Simulating Plume Capture by a Permeable Reactive Barrier Wall

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Abstract: Recent groundwater remediation research efforts have focused upon developing innovative, in-situ methods for treating impacted aquifer zones. One such method is the use of permeable reactive barriers (PRBs). These systems entail placing reactive materials into the subsurface to passively intercept a groundwater plume and treat the dissolved contaminants as they flow through the barrier. Target plumes for this treatment method are often not easily accessible via conventional construction techniques, therefore new installation methods have been developed. However, many questions arise regarding how these PRB emplacement methods may affect ultimate wall performance. To address these questions, numerical modeling was performed to simulate groundwater flow through a reactive barrier and to calculate hydraulic plume capture. Variations in wall hydraulic conductivity, wall skin effects, and seasonal changes in aquifer hydraulic gradient and flow direction were investigated. Results from the model simulations were used to provide a conceptual understanding of how changes in PRB design parameters may affect the hydraulic capture performance for a pilot-scale, deep, injected continuous PRB treatment wall.

During the past ten years, groundwater scientists have worked towards developing in-situ PRB treatment methods for remediating subsurface contaminant plumes. PRBs are passive, flow-through treatment systems designed to mimic the ambient aquifer hydraulic properties and have minimal impact on groundwater flow. A variety of innovative, in-situ PRB emplacement techniques have been developed (Day et al., 1999; Gavaskar, 1999) to address groundwater contamination in both shallow and deep aquifers systems. These methods have the potential to reduce installation costs, worker contaminant exposure, and waste handling, however their impact on the aquifer hydraulic conductivity (K_h) and groundwater flow is unknown. Numerical modeling was used to evaluate some of the uncertainties associated with the design and installation of in-situ PRBs by answering the following questions: 1) What happens when the installed PRB hydraulic conductivity (K_{PRB}) is not equal to the aquifer K_h?; 2) Are skin effects significant?; and 3) How do seasonal aquifer dynamics influence PRB performance?

A three-dimensional (3-D), finite-difference, steady state MODFLOW model (MacDonald and Harbough, 1988) was developed to simulate the performance of a deep, injected pilot-scale continuous PRB in a confined, homogeneous, isotropic, unconsolidated, sand aquifer. Constant head boundaries were assigned to the upgradient and downgradient extremes of the model domain using field head and hydraulic gradient measurements, and groundwater flow was assumed horizontal (no vertical gradient). The PRB was oriented perpendicular to the groundwater flow path and was simulated using the MODFLOW horizontal flow barrier package. The modeled wall dimensions mimicked the field pilot wall dimensions with a 110 ft width, a 0.5 ft thickness, and a height spanning the full thickness of the confined aquifer. Values for the aquifer K_h were obtained from field data, and K_{PRB} was defined as 10x, 1x, 0.1x, 0.01x, and 0.001x K_h to simulate different in-situ PRB installation results.

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The particle tracking model MODPATH (Pollock, 1994) was used to evaluate the groundwater flow patterns through the PRB and to determine the hydraulic capture efficiency of the wall (η, defined as the width of the upgradient groundwater plume passing through the PRB divided by the PRB wall width). A capture efficiency of 100% indicates that the entire 110 ft wide plume of upgradient groundwater flows through the simulated 110 ft wide wall. Hydraulic capture efficiencies <100% indicate that some of the upgradient groundwater is being diverted around the PRB, bypassing treatment. During the simulations, no vertical flow of water particles over the wall was observed, with all particles travelling laterally either through the PRB or around the wall. In simulations where $K_{PRB} \geq K_h$ there was no disturbance to the ambient flow field, and η equaled 100%. When $K_{PRB} < K_h$ η decreased with decreasing K_{PRB}, and capture results were very similar to those reported by Garon et al. (1998) for unconfined aquifer simulations. Figure 1a illustrates the groundwater flowpaths through/around the wall for the K_{PRB}/K_h = 0.001, simulation, while Figure 1b summarizes the results for η as a function of K_{PRB}/K_h. It is not unreasonable to expect that installation activities may result in a $K_{PRB}/K_h < 1$, suggesting that continuous PRBs may need to be designed slightly wider than the desired upgradient, undisturbed plume width to ensure adequate treatment volume.

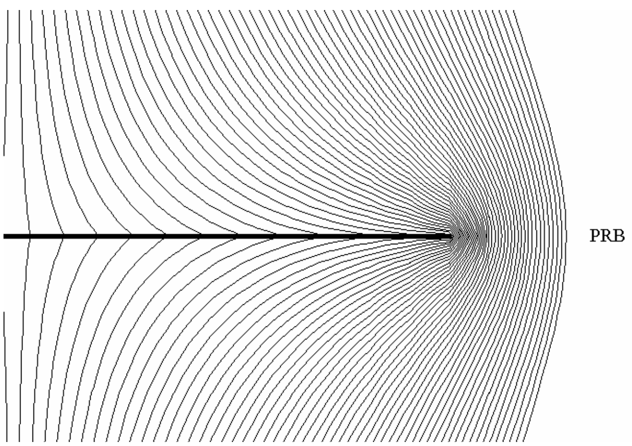

Figure 1a – Simulation results for PRB performance where K_{PRB}/K_h = 0.001.

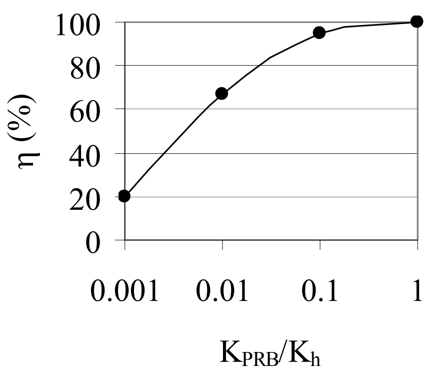

Figure 1b – Summary of the results for PRB hydraulic capture as a function of K_{PRB}/K_h.

These simulations were repeated with different values for the aquifer hydraulic gradient to investigate the impact that seasonal fluctuations in gradient will have on PRB hydraulic performance. The results indicated that varying the hydraulic gradient had no impact on η, which was consistent with findings previously presented by Garon et al. (1998) in their unconfined aquifer simulations. It is important to note that although changing the hydraulic gradient did not impact η, it will influence the residence time within the wall and may impact treatment efficiency.

Garon et al. (1998) postulated that in-situ installation methods could generate zones of reduced hydraulic conductivity (skins), both upgradient and downgradient of the PRB, as the native aquifer materials are laterally displaced during wall emplacement. Several model simulations were run to investigate the effect of skin formation on the wall hydraulic capture performance. Three types of skins were conceptualized: 1) compaction zones where the hydraulic conductivity is most impacted (reduced) immediately adjacent to the wall and then returns exponentially to the aquifer K_h with distance away from the wall; 2) discrete thin film skins (0.5 in thick) formed at the interface between the PRB and the aquifer materials; and 3) a combination of the previous two conceptualizations. Results from these simulations are presented in Table 1.

Table 1 Modeled Plume Hydraulic Capture as a Function of Wall Skin Effects

Skin Conceptualization	η (%)			
	$K_{PRB}/K_h = 1$	$K_{PRB}/K_h = 0.1$	$K_{PRB}/K_h = 0.01$	$K_{PRB}/K_h = 0.001$
No Skin	100	94.6	67.2	20.0
Compaction Zone	94.6	94.6	67.2	20.0
Discrete Skins				
$K_{Skin}/K_h = 0.1$	98.2	94.6	67.2	20.0
$K_{Skin}/K_h = 0.01$	90.9	87.3	65.5	20.0
$K_{Skin}/K_h = 0.001$	58.2	56.4	47.3	18.2
Compaction Zone Plus Discrete Skins				
$K_{Skin}/K_h = 0.1$	94.6	90.9	67.2	20.0
$K_{Skin}/K_h = 0.01$	87.3	85.5	63.3	20.0
$K_{Skin}/K_h = 0.001$	58.2	56.4	47.3	18.2

The data in Table 1 indicate that the presence of either a compaction zone and/or discrete skins will decrease the PRB hydraulic capture performance, with the discrete skins having a greater impact on η than the compaction zones. This phenomenon is most pronounced in simulations where K_{PRB} approaches K_h, the design goal of most PRB applications. As K_{PRB} decreases with respect to K_h, the wall becomes the limiting factor controlling hydraulic capture performance. These simulation results suggest that skin formation could become an important design consideration for PRB installations in aquifers with significant silt and clay content and/or clay lenses. The silt and clay minerals would be more likely to form the discrete skins, adjacent to the wall, which could dramatically impact PRB performance. In aquifers with minimal clay content, the skin effect would most likely be the denser compaction of the aquifer particles (sand grains) adjacent to the wall, resulting in an approximate 5% or less decrease in η.

Many continuous PRB applications are positioned perpendicular to the ambient groundwater flow to intercept the maximum volume of contaminated water for treatment. However, site conditions and/or seasonal changes in dynamic aquifer systems may result in an installed PRB that is oriented at an angle to the ambient groundwater flow field. A set of simulations was run with the PRB positioned at angles of 5, 10, 15, and 20 degrees from the perpendicular to investigate the effects of seasonal changes in groundwater flow direction.

The simulation results, presented in Figure 2, indicate that as the wall rotation angle increases, η decreases as untreated water flows past the edge of the PRB. Furthermore, the downgradient wall shadow is projected at an angle to the wall and may potentially by-pass downgradient monitoring wells installed along the wall centerline. Should this happen, review of the monitoring data could incorrectly indicate wall failure. The flow capture results presented in Figure 2 are a function of the specific system geometry and do not apply quantitatively to all wall applications. Qualitatively, for a given rotation angle, η would increase, relative to the table values, as the distance between the source and wall decreases or would decrease as the distance between the source and wall increases. The findings suggest that fluctuations in the transient flow field may have significant impacts on both wall performance and on the ability to accurately monitor wall performance should the wall shadow by-pass downgradient monitoring wells. The simulation results indicate that the PRB length will need to be greater than the upgradient plume width for complete contaminant plume capture in aquifer systems with seasonal variation in groundwater flow direction, and that monitoring wells will need to be properly positioned for accurate evaluation of PRB treatment performance.

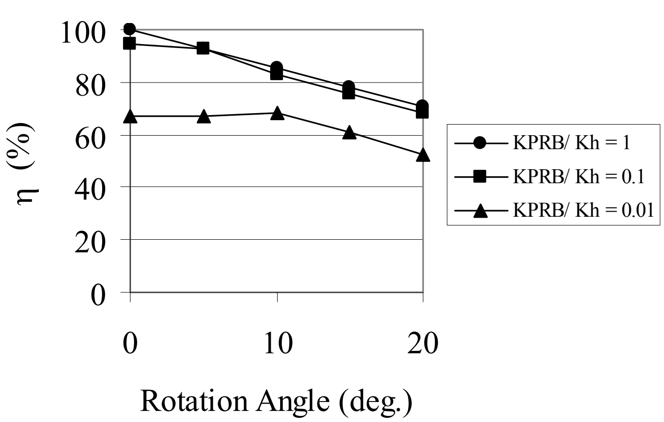

Figure 2a –Simulation results for η as a function of wall rotation angle.

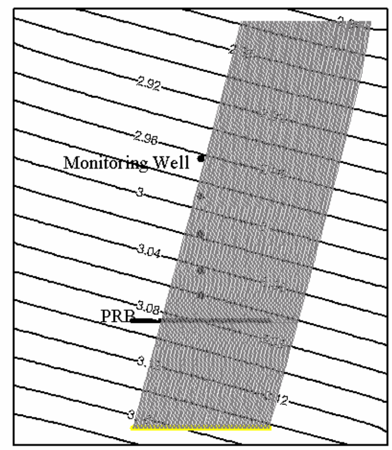

Figure 2b Simulation results for 15° shift in groundwater flow direction (K_{PRB}/K_h=1).

References

Day, S.R., O'Hannesin, S.F., and Marsden, L. (1999) "Geotechnical techniques for the construction of reactive barriers", *Journal of Hazardous Materials*, B67, pp. 286-297.

Garon, K.P., Schultz, D.S., and Landis, R.C. (1998) "Modeling of plume capture by continuous, low-permeability barriers", *GWMR*, Summer, pp. 82-87.

Gavaskar, A.R. (1999) "Design and construction techniques for permeable reactive barriers", *Journal of Hazardous Materials*, 68, pp. 41-71.

Freeze, R.A., and Cherry, J.A. (1979) *Groundwater*, Prentice Hall, Inc, Englewood Cliffs, New Jersey, 604p.

MacDonald, M. and Harbaugh, A. (1988) *A modular three –dimensional groundwater flow model (MODFLOW)*, USGS Open-File Report 83-875.

Pollock, D. (1994) *User's guide for MODPATH/MODPATH-PLOT, Version3: A particle tracking post-processing package for MODFLOW, the USGS finite-difference groundwater flow model"*, USGS Open-File Report 94-464.