Performance Comparison of Passive Structures with Multiple Gates and Funnels for Capturing Contaminated Groundwater

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Abstract

The objective of this study was to evaluate the capability of passive interceptors with multiple gates for directing the flow of contaminated groundwater. Linear structures consisting of multiple funnel (wall) and gate segments were aligned perpendicular to regional groundwater flow and fully penetrated a hypothetical unconfined aquifer. Five structures were evaluated: a structure with one interior gate, two structures with two gates, and two structures with three gates. Configurations with multiple gates included both interior and exterior gate positions. A particle tracking model and sub-regional water budget identified widths of capture zones and discharge patterns for each structure. Results suggest that, for equivalent total gate width, more (smaller) gates with exterior and central positions may enhance the overall performance of passive interceptors. Multiple gates more efficiently convey groundwater through structures and (especially external configurations) widen capture zones.

Introduction

Field and modeling studies demonstrate that permeable reactive barriers may be a viable alternative for capturing and treating contaminated groundwater in various settings (McMurtry and Elton, 1985; Puls et al., 1999; McGovern et al., 2002). By capturing naturally flowing groundwater, passive barriers use considerably less energy than alternative remediation systems. Passive interceptors may consist only of trenches filled with reactive media, or a combination of trench (gate) and funnel (wall) segments. Funnels direct contaminated groundwater toward permeable gate segments. Reactive media in gates promote physical, chemical, and/or biological processes that transform contaminants or reduce their concentrations to acceptable levels (Scherer et al., 2000). Requiring less reactive media, funnel-and-gate systems generally are less costly than gate-only systems of equivalent overall size (Striegel et al., 2001).

Previous authors modeled the performance of permeable reactive barriers (Eykholt et al., 1999; Gupta and Fox, 1999; Mayer et al., 2001; Elder et al., 2002; Hudak, 2004a, 2005; Hemsli and Shackelford, 2006) and funnel-and-gate systems with one gate (Sedivy et al., 1999; Bilbrey and Shafer, 2001; Cirpka et al., 2004; Hudak, 2004b). Starr and Cherry (1994) quantified the capability of several single-gate systems and illustrated capture zones for three multiple-gate systems. In that study, collinear systems with funnels on either side of a gate were effective among single-gate systems, and multiple-gate systems produced wider composite capture zones than single-gate systems. Gate segments had identical widths in alternative configurations.

The present study builds upon previous work by providing a quantitative comparison of width and discharge parameters for single- and multiple-gate passive interceptors. To facilitate performance comparison, total gate width was identical in alternative structures.

Methods

A numerical model, MODFLOW (McDonald and Harbaugh, 1988), simulated groundwater flow in a hypothetical, unconfined aquifer (Figure 1). The model utilized a block-centered finite-difference grid of 70 rows and 80 columns. Node spacing was 1 m along

![Figure 1. Modflow layout (top) and capture zones for Configuration 1-1 (bottom). Symbols: solid line - infinite-time capture zone; dashed line - 500-d capture zone; dotted area - gate; Q - discharge through adjacent gate or funnel segment.](image-url)
rows and columns. Constant-hydraulic head (H) boundaries at the west (H = 7.5 m) and east (H = 7.105 m) edges of the model established a regional hydraulic gradient of 0.005 (west to east). Flow did not traverse the north, south, or bottom edges of the model. Elevation at the bottom of the model was 0 m. The water table formed the top of the model. Input hydraulic conductivity was 5 m/d, 50 m/d, and 0.0005 m/d for the aquifer, gates, and funnels, respectively. Effective porosity was 0.30 for the aquifer, 0.50 for the gates, and 0.40 for the funnels.

Simulated funnel-and-gate structures were collinear, perpendicular to regional groundwater flow, and 30 m wide. Five different configurations were evaluated, each having a total gate width of 6 m (Figures 1-3). These configurations included: a 6-m long interior gate (Configuration 1-I), two 3-m long exterior gates (Configuration 2-E), two 3-m long interior gates (Configuration 2-I), three 2-m long gates, with two exterior gates and one interior gate (Configuration 3-E), and three 2-m long interior gates (Configuration 3-I). Gates and adjacent funnels were 1 m thick and completely penetrated the unconfined aquifer. Funnels simulated slurry walls often used in practice.

PMWIN (Chiang and Kinzelbach, 1998) processed model input and output data, the latter including hydraulic head fields and groundwater discharge through model cells. From hydraulic head distributions and model input parameters, the PMPATH module of PMWIN calculated and displayed groundwater flow paths terminating at gates, as well as travel times along those flow paths. Flow paths collectively defined widths and shapes of infinite-time and time-dependent capture zones. PMWIN also computed sub-regional water budgets for different zones in the model, including groundwater discharge: (a) toward the area occupied by the interceptor structure (through the 30-m, western model boundary segment directly upgradient of the structure), (b) through gates, and (c) through funnels. Flow around the ends of structures was computed as (a) minus the sum of (b) and (c). Dividing (b) by (a) established relative discharge through the structure. Alternative configurations were ranked according to widths of infinite-time capture zones and relative discharge. Shapes of 500-d capture zones were also compared among configurations.

Figure 2. Capture zones for Configurations 2-E (top) and 2-I (bottom). Symbols: solid line – infinite-time capture zone; dashed line – 500-d capture zone; dotted areas – gates; Q – discharge through adjacent gate or funnel segment.

Figure 3. Capture zones for Configurations 3-E (top) and 3-I (bottom). Symbols: solid line – infinite-time capture zone; dashed line – 500-d capture zone; dotted areas – gates; Q – discharge through adjacent gate or funnel segment.
Results and Discussion

Discharge (Q) through the area occupied by the structure was 5,479 m³/d. Despite equivalent total widths of gates and funnels, alternative structures produced markedly different results (Figures 1-3) (Table 1).

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Capture Zone Width (m)</th>
<th>Relative Discharge (%)</th>
<th>Average Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-I</td>
<td>16.39-17.89 (5)</td>
<td>51.8 (5)</td>
<td>5</td>
</tr>
<tr>
<td>2-E</td>
<td>19.36-30.14 (2)</td>
<td>56.6 (4)</td>
<td>3</td>
</tr>
<tr>
<td>2-I</td>
<td>19.60-21.76 (4)</td>
<td>62.9 (3)</td>
<td>3.5</td>
</tr>
<tr>
<td>3-E</td>
<td>22.25-30.03 (1)</td>
<td>69.9 (1)</td>
<td>1</td>
</tr>
<tr>
<td>3-I</td>
<td>21.34-23.70 (3)</td>
<td>68.8 (2)</td>
<td>2.5</td>
</tr>
</tbody>
</table>

*Rank in parentheses (capture zone rank based on midpoint of width range).

Configuration 1-I produced a relatively narrow capture zone, ranging from 16.39-17.89 m wide. The midpoint of the width range was 17.14 m, or approximately 57.1% of the total width of the interceptor. Though narrow, the infinite-time capture zone had relatively uniform width, varying by only 1.50 m over the model domain. Such uniformity facilitates capturing a similar width (measured perpendicular to regional groundwater flow) of contaminated groundwater both close to and farther upgradient of an interceptor. The upgradient edge of the time-dependent capture zone conformed to that of a typical contaminant plume, thus facilitating capture within a prescribed time frame. Total discharge through the gate and relative discharge were lowest, and end flow was highest, for Configuration 1-I compared to the other configurations. A small amount of water passed through the funnels, consistent with their low hydraulic conductivity.

Characterized by two smaller gates, Configuration 2-E produced a time-dependent capture with two distinct lobes propagating upgradient of the interceptor. The time-dependent capture zone extended the least upgradient of the funnel segment's midpoint. Groundwater approaching the midpoint of the structure took longer pathways and moved more slowly toward either gate; this tendency delays plume capture and reduces total gate discharge. With multiple gates accessing different areas, Configuration 2-E discharged more groundwater than Configuration 1-I. However, total gate discharge for Configuration 2-E was low among the entire set of alternatives. More ground-water flowed through the funnel(s) in Configuration 2-E than in other configurations, though this amount was low relative to gate discharge.

The infinite-time capture zone for Configuration 2-E attained much greater width, but also had considerably more range in width, than for Configuration 3-I. Relatively wide near the interceptor structure, the capture zone for Configuration 2-E tapered abruptly upgradient of the structure. This pattern reflects divergent flow induced by the interior funnel segment.

Groundwater passed more efficiently through Configuration 2-I. Interior gates and smaller funnels induced less outward flow, and the infinite-time capture zone had relatively uniform width. Groundwater flowing toward the middle of the interceptor moved more efficiently through either gate: thus, variations in the upgradient edge of the time-dependent capture zone were less pronounced for Configuration 2-I. Total gate discharge for Configuration 2-I was the median of the five configurations.

Configuration 3-E discharged the most groundwater through gates and the least groundwater through funnel segments and around the ends of the interceptor. A relatively large number of gates, including one in the center of the structure, efficiently captured groundwater relative to alternative configurations. Width of the infinite-time capture zone tapered upgradient of the structure, though not as pronounced as for Configuration 2-E. Average width of the infinite-time capture zone for Configuration 3-E was also highest among all configurations.

The irregular upgradient edge of the time-dependent capture zone for Configuration 3-E reflects alternating funnel and gate segments in the interceptor. Similar to other configurations, the time-dependent capture zone extended the least upgradient of the funnels and farthest upgradient of the gates.

Configuration 3-I had the second highest gate discharge of alternatives, reflecting a relatively large number of gates. Interior gate positions produced a relatively uniform infinite-time capture zone. The time-dependent capture zone was similar to that for Configuration 2-I, but with three lobes instead of two.

Results outlined above suggest that, for equivalent total gate width, interceptors with more gates may outperform those with fewer gates. More gates allow water to pass through interceptors more efficiently, with less groundwater moving through funnel segments or around the ends of structures. Using three gates enables placing one in the center of an interceptor while maintaining structural symmetry, an efficient arrangement for capturing groundwater. More gates (especially exterior positions) also widen capture zones, thus expanding the influence of interceptor structures. Upgradient edges of time-dependent capture zones for multiple-gate structures are irregular, extending the farthest and least upgradient of gate and funnel segments, respectively.

Particle tracking simulations such as those performed in this study may be effective for evaluating potential interceptor configurations. However, site-specific field and laboratory studies (Morgan et al., 2005), and mass transport simulations, should accompany particle-tracking analyses when designing interceptors in practice. Hydrologic and chemical monitoring should verify the performance of operating structures (EPA, 1998).

Passive interceptors are not suitable for all situations. For example, it may take too long for contaminated groundwater to move through interceptors in aquifers with low hydraulic conductivity. While interceptors may be excavated using several methods (Gavaskar, 1999), bedrock, buildings, and other structures may restrict or prohibit their use as

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remediation alternatives. In deep aquifers with predominantly horizontal flow, partially penetrating (hanging) interceptors may be an effective alternative to fully penetrating structures, which may be too costly or difficult to install.

References


