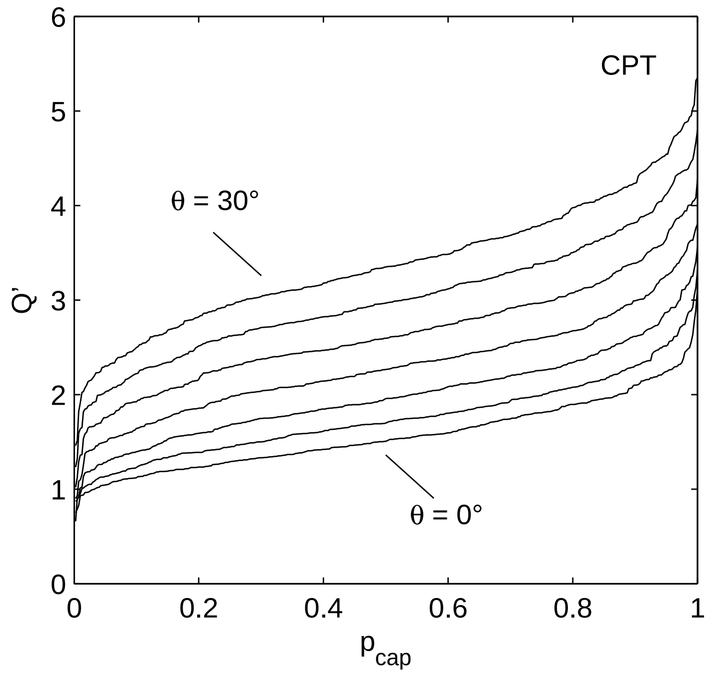

Fig. 2. Reliability trade-off curves for contaminant capture calculated for CPT. The influence of the deviation of the uniform regional gradient from the NS axis is depicted for 5° steps.

The decisive issue is whether the additional barrier influences and ideally reduces the pumping rate to capture the contaminated area. For this purpose, the results of the pumping rates for the BPT variants are related to *Q'* of CPT. The relative reduction or increase, expressed by Q'_{BPT}/Q'_{CPT}, is given in Fig. 3 as a function of the probability, p_{rel}. The functions are obtained by grouping all individual realisation-specific Q'_{BPT}/Q'_{CPT} values in ascending order. Accordingly, p_{rel} defines the probability of gaining a certain ratio Q'_{BPT}/Q'_{CPT}. The findings correspond to the results of Bayer et al. (2002), where a centrally positioned barrier was identified to be an efficient tool to reduce Q'_{BPT} over Q'_{CPT} in nearly all cases for a variety of different aquifer heterogeneities. For a detailed interpretation of this outcome, based on hydraulic aquifer characteristics and the potential alteration of the flow paths by vertical barriers, the reader is referred to (Bayer et al. 2002). The plots in Fig. 3a and 3b contrast probable minimum savings of up- and downgradient barriers. The downgradient barrier (Fig. 3b) is closer to the well, and this is expected to be the reason for the greater variance of the relative reduction of *Q'* versus CPT at a NS pointing hydraulic gradient.

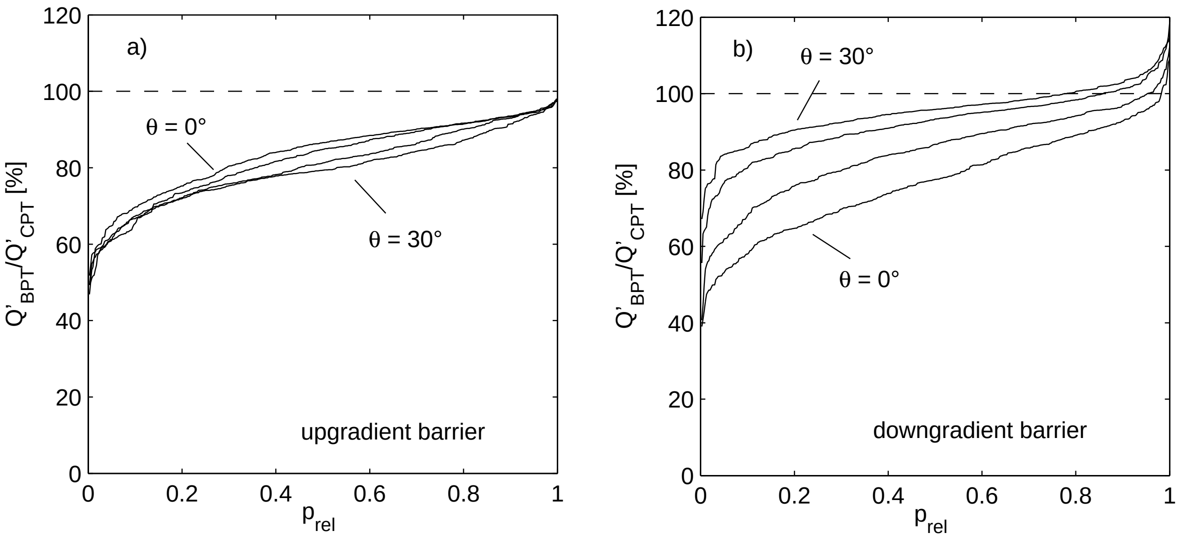

Fig. 3. Probability of ratios of pumping rates calculated for BPT versus CPT regarding an up- and downgradient barrier position.

The expected mean savings of both barrier settings are approximately 75%. While for the upgradient barrier no realisation gave higher *Q'* for BPT compared to that for CPT, a savings in *Q'* by installing a downgradient barrier can not be ensured for certain. However, the probability that *Q'* will be increased by installing this barrier type lies below 3%.

Apparently, a change in the direction of the hydraulic gradient ($\theta > 0°$) influences not only the calculated *Q'* for CPT (Fig. 2) but also the *Q'* for BPT. Fig. 3a reveals that statistically the sensitivity of *Q'* for the upgradient barrier to gradient deviations is nearly analogous to that for CPT (since the Q'_{BPT}/Q'_{CPT} ratio only slightly change with θ). Yet a remarkable tendency is that the efficiency of this BPT variant to reduce *Q'* compared to CPT tends to grow with increasing deviation of the hydraulic gradient from the NS axis. This is contrary to the results for the downgradient position. The higher θ is, the worse the performance of this barrier variant is to reduce *Q'* in relation to CPT. The minimum and average savings in *Q'* decrease with the deviation of the gradient direction, and the risk that more water has to be pumped than for CPT rises to 20 % at $\theta = 30°$.

ECONOMIC EVALUATION

A full economic evaluation of BPT is beyond the scope of this study. For a site-specific technical-economic assessment of remediation technologies a huge number of site specific critical parameters as well as hard and soft decision criteria have to be considered. Thus, in order to carry out a reasonable general assessment several simplifications are necessary to come up with generally valuable relationships and sensitivities. Even if the findings are based on simplifying assumptions, they can be a great support for individual decisions and system adaptation and may be taken as the starting point of a comprehensive site-specific assessment.

CPT has been analysed in a general economic framework by several authors (e.g. Culver & Shenk 1998) and the available tool sets comprise sophisticated cost models and databases (e.g. US

EPA 1997, Rast 1997). An advantage for the comparison between CPT and BPT is that many expenditures can considered to be equal. This especially refers to costs for planning, site investigation and maintenance, which, in general, are hard to determine. These cost elements are cancelled down, following the economic evaluation method presented by Bayer (1999) and Bayer et al. (2003), which utilize general cost functions for CPT- and BPT-elements. For a detailed description, the reader is referred to these studies.

In the subsequent investigation we construct a hypothetical scenario of a contaminated site in order to exemplarily expose differences of CPT and the BPT variants on the basis of economy. The site scenario is oriented at the model settings used within the hydraulic assessment previously mentioned herein. Further site characteristics and economically relevant parameter settings are summed up in Tab. 1. It is assumed that a quadratic source zone continuously feeds the passing groundwater with dissolved *cis*-Dichloroethylene. For our reference case we suppose that a constant concentration over time in the recharge water sufficiently describes the typical tailing mechanism (e.g. Grathwohl 1998) which stands for the long-term, barely decreasing concentrations that are typical for contaminations with organic contaminants. The operation period under consideration is set to 30 years.

Tab. 1: Site characteristics and parameter settings for economic assessment of CPT and BPT.

contaminant type	cis-Dichloroethylene	inflation rate	3%
constant concentration	1000 mg/m³	rate of interest	5%
estimated operation time	30 years	slurry wall installation cost	35,000.00 €
regional hydr. gradient	0.005	unit cost for slurry wall	75.00 €/m²
mean hydr. conductivity	0.001 m/s	cost of activated carbon	Ø 3.50 €/kg
aquifer width	10 m	unit electricity charge	0.08 €/kWh
aquifer top	8 m bgs.		
width of square cont. area	100 m		

The selected pumping and treatment devices are configured for a constant water throughput. Accepted as one of the most common clean-up technologies, sorption on granular activated carbon is chosen. Note that operational costs are continuously paid and subject to discounting. The lifetime of pumping, treatment and conduit elements are set to 10 years and consequently are replaced 2 times within the operation period. The resulting re-investment costs are also discounted. The initial price is deduced from the scenario-specific pumping rate and surmounts 20,000 to 50,000 €, depending on the pumping rate.

Regarding the direction of the hydraulic gradient, we subdivide two cases. The first implies a uniform hydraulic gradient pointing NS (θ = 0°). In the second case, the gradient direction deviates at an angle of θ = 30° anticlockwise from this axis. For our example case, a deviation in the NS direction reflects a change or wrong initial estimation of the gradient orientation, which is originally deemed to be NS. The question is now to decide if this aspect has an influence on the economic results and on the final selection of the optimal, most cost-effective solution.

In accordance with the results of the hydraulic investigation providing relationships between the pumping rates and the system reliability (probability of capture p_{cap}), total operation costs *TC* are also related to the system reliability (Fig. 4). The sigmoid shape of the curves in Fig. 4 reflects the dependency of the costs on the required abstraction rate or p_{cap}. Presuming a NS oriented gradient, the *TC* rise with p_{cap} from 500.000 € to nearly 1.5 Mio. € indicates a significant impact on the uncertainty of the heterogeneous aquifer conductivity on the prediction of remediation cost. This influence is even greater when changing the gradient direction by 30°, where the *TC*-reliability curves are slightly steeper. For each given p_{cap}, the considered *TC* of all pump-and-treat system variants are approximately doubled in the case of θ = 30°.

In case the regional gradient is oriented in the NS direction, both BPT variants end up with costs that are slightly below those calculated for CPT for a broad span of p_{cap}. The downgradient BPT shows to be the cheapest technology in this case and leads to *TC* savings (regarding to the considered cost elements) of up to over 15 % compared to CPT. Tab. 2 lists the proportions of different cost types to the *TC*. Gaining a higher system reliability is equivalent to a raise in required pumping rates. Consequently, the relevance of the *BC* is reduced versus the other capital costs (*CC*) and especially operational cost (*OC*). Due to the distinctively higher pumping rates, the *BC* especially becomes less important when considering a deviation of the hydraulic gradient direction.

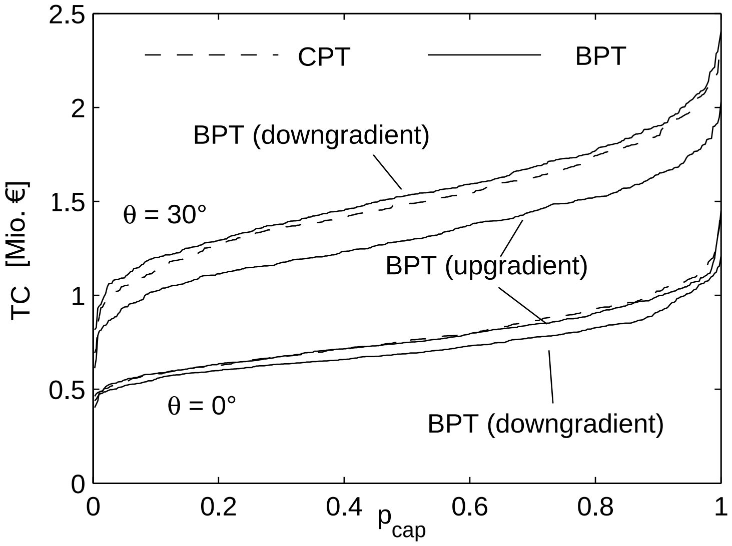

Fig. 4. Total costs *TC* of example site remediation versus probability of capture (p_{cap}) for the CPT and the BPT variants. The hydraulic gradient points NS and deviates 30° to the NW/SE direction, respectively.

A rearrangement of the hydraulic gradient to θ = 30° not only raises the *TC*, but also switches to another optimal technology. Here, the upgradient barrier is the ideal solution yielding cost savings compared to CPT of up to 350,000 €. Note that the *BC* are lower than one third of this amount (*BC* = 110,000 €). This outcome is caused by the minor sensitivity of the upgradient barrier to a change of the hydraulic gradient direction in comparison to the downgradient barrier. The results of the hydraulic analysis show nearly constant relative pumping rate savings (Fig. 3a) and simultaneously increasing absolute savings. Since, as mentioned above, the proportion of the *BC* to the *TC* are reduced, the absolute cost savings increase remarkably. The downgradient barrier performs considerably worse when a change of the gradient direction is considered. As depicted in Fig. 3b, its potential to reduce *Q'* compared to CPT decreases with increasing deviation. In the 30°-case *BC* are not completely compensated.

Tab. 2: Proportions of operational (*OC*), barrier (*BC*) and (other) capital costs (*CC*) to the total remediation costs of the considered cost elements (*TC*) for the example site at NS oriented hydraulic gradient. Listed are the ratios for three different given probabilities of contaminant capture (p_{cap}).

p_{cap}	ratio of cost type	CPT		BPT (downgradient)		BPT (upgradient)	
5%	OC/TC	87.1	90.1	65.9	79.1	67.1	73.9
	CC/TC	12.9	9.9	11.0	8.6	10.8	9.6
	BC/TC	-	-	23.1	12.3	22.0	16.5
50%	OC/TC	90.5	93.2	76.2	87.0	77.7	85.3
	CC/TC	9.5	6.8	9.2	6.5	8.9	7.0
	BC/TC	-	-	14.6	6.5	13.4	7.7
100%	OC/TC	93.2	94.5	84.5	90.6	86.5	89.4
	CC/TC	6.8	5.5	7.2	5.3	6.7	5.7
	BC/TC	0.0	0.0	8.3	4.1	6.8	4.9

CONCLUSIONS

The presented study throws light on the relationships between uncertainty of groundwater flow conditions, system reliability and final decision making for conventional and barrier-supported pump-and-treat systems. Given a fixed configuration of the well extraction system, the uncertain, probability-based description of the aquifer conductivity leads to a broad interval of possible minimal pumping rates required to capture the contamination. The inferred sigmoid reliability curves are crucial hints for the construction of an implementation plan, ensuring a robust performance of pump-and-treat technology variants. They expose the high sensitivity of required pumping rates when approaching a capture probability of p_{cap} = 100%, and accordingly the disproportional strong increase of the cost to gain a higher system reliability. For the chosen statistically fixed aquifer heterogeneity, CPT and both BPT variants have shown to be sensitive in different ways. A major finding is that the down- and upgradient positioning of a hydraulic barrier generally results in savings of *Q'*. In this case 25 % (on average) of the *Q'* calculated for CPT is saved. The question whether this is true also for other aquifer heterogeneity settings can not be answered. However, there is evidence that the downgradient barrier is more sensitive to uncertain aquifer conductivity, resulting in a greater variance of realisation-specific relative *Q'* compared to CPT. Contrary to the upgradient barrier, which leads to *Q'* reduction for all realisations, the downgradient barrier can have an albeit infrequent negative effect.

By consideration of a deviation of the hydraulic gradient direction from the expected one, e.g. due to seasonal changes, another source of uncertainty has been incorporated in the investigation. Surprisingly, even if the original positioning of the barriers perpendicular to the flow direction is maintained, the bended flow to the barriers for $\theta > 0°$ does not show to be principally a disadvantage with respect to the relative performance of BPT variants compared to CPT. Looking at the *Q'*-reliability trade-offs (Fig. 3), this can be attributed to the fact that both the *Q'* for BPT and CPT do increase with growing θ. However, while the efficiency of the upgradient barrier compared to CPT slightly increases, a reversed effect can be observed for the downgradient barrier. This decreasing benefit from a downgradient barrier with rising θ has an important impact on the economical ranking of the pump-and-treat variant.

Comparing CPT to BPT, the essential query is if barrier installation costs are worth the benefit from reduced operational costs. Thus, many factors increasing the cost of CPT simultaneously favour the selection of BPT. The given example site is used as a simplified template to illustrate the stimulus of hydraulic characteristics on the economic values. It is that the influence of both aquifer heterogeneity and deviation of the hydraulic gradient direction determine the optimal or cheapest solution, if no variability of other decision variables is considered. Interestingly, there is no principally optimal barrier configuration, which is shown by the influence of gradient direction on the performance of the upgradient barrier compared to the downgradient one.

The hydraulic modelling exposed several system sensitivities, but it is only a start for a more comprehensive analysis. Several other decision criteria have to be included, such as alternative barrier settings, variable barrier lengths, different well positions, principal uncertainty of the hydraulic gradient, structure of contaminations, etc. The main point is in which way a different, especially higher variability of the spatial conductivity distribution influences the performance of BPT compared to CPT. Aside from this, the unconditioned modelling concept must be replaced by a more realistic and conditioned one. Therefore, not only relative parameter sensitivities, but also a specific site application is of interest. Moving from the complete stochastic to a (more) deterministic modelling procedure might result in site-specific ideal barrier configurations for BPT.

REFERENCES

Bayer, P. (1999) *Kostenanalyse innovativer Pump-and-Treat Konzepte* (*Cost analysis of innovative pump-and-treat systems*). Diploma Thesis, Center for Applied Geoscience, University of Tuebingen, Germany.

Bayer P., Finkel M., Teutsch G. (2002) Reliability of hydraulic performance and cost estimates of barrier-supported pump-and-treat systems in heterogeneous aquifers. ModelCare 2002, Prague.

Bayer P., Finkel M., Teutsch G. (2003) Cost-optimal contaminant plume management with combined pump-and-treat – physical barrier systems. - Submitted 2003.

Bayer, P., Morio, M., Bürger, C., Seif, B., Finkel, M., Teutsch, G. (2001) Funnel-and-Gate vs. Innovative Pump-and-Treat Systems: A Comparative Economical Assessment. *Proceedings of the Groundwater Quality Conference 2001*, Sheffield, IAHS Publ. No. 275, 235-244.

Bowen, J.D., Johnson, K.D. (1993) Pumping or slurry walls - Which works best for groundwater containment.- *Engineering Hydrology, Proceedings of the Symposium*, New York, 808-813.

Cohen, R.M., Mercer, J.W., Greenwald, R.M., Beljin, M.S.(1997) *Design guidelines for conventional pump-and-treat systems*. EPA 540-S-97-504, Ada, Oklahoma.

Culver, T.B., Shenk, G.W. (1998) Dynamic optimal groundwater remediation by granular activated carbon. - *Journal of Water Resources Planning and Management*, 124(1), 59-64.

Deutsch, C.V., Journel, A.G. (1992) *GSLIB: Geostatistical software library and user's guide*. – Oxford University Press, New York, 340 p.

Grathwohl, P. (1998): *Diffusion in Natural Porous Media: Contaminant Transport, Sorption/Desorption and Dissolution Kinetics*.- Kluwer Academic Publishers, Boston, 224 p.

MacDonald, J.A., Kavanaugh, M.C. (1994) Restoring contaminated groundwater: An achievable goal? *Environmental Science and Technology* 28(8), 362A-368A.

McDonald, M.G., Harbaugh, A.W. (1988) A Modular Three-Dimensional, Finite Difference Ground-Water Flow Model. In: *U.S. Geological Survey Techniques of Water Resources Investigations*, Book 6, Chapter A1. Washington, DC.

Pollock, D.W. (1994) *User's Guide for MODPATH/MODPATH-PLOT, Version 3: A particle tracking post-processing package for MODFLOW, the US Geol. Survey finite-difference ground-water flow model*. US Geological Survey Open-File Report 94-464.

Press, W.H., Flannery, B.P., Teukolsky, S.A., Vetterling, W.T. (1990) *Numerical Recipes – The Art of Scientific Computing*. Cambridge University Press, 2nd edition.

Rast, R.R. (1997) Environmental remediation Estimating methods. R.S. Means Company, 550 p.

Reeves, H.W., Dowding, C.H., Igusa, T. (2001) *An Efficient Reliability-Based Approach to Aquifer Remediation Design*. NCER final report, Northwestern University, 60 pp.

Russell, K.T., Rabideau, A.J. (2000) Decision Analysis for Pump-and-Treat Design. - *Groundwater Monitoring and Remediation*, 20(3), 159-168.

Starr, R.C., Cherry, J.A. (1994) In Situ Remediation of Contaminated Ground Water:The Funnel-and-Gate System: *Ground Water*, 32(3), 465-476.

US EPA (1996). *Pump and Treat Ground-Water Remediation: A Guide for Decision Makers and Practitioners*. EPA 625-R-95-0005. Washington, DC.

US EPA (1997) *Cleaning Up the Nation's Waste Sites: Markets and Technology Trends*. EPA 542-R-96-005, Washington, D.C.

US EPA (2001a) *Cost Analyses for Selected Groundwater Cleanup Projects: Pump and Treat Systems and Permeable Reactive Barriers*. EPA 542-R-00-013, Washington, D.C.

US EPA (2001b) *A Citizen's guide to In Situ Flushing*. EPA 542-F-01-011, Washington, D.C.

Please cite as:

Bayer, P., Finkel, M. & G. Teutsch (2003): Bridging the gap between conventional pump-and-treat systems and permeable walls: Hydraulic and economic aspects of barrier-supported pump-and-treat systems. - Proc. of 8th International FZK/TNO Conference on Contaminated Soil (CONSOIL), Gent, Belgium, May 12 - 16 2003, pp. 1592-1600.