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# Application of economic-risk analysis for design and optimization of the Kansas City Plant interceptor system

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**Abstract** In times of diminishing budgets the act of over-designing remedial systems to compensate for hydraulic parameter and site conceptual-model uncertainty is no longer practical. This new reality creates a necessary compromise between cost and uncertainty. Economic-risk analysis provides the required balance by summing expected remedial system and potential failure costs. Remedial system costs consist of capital and operation and maintenance expenditures. Potential failure costs are the product of the cost of failure and the probability of failure. Cost of failure consists of potential fines and legal expenses associated with remedial system failure and the expense of additional remedial activities needed to rectify the failure. Probability of failure is the likelihood that a remedial design will fail due to hydraulic parameter and site conceptual model uncertainty. Economic-risk analysis was used at the US Department of Energy, Kansas City Plant to design and evaluate various groundwater interceptor systems consisting of vertical and horizontal wells. The probability of failure of the remedial designs was determined using Monte Carlo groundwater flow and particle tracking analysis. Parameter statistical input distributions for the Monte Carlo model were generated from a companion inverse-modelling study that evaluated alternative site conceptual models. Particles outlining the plume were placed within the model domain. If all the particles were captured in a given realization it was deemed a success and given a probability of one. Conversely, if any of the particles escaped capture the realization was considered a failure and given a probability of zero. The overall probability of failure was calculated as the average of all the realization probabilities. Likely remedial design costs were obtained by summing capital and operation and maintenance costs with the expected cost of failure. The optimal design is the one that resulted in the least cost.

## INTRODUCTION

As a result of manufacturing activities at the US Department of Energy (DOE) Kansas City Plant (KCP) an estimated $6.6 \times 10^2$ m$^3$ of alluvial aquifer groundwater is contaminated with 114 kg of dissolved trichloroethylene and associated degradation products (Fig. 1). To prevent this contamination from reaching the surrounding surface water bodies, an interceptor system consisting of fourteen wells and a trench was installed. Since 1990, the interceptor system has pumped $3.4 \times 10^3$ $m^3$ of contaminated water resulting in the removal of 979 kg of volatile organic compounds from the alluvial aquifer. Despite the removal of more than one plume pore volume and almost nine times the estimated dissolved contaminant mass, plume contaminant concentrations remain unchanged suggesting the presence of dense non-aqueous phase liquid.

This study was performed in response to a request by the US Environmental Protection Agency (EPA) that the interceptor system undergo evaluation to determine if changes in the pumping schedule and/or the addition of new wells, both vertical and horizontal, would improve the system's efficiency with respect to contaminant mass removal. Based on EPA guidance (EPA, 1994), annual plume pore volume removal rates (APPVRR) of 0.3 to 2.0 were suggested as appropriate interceptor system design criteria. This evaluation was performed using a combination of parameter estimation, optimization and Monte Carlo modelling coupled with economic-risk analysis. Interceptor systems were designed and optimized for containment and APPVRR of 0.3 and 2.0 for the entire KCP plume. However, for brevity only those systems designed and optimized for the darker shaded portion of the plume (Fig. 1) will be discussed further.

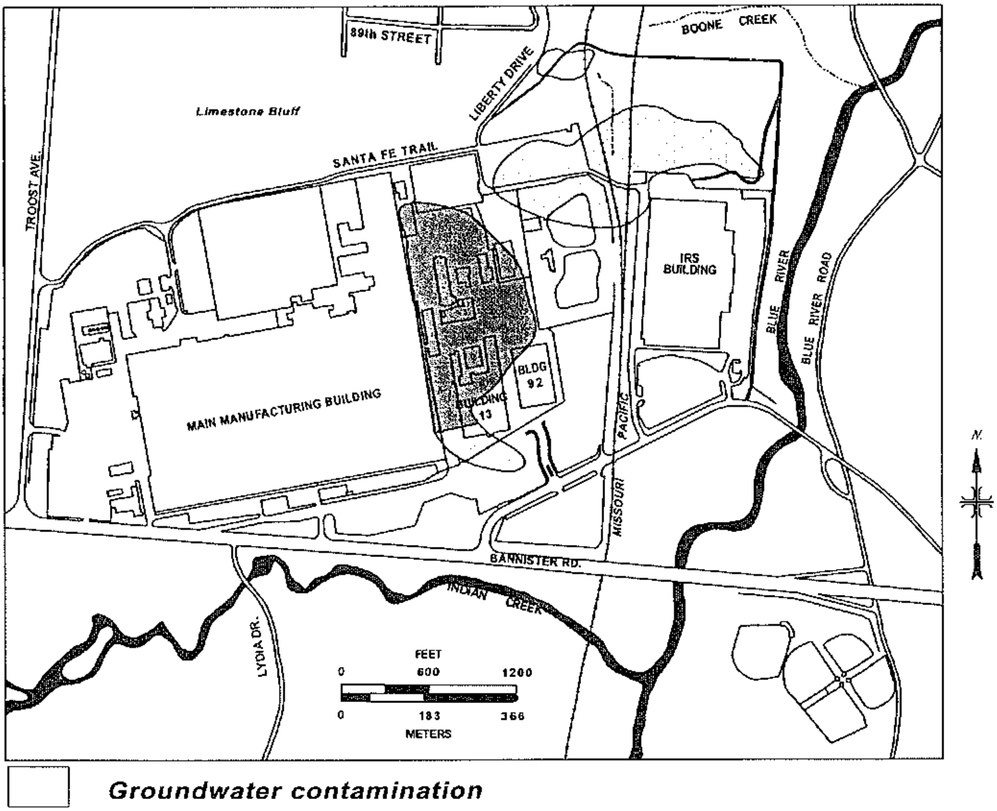

Fig. 1 Groundwater contamination at the Kansas City Plant.

## METHODOLOGY

Multiple consultants working at the KCP over the past 20 years have created a myriad of site conceptual models. Thus, before proceeding with interceptor design and optimization, it was necessary to determine which of the many site conceptual models was most representative. Evaluation was initiated by reducing the various site conceptual models to a suite of 15 that represented combinations of all the hydrological components in question. Parameter estimation modelling was then used to determine which conceptual model was the most representative based on parameter estimates, parameter statistics and the weighted sum of residuals squared. The conceptual model yielding the most realistic parameter estimates, having the smallest parameter standard deviations and lowest weighted sum of residuals squared, was deemed the most representative. The predicted parameter values and standard deviations were later used as input to the Monte Carlo model. All 15 conceptual models were evaluated using the same weighted water-level elevation and basement tile drain flux targets. In addition to the water-level elevation and flux targets, conceptual model number 15 was also calibrated using three hydraulic conductivity targets.

Particle tracking optimization modelling was then used to determine the optimal well locations and pumping rates for the plume areas. Particle tracking optimization was chosen over gradient optimization techniques such as MODMAN (Greenwald, 1993), because travel time could then be included as an optimization criterion. To implement particle tracking optimization, particles were distributed equally over the areal extent of groundwater contamination. While particles can be weighted to put greater emphasis on the more contaminated portions of the plume, that option was not used in this study. Next, potential interceptor well and other legal capture locations within the model were identified. Potential pumping well locations were excluded from inaccessible areas, buildings and roadways. The KCP basement tile drains were considered legitimate capture locations because drain discharge is routed to the treatment system for treatment prior to discharge to the sanitary sewer system. After identification of potential well locations, automated sequential groundwater flow and particle tracking model runs (the number of runs being equal to the number of potential well locations), were performed where each potential pumping well location was individually pumped at a prescribed minimum rate. The well location that resulted in the most particles being captured within the prescribed travel time constraints was chosen for further optimization.

For containment scenarios, the travel time constraint was a very high number (i.e. one million days). Otherwise, the travel time constraint corresponded to the required plume pore volume removal rate. For example, to remove one plume pore volume per year requires that all the particles representing the plume be captured within 365 days. Optimization then proceeded by incrementally increasing pumping until all particles were captured or a maximum prescribed drawdown or pumping constraint was exceeded. The maximum drawdown and pumping rate constraints were based on site conditions. If existing wells could not be pumped at much more than 8 l $\text{min}^{-1}$ without going dry, then the design of an interceptor system with pumping rates of 16 l $\text{min}^{-1}$ is unwarranted. Similarly, because of pump placement within the pumping wells, drawdowns of more than a given amount (e.g. 8 m) were not possible. If a single well could not capture all the particles without exceeding the drawdown, pumping or travel time constraints, the optimization process was repeated, with the first well pumping at the prescribed optimal rate. The process was continually repeated and wells added until all the particles representing the plume were captured within the optimization constraints or the code determined that a solution was not feasible.

After the optimization modelling, Monte Carlo modelling was used to determine the optimized well configuration's potential for failure (both design and capture) due to hydrogeological and conceptual model uncertainty. Design failure is the probability that one or more pumping wells will go dry due to uncertainty. Capture failure is the probability that contamination will escape capture by the interceptor system due to uncertainty. The probability of capture failure for a given design was calculated by dividing the number of failed simulations by the total number of simulations. For example, if particles representing contamination escaped capture 200 times out of 1000 model runs, the probability of failure for that design was 20%. Similarly, if a pumping well goes dry 450 simulations out of 1000 model runs, the probability that the design would fail was 45%.

Finally, probability of failure generated by the Monte Carlo modelling (based on 1000 realizations) was used as input for economic-risk evaluation. Economic-risk analysis combines the cost of system installation and operation with the likelihood of failure and cost of fixing the failure to determine the best interceptor design. In a hypothetical example, economic-risk analysis works as follows: assume that the cost of failure for a given interceptor system design is US$2 million. The interceptor system could be operated such that failure is impossible (0% probability of failure) at a cost of US$5 million. Alternatively, the interceptor system could be operated at a cost of US$4 million with a 20% probability of failure. Based on economic-risk analysis the latter is the better design. Operating the system such that failure is impossible results in guaranteed costs of US$5 million. Operating the system such that failure could occur at a rate of 20% results in potential costs of US$4.4 million (US$4 million + 20% failure × US$2 million), a potential savings of US$0.6 million.

For this study, the following economic-risk analysis equation was utilized:

$$C_{\mathrm{A}} = (Q_{\mathrm{A}} \times C_{\mathrm{TR}}) + (n_{\mathrm{VW}} \times C_{\mathrm{W}}/L_{\mathrm{W}}) + (\mathrm{L}_{\mathrm{HWS}} \times C_{\mathrm{HW}}/L_{\mathrm{W}}) + ((n_{\mathrm{VW}} + n_{\mathrm{HW}}) \times C_{\mathrm{AWM}}) + (C_{\mathrm{AOM}}) + (C_{\mathrm{F}}/L_{\mathrm{F}} \times P_{\mathrm{F}}). \qquad (1)$$

$C_{\mathrm{A}}$ = annual cost to operate an interceptor system [US$ per T],
$Q_{\mathrm{A}}$ = annual pumping volume [$\mathrm{L}^3\,\mathrm{T}^{-1}$],
$C_{\mathrm{TR}}$ = treatment cost per volume of the pumped water [US$ per $\mathrm{L}^3$],
$n_{\mathrm{VW}}$ = number of new vertical wells [–],
$C_{\mathrm{W}}$ = cost to install a vertical well [US$],
$L_{\mathrm{W}}$ = vertical or horizontal well life expectancy, assumed to be 15 years [T],
$L_{\mathrm{HWS}}$ = length of horizontal well screen [L],
$C_{\mathrm{HW}}$ = cost per length of horizontal well screen [US$ per L],
$n_{\mathrm{HW}}$ = number of new horizontal wells [–],
$C_{\mathrm{AWM}}$ = annual maintenance cost for horizontal and vertical wells [US$ per T],
$C_{\mathrm{AOM}}$ = annual treatment system operation and maintenance costs [US$ per T],
$C_{\mathrm{F}}$ = cost of failure [US$],
$P_{\mathrm{F}}$ = probability of failure [–],
$L_{\mathrm{F}}$ = life expectancy of the failure corrective action [T].

The cost of failure, $C_F$, is difficult to quantify but is likely to be a combination of fines, litigation settlement amounts, and costs for additional pumping wells if the plume alludes capture. Potential costs for fines and litigation settlements can be garnered from the literature, but given the positive relationship between the KCP and regulatory agencies and surrounding community, are expected to be zero. Therefore, at the KCP, the $C_F$ is likely to consist only of the cost to install additional pumping wells and treat the water pumped by them. Table 1 lists the costs used in the economic-risk analysis. For this analysis, expenditures were not discounted.

**Table 1** Well installation, maintenance and treatment costs (US$).

| Cost to treat a litre of water | Annual O & M costs | Annual well maintenance costs | Vertical interceptor well installation cost | Horizontal interceptor well installation cost |
|---|---|---|---|---|
| $0.0013 | $196 644 | $2143 | $198 400 | $8061 m of well screen |

## RESULTS

Interceptor systems were optimized for the central portion of the KCP for containment and maximum contaminant removal using the existing wells, new vertical wells and new horizontal wells. Table 2 summarizes the results of the economic-risk analysis.

**Table 2** Summary of results for the central portion of the KCP.

| Interceptor system design | Total pumping rate (l min$^{-1}$) | APP VRR | Probability of: Design failure | Capture failure | Costs of (US$): Annual design | Expected annual failure | Total annual operating | Removing one plume pore volume |
|---|---|---|---|---|---|---|---|---|
| **Containment** | | | | | | | | |
| 2 existing wells | 15.1 | 0.06 | 0.000 | 0.651 | 207 551 | 13 556 | 221 107 | 3 685 120 |
| 2 new vertical wells | 9.5 | 0.06 | 0.000 | 0.758 | 234 200 | 15 784 | 249 984 | 4 166 407 |
| 1 horizontal well | 37.9 | 0.06 | 0.000 | 0.000 | 412 302 | 0 | 412 302 | 6 871 707 |
| **Maximum contaminant removal** | | | | | | | | |
| 10 existing wells | 75.7 | 0.26 | 0.000 | 0.224 | 251 180 | 4664 | 255 844 | 984 018 |
| 12 new vertical wells | 92.7 | 0.49 | 0.100 | 0.000 | 447 887 | 0 | 447 887 | 914 055 |
| 32 new vertical wells | 145.7 | 0.32 | 0.163 | 0.000 | 793 455 | 0 | 793 455 | 2 479 548 |
| 2 horizontal wells | 202.5 | 0.65 | 0.365 | 0.036 | 793 027 | 750 | 793 777 | 1 221 195 |

While having a zero probability of capture failure, because of high well installation and treatment costs, the horizontal well was the least economical of all the containment systems. The most economical system, despite a 65% probability of capture failure, was operation of two of the existing wells at a combined discharge rate of 15.1 l min$^{-1}$. The probability of design failure for all three containment systems was zero. With respect to APPVRR, all three systems performed comparably.

For the maximum contaminant removal systems, based on annual operating costs, use of the 10 existing wells operating at 75.7 l min$^{-1}$ was most economical despite the highest probability of capture failure. However, this was the only maximum contaminant removal system that had an APPVRR below 0.3, the minimum suggested rate for effective interceptor operation (EPA, 1994). Based on the cost to remove one plume pore volume, calculated by dividing the annual operating cost by the APPVRR, the 12 new vertical well system was most economical. However, lessening the attractiveness of the system was the cost (US$ 2 380 800) to install the 12 vertical wells, which represented an immediate capital expenditure. A benefit of using existing wells is that capital expenditure is not required. The horizontal well design had the highest APPVRR but, based on total annual operating costs, was the most expensive system to operate. Because of flow system mass balance limitations, APPVRR of 2.0 were not achievable. As expected, the probability of design failure for the maximum contaminant removal systems increased as the total pumping rate increased.

## CONCLUSIONS

Robust interceptor systems, those that captured all contamination for all possible ranges of parameter values, were designed and optimized for the KCP. However, this study demonstrated that operating the robust systems costs approximately twice, at a minimum, that required to operate the less robust systems, even when including the potential failure costs.

Ideally the optimal design is the one that results in the least cost regardless of the probability of capture failure. However, reality is the chosen design is likely to be a compromise, with the site owner fixating on cost and the regulators on probability of capture failure. By quantifying the cost–probability of failure relationship, economic-risk analysis provides the information necessary for negotiating a design satisfactory to both parties.

## REFERENCES

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Greenwald, R. M. (1993) *MODMAN, An Optimization Module for MODFLOW, Version 3.0.* GeoTrans, Sterling, Virginia, USA.