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Effects of Funnel and Gate Geometry on Capture of Contaminated Groundwater

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Groundwater is the primary source of drinking water for more than 1.5 billion people worldwide (Sampat 2000). It accounts for nearly half of the public and domestic water supplies and more than 95% of rural water supplies in the U.S. (Solley et al. 1998; Sampat 2000). Numerous pollution sources can render groundwater unfit for consumption. Efficiently removing plumes of contaminated groundwater reduces risks of water quality degradation at downgradient receptors such as water wells, lakes, and streams. There are several methods for remediating contaminated aquifers. Funnel (low-permeability wall) and gate (high-permeability trench or cylinder) structures excavated into aquifers downgradient of contaminant plumes offer certain advantages over more commonly deployed groundwater extraction wells (Starr and Cherry 1994). Spanning the width of a contaminant plume and in its travel path, funnels and gates require less maintenance and energy than using several groundwater extraction wells. While extraction wells may target the most polluted areas of an aquifer, multiple wells often induce stagnant zones of low velocity, in which contaminants linger as neighboring wells compete for groundwater (EPA 1989). Placing wells further apart reduces the potential for stagnant zones, but increases the chance that contaminants move offsite through gaps between them.

In contrast, funnel and gate structures rely upon prevailing groundwater flow to carry contaminated water toward them. Pumping water from gates increases hydraulic gradients and may hasten removal of contaminated groundwater. Of numerous potential funnel and gate configurations, one of the simplest and most widely used comprises a gate perpendicular to ambient groundwater flow (NRC 1994), with funnels extending diagonally outward (hydraulically upgradient and cross gradient) from either end of the gate. Despite a wide range of potential funnel and gate structures, and alternative gate-only structures, few published modeling studies quantitatively compare the efficiency of such configurations under both passive and active (groundwater pumping) conditions. Previous work focused on passive funnel and gate combinations, and for diagonal configurations, simulated short gates, on the order of 1 m (Starr and Cherry 1994; Sedivy et al. 1999). This study's objective was to compare the relative efficiency of gate-only and diagonal funnel and gate combinations with longer gates, under conditions of passive and active groundwater discharge, for capturing a plume of contaminated groundwater.

MATERIALS AND METHODS

Three groundwater interceptor structures were evaluated: a gate without funnels, and 150° and 135° funnel and gate combinations (Figures 1-3). Each structure was 30 m long (gate and funnels combined), and the gate was located 5 m downgradient of the leading tip of a contaminant plume. Consistent with practice, the perpendicular bisector of each structure was aligned parallel to regional groundwater flow.

MAP (Golder Associates, Richland, WA), MODFLOW (U.S. Geological Survey, Reston, VA), and MODPATH (U.S. Geological Survey, Reston, VA) simulated horizontal contaminant transport, the hydraulic effects of interceptor structures, and transport pathways, respectively, in a hypothetical, unconsolidated sand aquifer. ModelCad (Geraghty and Miller, Reston, VA) processed input and output data for MODFLOW and MODPATH. Surfer (Golden Software, Golden, CO) and CorelDraw (Corel Corporation, Ottawa, ON) displayed hydraulic head contours and groundwater flow paths.

The simulated aquifer had a saturated thickness of 5 m and regional hydraulic gradient of 0.03. Additional aquifer properties included a hydraulic conductivity of 1.0 m/d, effective porosity of 0.30, and regional hydraulic gradient of 0.03. Hydraulic conductivity of gates and funnels was 1000 m/d and 10^{-6} m/d, respectively. The above values are consistent with previous reports for sand aquifers and slurry cutoff walls (API 1989; Fetter 2001). A dilution contour of 0.001 (1/1000 of source concentration) defined the boundaries of a chemically conservative contaminant plume.

MAP generated a contaminant plume for a 10-m line source active for one year. The plume layout and interceptor structures were input to ModelCad. Funnels and gates were keyed into the base of the aquifer.

MODFLOW utilized a block-centered finite difference grid with 150 rows, 200 columns, and a uniform node spacing of 1 m. Edges of the rectangular model domain were set back from the contaminant source and interceptor structures to reduce boundary effects. Respectively, left-lateral, right-lateral, top, and bottom model boundaries were 54 m, 146 m, 75 m, and 75 m from the center of the contaminant source.

Reverse particle tracking along transport pathways reaching gates in the steady (equilibrium) hydraulic head field output by MODFLOW indicated the amount of time required to capture the contaminant plume for each of six gate discharge scenarios: 0.0 m^3/d/m to 0.5 m^3/d/m, in increments of 0.1 m^3/d/m (cubic meters per day per meter of trench). A contaminant plume was considered removed if a capture zone connecting the endpoints of reverse pathlines collectively covered the plume. For each discharge scenario, multiplying capture time and gate

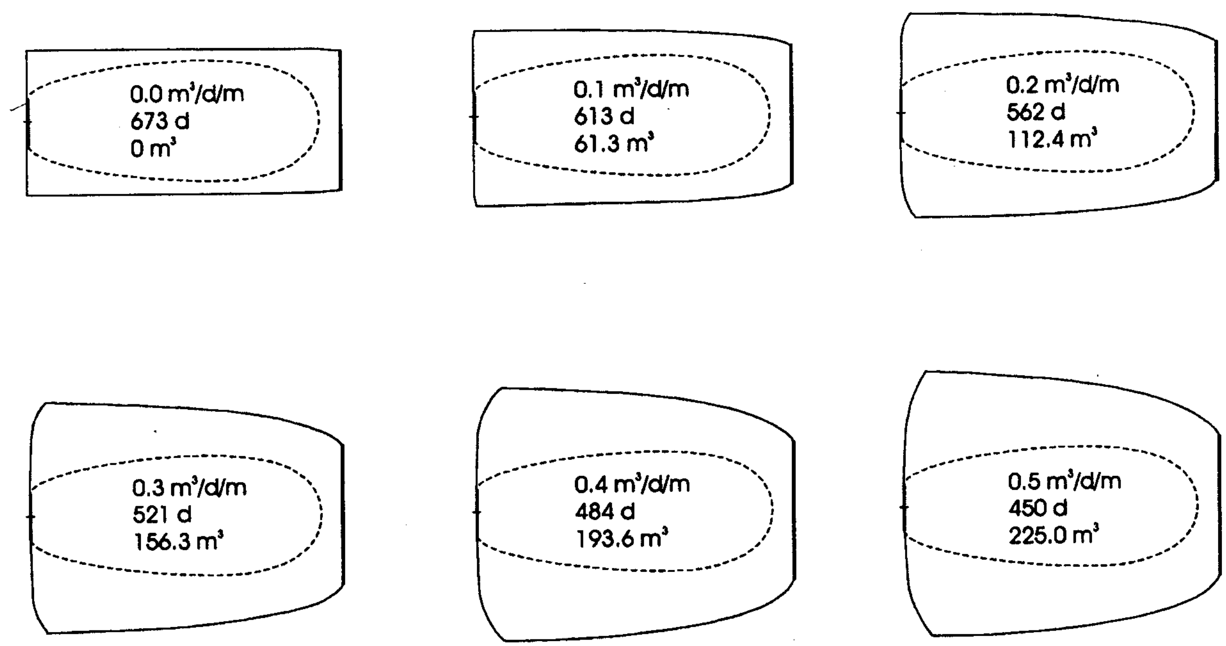

Figure 1. Map views of capture zones for gate-only structure; bold lines mark line source (to left) and gate (to right); numbers indicate gate discharge, capture time, and volume of water removed.

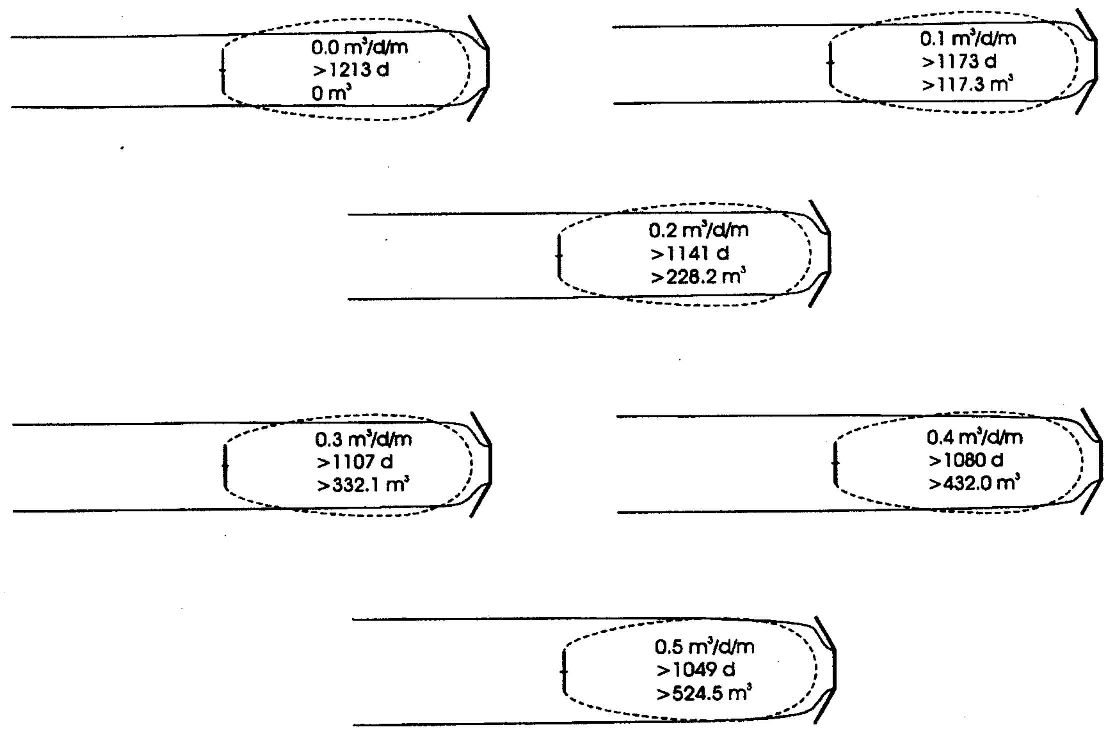

Figure 2. Map views of capture zones for 150° structure; bold lines mark line source (to left) and interceptor structure (to right); left edges of capture zones coincide with model boundary; numbers indicate gate discharge, travel time from left edge of model domain, and volume of water removed (without capture).

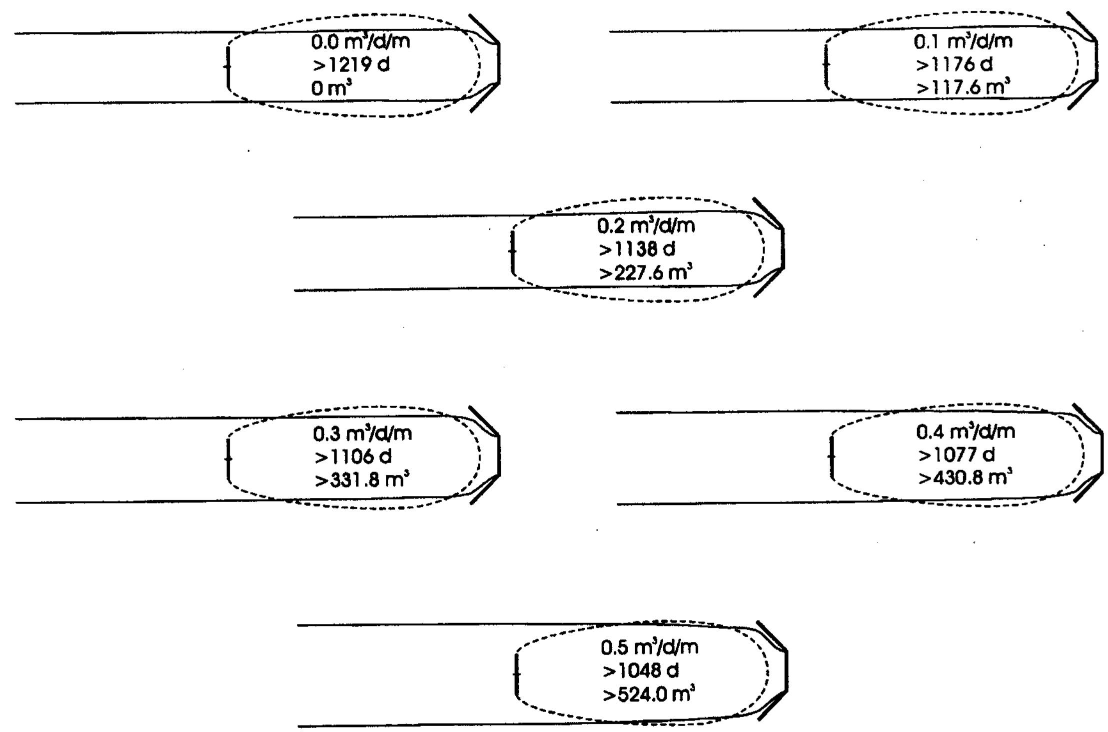

Figure 3. Map views of capture zones for 135° structure; bold lines mark line source (to left) and interceptor structure (to right); left edges of capture zones coincide with model boundary; numbers indicate gate discharge, travel time from left edge of model domain, and volume of water removed (without capture).

discharge yielded the total volume of water removed from the aquifer. This volume rated the efficiency of an interceptor structure: smaller volumes reduce pumping and treatment costs.

RESULTS AND DISCUSSION

Figures 1-3 illustrate capture zones for six discharge scenarios for each of three trench configurations. The gate-only structure captured the contaminant plume within 450 to 673 days, with shorter time frames acheived at higher gate discharge rates. Higher discharges also increased hydraulic gradients toward the gate, from both upgradient and cross gradient areas of the aquifer, thus widening the capture zone. Wider capture zones provide a margin of safety on either side of the plume, to help ensure capture of contaminated water, but also increase remediation costs by capturing and treating clean water. Higher gate discharge scenarios also increased the total volume of water removed from the aquifer: the percentage decrease in capture time was insufficient to offset a higher discharge rate. Thus, higher discharge scenarios were progressively less efficient at removing the contaminant plume.

Funnel and gate structures performed less efficiently than the gate-only structure. None of the funnel and gate structures induced a wide enough capture zone in the active area of groundwater flow (outside the funnels) to remove the contaminant plume. (The 135° structure at the highest discharge nearly captured the plume.) Similar to the gate-only structure, travel times decreased, capture zones widened, and the total volume of water pumped from the aquifer increased with increased discharge from funnel and gate structures. Much of this volume was clean water upgradient of the contaminated zone.

Simulations of funnel and gate structures illustrated two distinct problems: (1) funnels induced convergent flow in the aquifer, narrowing the capture zone (with smaller funnel-gate angles inducing more narrowing), and (2) water entering the funnels moved exceedingly slow, substantially delaying capture by the gate. The simulated funnels are analogous to slurry cutoff walls used in practice. Typically these consist of bentonite and soil mixed with water, injected along a trench excavated into an aquifer. The resulting cutoff wall has a low permeability, but still absorbs and slowly transmits water. In practice, using longer interceptor structures, especially structures with long gates relative to funnels (Starr and Cherry 1994), and impervious walls would address the above problems, but also increase remediation costs relative to a gate-only structure. For example, impervious steel piles would prevent water entry, but they are not as versatile as slurry walls.

Funnels and gate structures are not useful for all groundwater cleanup applications. They are best suited to unconsolidated aquifers resting on natural barriers such as shale or clay, into which trenches can be keyed. Rapid transport of contaminants under ambient groundwater flow may further enhance the recovery potential of some structures, by enabling lower pumping rates and shorter remediation time frames. Gates also offer the potential for in situ treatment by physical, chemical, and biological processes, though reactive media may require periodic replacement (Starr and Cherry 1994; NRC 1994).

Results of this study suggest that gate-only structures spanning the width of a contaminant plume, operating under ambient flow conditions, may be an effective groundwater cleanup alternative for shallow, unconsolidated aquifers. However, no interceptor structure is universally suited to all groundwater cleanup applications. In practice, site specific conditions and computer trials should guide the selection of an appropriate groundwater remediation scheme. In this manner, an efficient structure that captures a contaminant plume while removing a minimal amount of water my be identified and implemented.

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