ECONOMIC AND PERFORMANCE BASED DESIGN OF MONITORING SYSTEMS FOR PRBS

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Summary: This paper evaluates monitoring well configurations for horizontal (HPRB), and funnel and gate permeable reactive barriers (FGPRBs) on their ability to detect the median (C_{50}), 75th percentile (C_{75}), and 90th percentile (C_{90}) of effluent concentration. The framework for the study is a series of heterogeneous aquifers created using a second-order stochastic model and input into MODFLOW. A HPRB or FGPRB is simulated within the each heterogeneous aquifer by replacing appropriate finite difference cells of the model with the hydraulic conductivities representative of the barrier. MODFLOW and an adapted particle tracking code are used to predict steady-state flow and advective mass transport through the aquifer and PRB. The probabilities of twenty-five monitoring systems for the HPRB and twenty-four monitoring systems for the FGPRB at detecting C_{50}, C_{75}, and C_{90} are evaluated in each aquifer. Results are combined to determine lateral and vertical well spacings having the greatest probability of detecting C_{50}, C_{75}, and C_{90} for each types of PRB. The most economical lateral and vertical well spacing are about 5 m and 3 m, respectively for the HPRB, and approximately 2 m and 4 m, respectively for the FGPRB. The probability of detecting C_{50}, C_{75}, and C_{90} for these spacings is provided.

Purpose and Scope: Designers and regulators judge the performance of a PRB using a limited number of point measurements of concentration obtained from monitoring wells. From these data, the distribution of effluent concentrations is estimated and decisions regarding the safety of down-gradient receptors are made. However, there are few guidelines for the horizontal and vertical spacing of monitoring wells around PRBs. For example, Lowry Air Force Base in Denver, Colorado has a FGPRB where the 3.05 m wide gate is instrumented with three down-gradient monitoring wells spaced approximately one meter apart. The outside wells have a single 3.05 m screen and the center well has two, 0.305 m screens. In contrast, a 750 m long FGPRB at a manufacturing facility in Oregon has two 15.2 m gates, each instrumented with two monitoring wells spaced about 5 m apart. For the designer, such contrasts in existing monitoring schemes and a dearth of data on the effectiveness of any particular scheme make it difficult to propose monitoring schemes for future PRBs although the effective placement of monitoring wells is critical for evaluating PRB performance and ensuring the safety of down-gradient receptors.

Guidance on monitoring PRBs is currently needed to provide designers and regulators with a better understanding of the expectations of various monitoring schemes so that cost/benefit analyses and appropriate quality assurance monitoring can be performed. This paper presents the results of an investigation of monitoring schemes ranging from a single well screen to several multilevel monitoring wells for two types of PRBs located in heterogeneous aquifers. The ability of twenty-five different monitoring schemes for a HPRB and twenty-four schemes for a FGPRB to detect the 50th, 75th, and 90th percentile of effluent concentration was calculated for over 500 aquifers and averaged. Once the ability of many systems at detecting higher effluent concentrations is known, the system with the maximum probability of detection per well screen is identified, monitoring well spacing and monitoring screen separations are recommended for a HPRB and FGPRB, and the expected probabilities of detecting higher effluent concentrations with the recommended monitoring systems are provided.

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Method: A second-order stochastic approach was used to assign hydraulic conductivities to modeled aquifers. This method assumed that the distribution of hydraulic conductivities in a natural aquifer are correlated and log-normally distributed so that mathematically generated correlated random fields are a reasonable representation of the natural distribution of hydraulic conductivities. Hydraulic conductivities within the aquifer are described by the mean and standard deviation for the logarithm of hydraulic conductivity (μ_{lnK} and σ_{lnK}, respectively) and correlation lengths (λ). For this study, aquifers encompassing the typical ranges of μ_{lnK}, σ_{lnK}, and λ were considered (i.e., $-9 \geq \mu_{lnK} \geq -15$ [m/s]; $0.25 \geq \sigma_{lnK} \geq 4.0$; $3m \geq \lambda_x \geq 9m$; $1m \geq \lambda_y \geq 5m$)

Three-dimensional aquifers were constructed numerically by assigning correlated random variables to finite difference cells within MODLFOW. A homogeneous HPRB or FGPRB was then simulated by substituting for appropriately located finite difference cells in the numerical model. A modified version of Path3D was used to estimate advective transport from a 15 m wide, constant concentration source located 20 m upgradient of the PRB, to the effluent face of the PRB. Greater detail on aquifer simulation and the numerical modeling can be found at http://www.engr.wisc.edu/cee/faculty/eykholt_Gerald / elder_PhD.pdf.

Twenty-five monitoring schemes at the effluent face of the PRB were investigated for the HPRB and twenty-four monitoring schemes were investigated for the FGPRB for each aquifer simulated. All monitoring schemes have wells located symmetrically around the lateral and vertical centerlines of the effluent face of the PRB but differ in the number of monitoring locations and the number of well screens per monitoring location. For all systems, 1 m long well screens were used and each screen was assumed to measure the average concentration for a square meter of soil around the well over the depth of the well screen.

The measure of effectiveness for judging the monitoring schemes is the probability that any well screen for a scheme detects a concentration greater than or equal to a threshold concentration. For this study, three threshold concentrations were considered, the median (C_{50}), 75th percentile (C_{75}), and 90th percentile (C_{90}) of the complete distribution of effluent concentrations obtained from the numerical model. Since the location of higher or lower effluent concentration is a random variable (i.e., based on the distribution of hydraulic conductivities) and independent of monitoring location, probabilities of a monitoring scheme at detecting C_{50}, C_{75}, or C_{90} for all μ_{lnK}, σ_{lnK}, and λ are averaged to yield the average probability of detection, which will only be a function of the monitoring scheme and PRB type.

Detection for this study (i.e., measuring a concentration above the threshold concentration) is assumed to be a Bernoulli random variable with a value of one if any monitoring well for a given scheme detects a concentration greater than the threshold concentration and zero otherwise. The probability of a given monitoring scheme at detecting a concentration greater than the threshold concentration is therefore the sum of Bernoulli random variables for all realization divided by the number of realizations tested.

Results For a HPRB: The probabilities of twenty-five monitoring schemes with different lateral (Δy) and vertical (Δz) well spacing at detecting C_{50}, C_{75}, and C_{90} for a HPRB are given in Fig. 1. The densest lateral spacing (i.e., smaller Δy) is shown near the origin and the coarsest spacing (a single well located at the lateral centerline of the PRB) is shown at the right side of Fig. 1. Lines connect schemes with constant vertical spacing.

A monitoring scheme with wells located 5 to 6 m apart and well screens separated by 2 to 3 m appears to yield the highest probability of detecting C_{50}, C_{75}, and C_{90} with the fewest well screens. Such a system is expected to have at least 95% chance of detecting C_{50}, 80% chance of detecting C_{75}, and 50% chance of detecting C_{90}. Systems with greater well separation will have a 10 to 15% lower probability of detection for each additional meter of Δy beyond 6 m, and 15 to 20% lower probabilities of detection for each additional meter of Δz beyond 3 m. A function describing the benefit gained by adding one more well to an existing monitoring systems was calculated by plotting the probability of detection versus the number of wells, fitting a function to these data, and differentiating the function. When this is done for the HPRB, only small increases in the probability of detection occur for $\Delta y \leq 6$ m and $\Delta z \leq 3$ m.

Results For a HPRB: The probabilities of detecting C_{50}, C_{75}, and C_{90} for the twenty-four monitoring well schemes at the effluent face of a FGPRB are given in Fig. 2. FGPRBs appear to require smaller Δy but larger Δz than HPRBs to achieve the same probability of detection. For example, there is an 80% probability of detecting C_{75} from a HPRB when 9 well screens are used (i.e., $\Delta y = 6$ m, $\Delta z = 3$ m). To achieve the same probability of detecting C_{75} from a FGPRB requires four wells with $\Delta y = 2$ m and $\Delta z = 4$ m. Although FGPRBs may require a smaller Δy than HPRBs, the total number of monitoring wells required for the FGPRB may be less than required by a HPRB because the effluent face of the FGPRB is expected to be smaller than a comparable HPRB. The recommended monitoring system for a FGPRB is $\Delta y \leq 2$ m and $\Delta z \leq 4$ m located symmetrically around the effluent face of the gate. Such a system is expected to have about 95% chance of detecting C_{50}, 70% chance of detecting C_{75}, and 40% chance of detecting C_{90}.

Probabilities of detecting C_{50}, C_{75}, and C_{90} as a function of the number of well screens can be plotted and fit with a curve. The function describing these data can then be differentiated to yield an expression for the additional probability of detecting C_{50}, C_{75}, or C_{90} gained by adding a well screen to an existing system. Diminishing returns (i.e., increasing probability of detection < 5%) occur when systems have $\Delta y \leq 2$ m and $\Delta z \leq 4$ m.

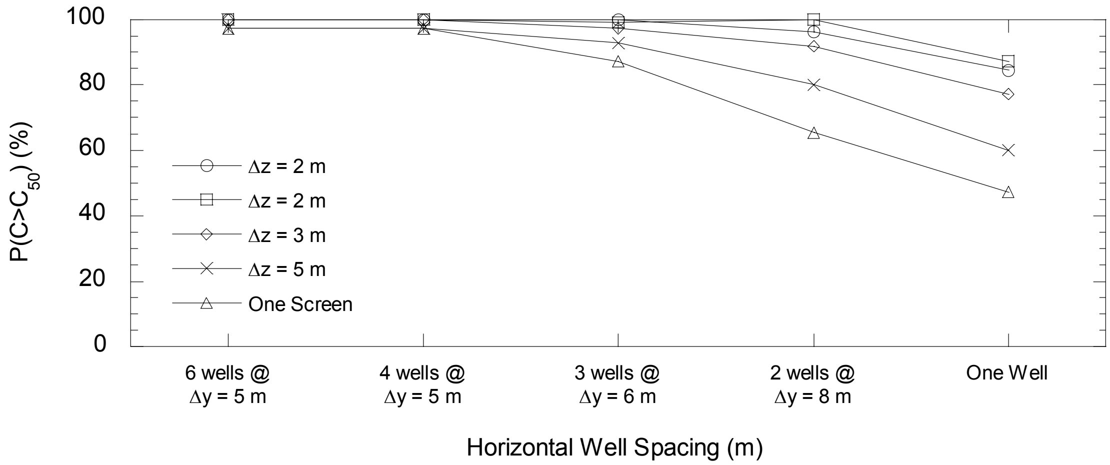
Recommendations for Monitoring PRBs: Monitoring systems that yield the highest probability of detecting C_{50}, C_{75}, and C_{90} with the fewest monitoring wells were determined for a HPRB and FGPRB. The recommended lateral well spacing (Δy) and vertical well screen spacing (Δz) for both PRBs are listed in Table 1 along with the expected probabilities of detecting C_{50}, C_{75}, and C_{90} for these systems.

Table 1 Recommended Monitoring Systems for PRBs.

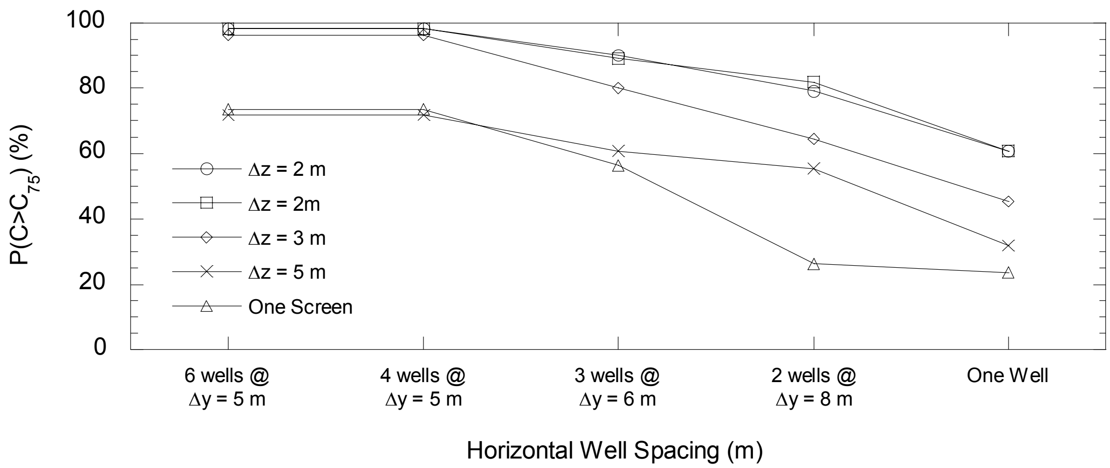
	Lateral Monitoring Well Spacing (Δy)[1]	Vertical Well Screen Separation (Δz)[1]	Expected Prob. of Detection		
			C_{50}	C_{75}	C_{90}
HPRB	5 m	3 m	95%	80%	45%
FGPRB	2 m	4 m	95%	70%	40%

1 – center to center spacing of 1 m long well screens

a) Probability of Detecting C_{50}



b) Probability of Detecting C_{75}



c) Probability of Detecting C_{90}

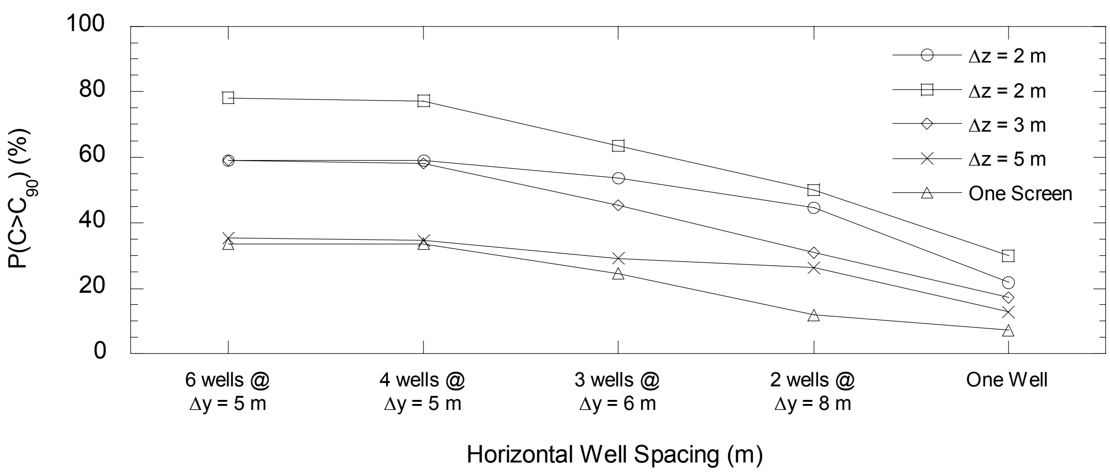
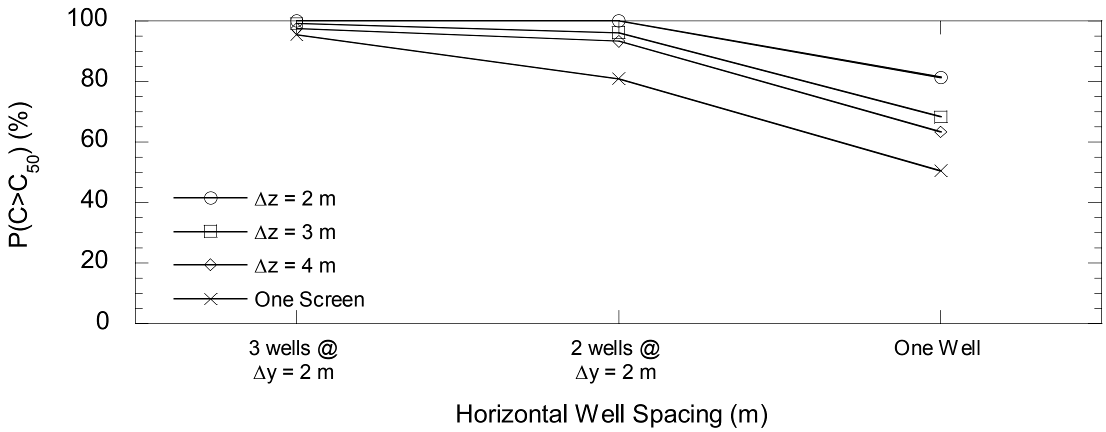
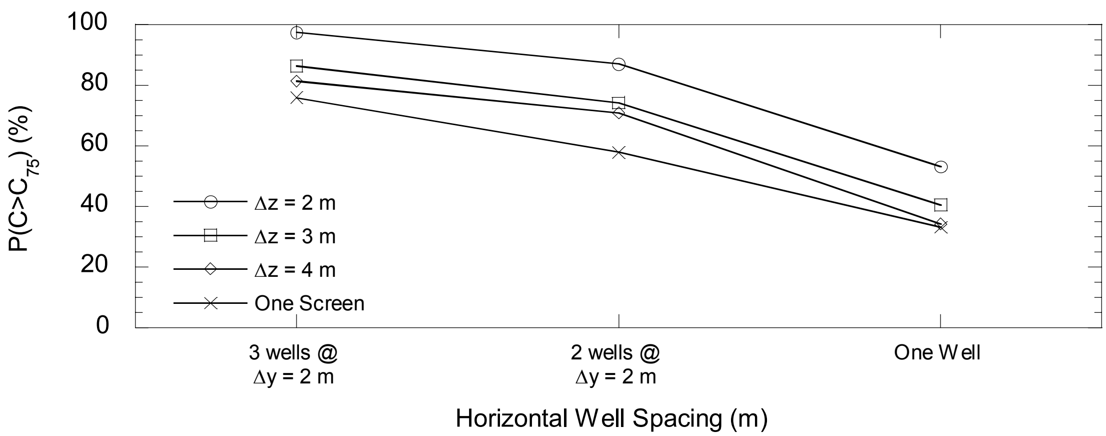


Fig. 1Probability of Detecting C_{50} (a), C_{75} (b), and C_{90} (c) from a HPRB as a Function of Δy and Δz.

a) Probability of Detecting C_{50}



b) Probability of Detecting C_{75}



c) Probability of Detecting C_{90}

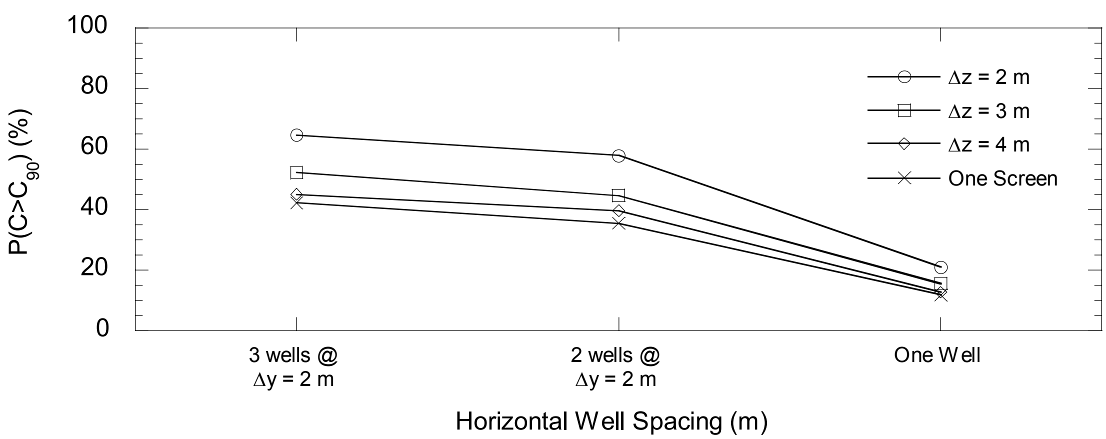


Fig. 2Probability of Detecting C_{50} (a), C_{75} (b), and C_{90} (c) from a FGPRB as a Function of Δy and Δz.