Bull Environ Contam Toxicol (2011) 87:96–100
DOI 10.1007/s00128-011-0295-y

Assessment of Multi-Gate Interceptors Equipped with Baffles in Contaminated Aquifers

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Received: 14 April 2011 / Accepted: 28 April 2011 / Published online: 7 May 2011

Abstract Funnel-and-gate structures with three gates, two funnels (collinear with gates), and two perpendicular flow-directing vanes (baffles) were assessed for capturing contaminated groundwater in a hypothetical unconfined aquifer. Simulated structures, anchored into an underlying aquiclude, were 35 m wide. One 5-m wide gate occupied the center, and two 3-m wide gates occupied the ends, of each structure. Both homogeneous and heterogeneous (with respect to hydraulic conductivity) aquifers were modeled, with baffles at various positions along funnels in alternative configurations. A contaminant transport model, accounting for advection and hydrodynamic dispersion, tested the capability of various structures for capturing contaminant plumes. Based upon modeling results: (1) structures with baffles performed up to 17% better (homogeneous case), but also up to 48% worse (heterogeneous case), than structures without them; (2) the most effective baffles generally occupied interior portions of funnels; and (3) small (1-m) shifts in the locations of baffles resulted in up to a 33% increase (homogeneous case) in remediation timeframe.

Keywords Groundwater · Funnel-and-gate · Baffle · Contaminant transport

Over the past two decades, numerous field experiments have demonstrated the viability of permeable reactive barriers for transforming or removing various contaminants from groundwater [HWC (Hazardous Waste Consultant) 1999; EPA (US Environmental Protection Agency) 2003]. Many computer modeling studies also demonstrate the capability of in situ barrier approaches. For example, several investigators simulated the distribution of groundwater flow lines near alternative designs for permeable reactive barriers (Eykholt et al. 1999; Mayer et al. 2001; Elder et al. 2002; Painter 2004) or funnel-and-gate systems (Starr and Cherry 1994; Gupta and Fox 1999; Sedivy et al. 1999; Cirpka et al. 2004). Results of these studies demonstrated the influence of site-specific conditions on system performance, indicating a need for thorough site characterization. Additionally, results showed that heterogeneous settings with irregular flow paths generally warranted thicker and wider structures to facilitate containment (Bilbrey and Shafer 2001; Hemsi and Shackelford 2006). Moreover, multi-gate structures tended to capture contaminant plumes more reliability than single-gate structures in heterogeneous aquifers (Burger and Finkel 2005). Using a mass transport model, Hudak (2008) showed that contaminant spreading induced by hydrodynamic dispersion requires wider structures and longer time frames for plume capture than those predicted strictly by particle tracking.

Usually, in situ interceptors comprise a trench filled with permeable reactive media (gate), or a combination of one or more gate(s) and low-hydraulic conductivity walls (funnels). Where used, funnels direct contaminated groundwater toward gates, where reactions treat contaminants in groundwater. Especially for large contaminant plumes, in situ reactive structures generally require less energy to operate and maintain than traditional pump-and-treat approaches to remediating contaminated aquifers [EPA (US Environmental Protection Agency) 2003]. In situ structures also reduce human exposure to pollutants and create fewer above ground obstructions. While in situ

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structures are sometimes viable for groundwater remediation, previous work has not addressed the capability of flow-directing vanes (baffles) constructed perpendicular to funnels. The present modeling study evaluated various structures, several incorporating baffles, for their capability to capture contaminated groundwater.

Materials and Methods

Two numerical models—MODFLOW (McDonald and Harbaugh 1988) and MT3D (Zheng and Wang 1999)—were used to simulate groundwater flow and contaminant transport in a hypothetical, unconfined aquifer (Fig. 1). The finite-difference grid consisted of 155 rows, 200 columns, and 31,000 block-centered nodes 1 m apart. Elevation was 0 m at the base of the aquifer. Water table elevation (H) was constant at the west (H = 10.00 m) and east (H = 8.01 m) edges of the model domain, producing a regional hydraulic gradient of 0.01 (west to east). No groundwater flowed across the other edges of the model domain.

Both homogeneous and heterogeneous aquifers were simulated. In the homogeneous case, hydraulic conductivity was 2, 20, and 0.00009 m/d in the aquifer, gates, and funnels, respectively. Effective porosity was 0.25 in the aquifer and funnels, and 0.35 in the gates. Gates and funnels were 1 m thick and traversed the entire thickness of the aquifer. Funnels were simulated as mixtures of soil and bentonite (slurry walls) used in practice. Gates were modeled as contaminant sinks with a concentration of 0 mg/l. Each interceptor was a collinear combination of two funnel and three gate segments: one gate in the center and two gates at the ends of the structure. Center and end gates allowed for the possibility of effective plume capture and containment, respectively.

For the heterogeneous case, a random hydraulic conductivity field was obtained from a lognormal probability distribution with the following parameters: mean log10 hydraulic conductivity (m/d) = 0.301; standard deviation log10 hydraulic conductivity = 0.3; and correlation length of hydraulic conductivity = 2 m.

Initially, groundwater simulations excluded interceptor structures. Using output from the groundwater flow model, MT3D simulated solute transport from a 3 m by 3 m source near the western edge of the model domain (Fig. 1a). Active for 1,000 d in the homogeneous aquifer and 1,080 d in the heterogeneous aquifer, the contaminant source had a constant concentration of 100 mg/l. A 1 mg/l contour defined contaminant plume boundaries; leading

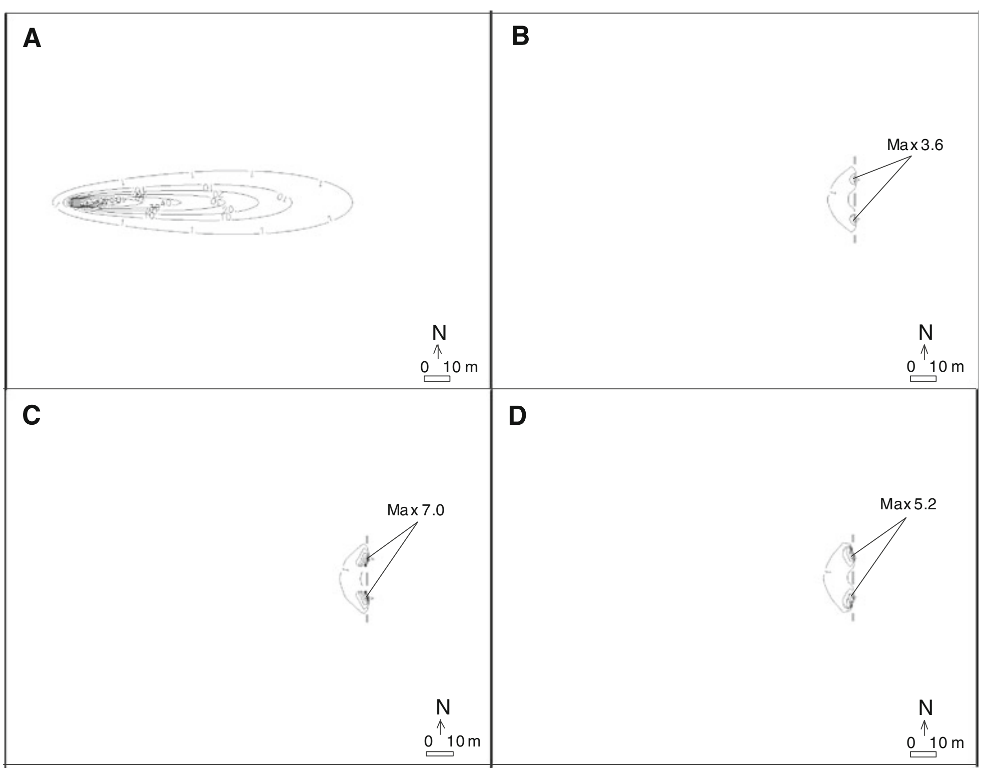

Fig. 1 **a** Initial contaminant plume (contours 1–100 mg/l, interval = 10) in homogeneous aquifer; **b** plume after 2,000 d with no baffles (contours 1–3, interval = 1); **c** plume after 2,000 d with baffles at 8-m *offset* (best performer, contours 1–7, interval = 1); and **d** plume after 2,000 d with baffles at 11-m *offset* (worst performer, contours 1–5, interval = 1)

tips of initial contaminant plumes in homogeneous and heterogeneous aquifers occupied the same finite-difference column.

Longitudinal and transverse horizontal dispersivity were 2.0 and 0.2 m, respectively. The effective molecular diffusion coefficient was 0.00001 m^2/d.

The groundwater flow model recomputed hydraulic head distributions resulting from each interceptor structure. Incorporating these hydraulic head fields, MT3D simulated removal of initial contaminant plumes by each interceptor. Approximately 5 m downgradient of the initial contaminant plume and perpendicular to regional groundwater flow, simulated interceptors consisted of collinear funnel and gate segments: a 5-m wide central gate; two 3-m wide end gates; and two 12-m wide funnels between gates. In alternate simulations, 3-m baffles were placed perpendicular to funnels on either side of the central gate. Collectively, simulations accounted for each of 12 possible positions for baffles along funnels. Baffles were keyed into funnels, extended hydraulically upgradient of funnels, and simulated as the same material as funnels.

Results and Discussion

Initial contaminant plumes typified quasi-elliptical and irregular forms often found in homogeneous and heterogeneous aquifers, respectively (Fig. 1a, b).

In the homogeneous case, all structures prevented the contaminant plume from reaching the eastern model boundary (i.e., prevented offsite migration), with an average time of 3,520 d required to remove the plume (Table 1, Fig. 1). The structure without a baffle performed worse than the average; however, several structures with baffles also performed relatively poorly, and one of the baffled structures was the worst performer. The most effective structure had a baffle eight meters from the central gate and required 3,080 d to remove the contaminant plume. In contrast, the least effective structure had a baffle 11 m from the central gate, requiring 4,220 d to remove the plume.

In all structures, the contaminant plume lingered upgradient of funnels on either side of the central gate (Fig. 1). Flow tends to be divergent and stagnant in this area between gates, accounting for lingering contaminants in groundwater.

Generally, interior baffle positions, as opposed to locations at the extreme edges of funnels, deflected contaminated groundwater toward gates and thus performed relatively well (Table 1). However, the most effective (baffled) structure reduced the remediation timeframe by only about 16% compared to the baffle-free structure; the worst performing (baffled) structure increased the remediation timeframe by 14%. Moreover, varying the baffle position by only a few meters had considerable impact on remediation timeframe. That is, moving the baffle just 1 m resulted in up to a 33% increase in remediation timeframe. Poorly positioned baffles have the potential to slow down remediation, because contaminants that might otherwise move quickly to one gate (especially the large central gate) are forced to move to a farther, alternative gate (especially the smaller end gates).

By contrast, in the heterogeneous case, no structures prevented offsite plume migration (Table 1, Fig. 2). On average, it took 4,200 d to reduce concentrations at all model cells to less than 1 mg/l. The structure with no baffle performed better, but several baffled structures performed worse, than the overall average. Moreover, baffled structures

Table 1 Plume removal timeframes

Baffle position	Days to eliminate plume		Offsite migration	
	Homogeneous	Heterogeneous	Homogeneous	Heterogeneous
No baffle	3,690	3,550	No	Yes
1	4,170	3,730	No	Yes
2	3,460	3,380	No	Yes
3	3,550	3,390	No	Yes
4	3,500	3,490	No	Yes
5	3,510	3,710	No	Yes
6	3,560	4,070	No	Yes
7	3,480	4,290	No	Yes
8	3,080	4,770	No	Yes
9	3,090	4,820	No	Yes
10	3,180	4,920	No	Yes
11	4,220	5,180	No	Yes
12	3,320	5,250	No	Yes
Average	3,520	4,200		

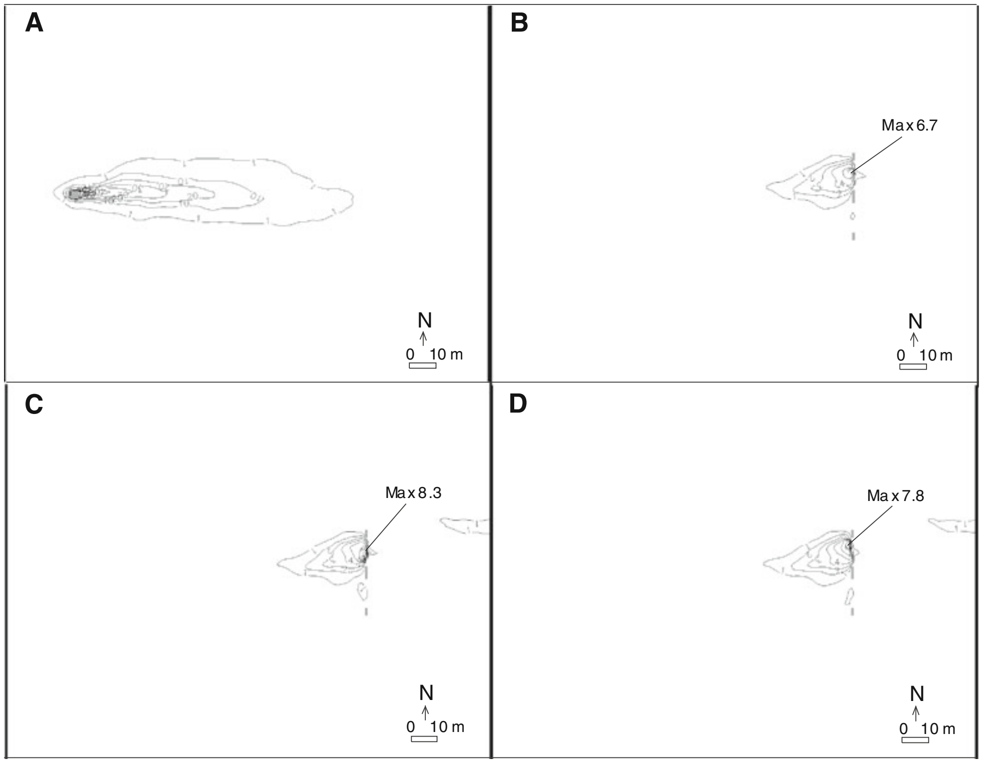

Fig. 2 **a** Initial contaminant plume (contours 1–100 mg/l, interval = 10) in heterogeneous aquifer; **b** plume after 2,000 d with no baffles (contours 1–6, interval = 1); **c** plume after 2,000 d with baffles at 2-m *offset* (best performer, contours 1–8, interval = 1); and **d** plume after 2,000 d with baffles at 12-m *offset* (worst performer, contours 1–7, interval = 1)

accounted for the worst-performing alternatives; in these cases, contaminants lingered upgradient of the northern funnel, as flow variations induced by aquifer heterogeneity directed most of the plume in this direction. The best performing structure, featuring an interior baffle, required about 16% less contaminant removal time than the structure with no baffle. However, the worst performing structure required 48% more time than the structure without a baffle. Again, there were large variations in removal time, up to an 11% increase, with small (1-m) shifts in baffle location.

Further, the heterogeneous simulations demonstrated a general trend toward longer removal times with baffles farther away from the central gate. In this case, the northern end gate was important for capturing the plume, as flow directed contaminants in this direction; however, placing a baffle close to the northern end gate effectively blocked or delayed contaminants from entering the gate.

In conclusion, results outlined above suggest that baffles offered little improvement in remediation timeframe and were often counterproductive. Where effective, baffles tend to be in interior locations versus the extreme edges of funnels. Edge locations tend to delay movement of contaminants toward the closest gate. Given large swings in detection efficiency with small shifts in baffle location, the potential for significantly delaying remediation, and the added costs of baffles, it may be advantageous to not use them at all along internal funnels such as those simulated here. In practice, laboratory and field studies should inform modeling investigations, which should be followed up with careful field monitoring to verify the performance of operational structures.

Successful structures featured in this study involved remediation timeframes of roughly 10 y. Much slower groundwater flow would render such passive structures infeasible, due to excessive remediation timeframes. This study also showed that heterogeneous conditions may hamper prospects for onsite containment (without increasing the size of a structure).

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