In Situ Remediation of Contaminated Ground Water: The Funnel-and-Gate System

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Abstract

The funnel-and-gate system for in situ treatment of contaminant plumes consists of low hydraulic conductivity cutoff walls with gaps that contain in situ reactors, such as reactive porous media, that remove contaminants by abiotic or biological processes. Funnel-and-gate systems can be installed at the front of plumes to prevent further plume growth, or immediately downgradient of contaminant source zones to prevent contaminants from moving into plumes. Cutoff walls (the funnel) modify flow patterns so that ground water flows primarily through high conductivity gaps (the gates). This approach is largely passive in that after installation, in situ reactors are intended to function with little or no maintenance for long periods. This approach contrasts with the energy and maintenance-intensive character of pump-and-treat systems. This paper describes the funnel-and-gate concept, and uses two-dimensional computer simulations to illustrate the effects of cutoff wall and gate configuration on capture zone size and shape and on the residence time for reaction of contaminants in gates.

Introduction

Plumes of contaminated ground water that emanate from contaminant source zones (Figure 1a) are often managed by operating pump-and-treat systems (Figure 1b). These systems are effective for preventing migration of plumes beyond extraction wells, but they have several limitations with respect to long-term ground-water remediation as discussed by Mackay and Cherry (1989). Pump-and-treat is usually not effective for restoring aquifers in contaminant source zones, particularly if LNAPL or DNAPL is present. Dissolved plumes form again at many sites if pump-and-treat systems are shut down unless the source zone is controlled by some other means, such as isolating it with a cutoff wall enclosure. This suggests that pump-and-treat systems must be operated for very long periods of time—decades or centuries—to prevent continued growth of contaminant plumes. Pump-and-treat systems require a continuous input of energy for pumping water from extraction wells and operating water treatment systems, as well as periodic maintenance and monitoring, so long-term pump-and-treat is an expensive process that will be a burden on future generations unless other remedial techniques are developed. Finally, extraction and disposal of ground water wastes scarce water resources. These factors indicate that alternatives to pump-and-treat for controlling plumes of contaminated ground water would be beneficial.

In situ reaction curtains (Figure 1c) are an alternative to pump-and-treat (Burris and Cherry, 1992). A ground-water plume flows into an in situ reaction curtain, where physical, chemical, or biological processes remove contaminants from ground water. Remediated ground water exits the downgradient side of the curtain. Reactors that can be used for in situ reaction curtains are described in a subsequent section.

To successfully remediate a plume, an in situ reaction curtain must be large enough that the entire plume passes through it. If a plume is quite wide or extends to great depth, the necessary dimensions could be so large that an in situ reaction curtain would be impractical. To circumvent this problem, low hydraulic conductivity cutoff walls can be used to focus ground-water flow, allowing a smaller in situ reactor to treat a plume (Figure 1d). The combination of cutoff walls and in situ reactors is known as the *Funnel-and-Gate System.* This concept was discussed qualitatively by McMurty and Elton (1985). In spite of this earlier discussion, application of in situ reactors and the funnel-and-gate approach to ground-water remediation remains largely a research activity.

Several funnel-and-gate configurations are illustrated in Figure 2. The simplest is a single gate with cutoff walls that extend to each side (Figure 2a). Single or multiple gates can be used with funnels that have upstream projections and partially surround a contaminant source zone. A contaminant source zone can be completely surrounded by cutoff walls, except for a gap that is left on the downgradient side. The upstream wall deflects most ground water around the contaminant source zone. Water that infiltrates into the enclosure or flows through the cutoff walls into the cell exits

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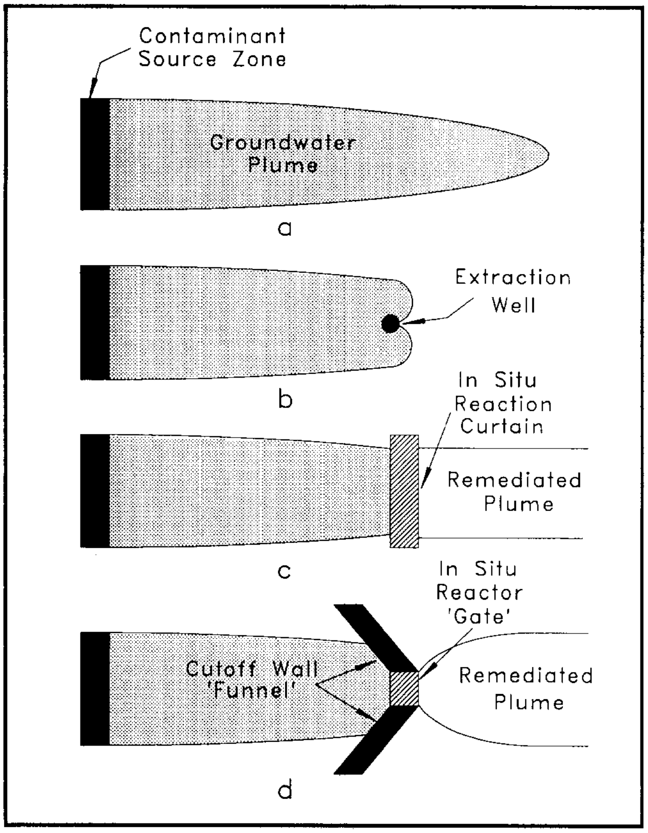

Fig. 1. Ground-water plume management options. a. Unremediated plume. b. Pump-and-treat system. c. In situ reaction curtain. d. Funnel-and-gate system.

through the gap, where an in situ reactor remediates the ground water. This configuration minimizes the amount of water that flows through the contaminant source zone and hence the amount of contaminated ground water that must be treated, and thereby maximizes the retention time in the gate which leads to more complete treatment. Multiple gates in parallel can be used for controlling wide plumes (Figure 2b). Plumes with a mixture of contaminants that require more than one type of in situ reactor can be controlled using multiple gates in series. For example, a plume at an electroplating facility that contains both chlorinated hydrocarbons and metals can be treated using one reactor to degrade the organics and a second to precipitate the metals.

In situ reaction curtains and funnel-and-gate systems can be constructed through the entire thickness of an aquifer if ground-water plumes extend from top to bottom of the aquifer (Figure 2c), as might be the case for DNAPL contamination. If a ground-water plume occupies only the uppermost portion of an aquifer, for example if the contaminant source is an LNAPL or a volatile liquid in the vadose zone, then an installation that extends only through the upper portion of the aquifer will be sufficient.

The in situ reactor is the heart of the funnel-and-gate system, and several types can be envisaged. The first type modifies pH or Eh conditions in the subsurface. These changes affect the solubility of pH or redox sensitive species, and rates of degradation reactions. For example, chromium is less soluble under reducing conditions than under oxidizing conditions. Blowes and Ptacek (1992) describe a reactor that causes chromium precipitation by generating reducing conditions in the subsurface. Some classes of organic compounds, such as aromatics derived from gasoline, are more readily biodegradable under aerobic conditions than under anaerobic conditions (Wilson and McNabb, 1983). Modifying redox conditions could increase rates of degradation of these compounds. Shields and Reagin (1992) describe bacteria that degrade trichloroethylene and other chlorinated hydrocarbons under aerobic conditions. An in situ reactor that contains these microorganisms could be used in an aerobic aquifer, or combined with a reactor that aerates a plume. Abiological reaction rates are also affected by redox state. Gillham and O'Hannesin (1992) describe a reactor that causes abiotic degradation of halogenated aliphatic hydrocarbons such as tri- and tetrachloroethylene under reducing conditions.

The second class of in situ reactor contains a material that dissolves and causes precipitation of a mineral phase that immobilizes the contaminant. For example, Xu and Schwartz (1992) describe a reactor that contains hydroxyapatite (calcium phosphate). Hydroxyapatite dissolution increases the concentration of phosphate, which then causes precipitation of lead phosphate minerals.

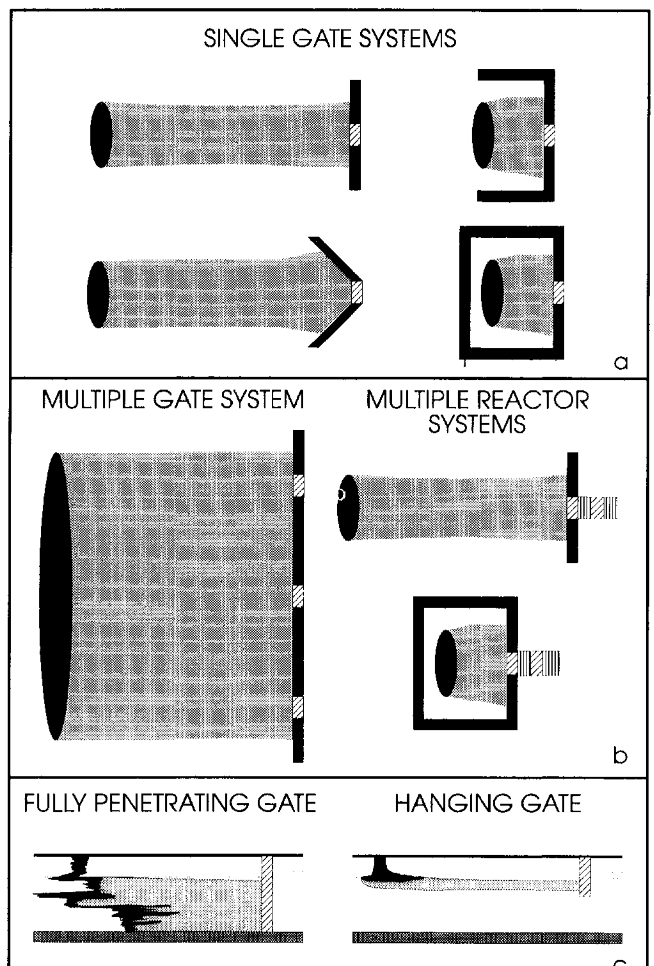

Fig. 2. Funnel-and-gate configurations.

The third type of in situ reactor removes materials from solution by sorption. For example, activated carbon could be used for removing hydrophobic organic compounds, and zeolites or synthetic ion exchange resins for removing ionic contaminants from ground water. Sorption is reversible, so periodic removal and replacement of spent sorbents would be necessary. Burris and Antworth (1992) describe a technique for creating a sorption barrier by augmenting the capacity of a porous medium to sorb hydrophobic organic solutes by injecting a cationic surfactant solution into the subsurface. The ionic end of the surfactant molecules is sorbed by mineral surfaces, and organic solutes are sorbed by the hydrophobic end of the surfactant molecules.

A fourth type of in situ reactor supplies nutrients whose availability limits the rate of biodegradation: Devlin and Barker (1993) describe a method of injecting a nutrient solution that promotes mixing with a ground-water plume. Alternatively, solid material that leaches dissolved nutrients could stimulate biodegradation. Robertson and Cherry (1993) and Vogan (1993) describe laboratory and field trials in which sawdust was used to supply soluble organic carbon for increasing nitrate degradation rates.

The fifth type of reactor is one in which a physical removal or transformation process is carried out. Pankow et al. (1992) describe in situ air sparging for removing volatile compounds from ground water. This type of reactor differs from the others in that contaminants are removed from ground water and transferred aboveground, where subsequent treatment may be necessary.

In situ treatment reactors and funnel-and-gate systems are concepts developed very recently, and research on in situ reaction media is in its infancy. We expect rapid advances in the next few years in the numbers and types of in situ reactors that are available, and their performance. The modeling analysis presented in this paper does not depend on the type of in situ reactor, and is intended to advance our general understanding of funnel-and-gate systems. It provides insight into factors that influence plume containment using these systems, and the residence time of contaminants in the gate. Residence time is critical to the selection and design of reaction media for the gates.

The other components of a funnel-and-gate system are the cutoff walls that form the funnel, and a container for housing the in situ reactor. The type of cutoff wall used is not critical, as long as the gate area does not become plugged with low hydraulic conductivity material during wall construction. Sealable joint sheet piling (Starr et al., 1992) is particularly well-suited to funnel-and-gate construction because it can be easily connected to screens that house in situ reactors, and the area around the cutoff wall does not become plugged with low conductivity material. In contrast, the area adjacent to cutoff walls constructed using slurry trench or grouting methods can become plugged by the low conductivity material used in the wall. Nevertheless, construction techniques are available for placing gates in conventional soil-bentonite or cement-bentonite cutoff walls. The practical aspects of design and construction of funnel-and-gate systems will be presented in a subsequent paper.

An in situ reactor can be placed into the subsurface without being enclosed in a structure, but placing it in a container such as a well screen facilitates removal if the reactor must be rejuvenated. A container has been constructed by modifying a well screen to allow connection to sealable joint sheet piling. A funnel-and-gate system that includes this type of gate was installed at Canadian Forces Base Borden, Ontario, during the Fall of 1992, and is currently undergoing performance evaluation. The reactive porous medium in the gate was described by Gillham and O'Hannesin (1992). The container was made by cutting a series of windows in opposite sides of a 24-inch diameter steel pipe and welding pieces of stainless steel continuous slot well screen into the openings. The container was oriented with one set of screened windows facing upstream and the opposite set facing downstream, allowing ground water to easily flow through the reactive medium inside.

In theory, plume management using in situ reactors, either as a reaction curtain well or a funnel-and-gate system, has several advantages over pump-and-treat. Many in situ reactors degrade contaminants or immobilize them in situ, instead of bringing them to ground surface and transferring them into another medium. Most in situ reactors do not require a continuous input of energy for pumping water or air, and therefore will not be prone to failure due to mechanical breakdown or power outage. An in situ reactor should function until either the reactive capacity is consumed or it is clogged by precipitants or microorganisms. At that time, the reactor can be removed and replaced. Assuming that the useful life of a reactor is years or decades, an in situ reactor would be operated with only infrequent or minor inputs of energy and maintenance. This is in marked contrast to the continuous energy input and ongoing maintenance necessary for pump-and-treat systems. Water is not brought to ground surface for treatment, so technical and regulatory problems related to discharge of treated water are avoided and scarce ground-water resources are not wasted.

These advantages apply to both in situ reaction curtains and funnel-and-gate systems. The advantages of a funnel-and-gate system over an in situ reaction curtain are that a smaller reactor can be used for treating a given plume, which may lead to lower cost. If a reactor requires periodic replacement, it will be easier to accomplish if the reactor is enclosed in a relatively small gate than if it is spread across a large extent of aquifer in an in situ reaction curtain.

When faced with the task of selecting a funnel-and-gate configuration, a designer must balance several conflicting criteria. First, the system must be located so that all of the water that flows through a contaminant source zone subsequently flows through the gate. In other words, the funnel-and-gate must be designed so that its capture zone encompasses the contaminant source that the system is intended to manage. Ground-water flow directions fluctuate and cause the location of ground-water plumes and capture zones to vary in time, so this is not a trivial task. Second, the residence time of contaminated ground water in the gate must be long enough that the desired reduction in concentration is achieved. The necessary residence time depends on the influent concentration, the required effluent concentration, and the reaction rate. Third, the amount of cutoff wall and the number of gates should be as small as possible to minimize cost. Faced with meeting these objectives, a designer would be likely to use flow and transport models to evaluate proposed funnel-and-gate configurations. Simulations of a variety of generic funnel-and-gate systems are presented in this paper, with the overall objective of illustrating how the configuration of a funnel-and-gate system affects its performance. This sensitivity analysis provides the basis for making initial selections of funnel-and-gate configurations to be evaluated for use at ground-water remediation sites.

The goals of this paper are to illustrate the effects of funnel-and-gate geometry and gate hydraulic conductivity on the size and shape of the capture zone, the discharge through the gate, and the residence time in the gate. The term *funnel-and-gate geometry* means the dimensions of the cutoff walls and gate, the location and number of gates, the angle between the sides of the funnel, and the orientation of the funnel-and-gate to the regional hydraulic gradient. The degree of concentration attenuation as ground water passes through a gate is controlled by the reaction rate and the residence time in the gate, which in turn depends on the gate size and the discharge through the gate. These effects were evaluated using two-dimensional plan view simulations, which are applicable to funnel-and-gate systems that penetrate the entire thickness of aquifers and extend into underlying aquitards. Systems that extend only partially through an aquifer, perhaps because ground-water plumes occupy only the shallow portions of an aquifer, are best described by three-dimensional simulations. Three-dimensional simulations of funnel-and-gate systems will be reported in a subsequent paper.

Methods

A variety of funnel-and-gate configurations were simulated using FLONET version 2.0 (Guiguer et al., 1992), a two-dimensional steady-state flow model based on the dual formulation of flow (Frind and Matanga, 1985). All figures that depict ground-water flow (Figures 5-7 and 11-16) are in plan view and show streamlines and contours of equal hydraulic head. An equal discharge of ground water flows through the streamtube between adjacent streamlines, so the discharge of ground water through a gate is proportional to the number of streamtubes that pass through the gate. A unit thickness of aquifer was simulated, so values of discharge have the units cubic meters per day per meter vertical saturated thickness of aquifer, or $m^3/d/m$.

The simulated systems have aquifer hydraulic properties that are similar to those of the surficial aquifer at Canadian Forces Base Borden, Ontario, Canada, which is described by Sudicky (1986). The simulated aquifer has an isotropic, homogeneous hydraulic conductivity of 1×10^{-2} cm/s, and a hydraulic gradient of 0.005, which are typical values for many unconfined sand aquifers in North America. The cutoff walls are 1 m thick with hydraulic conductivity equal to 1×10^{-6} cm/s, which are reasonable values for conventional soil-bentonite cutoff walls used in the geotechnical construction industry (Starr and Cherry, 1990). The hydraulic conductivity of the material in the gate is 1×10^{-1} cm/s, except where noted. All materials have a porosity

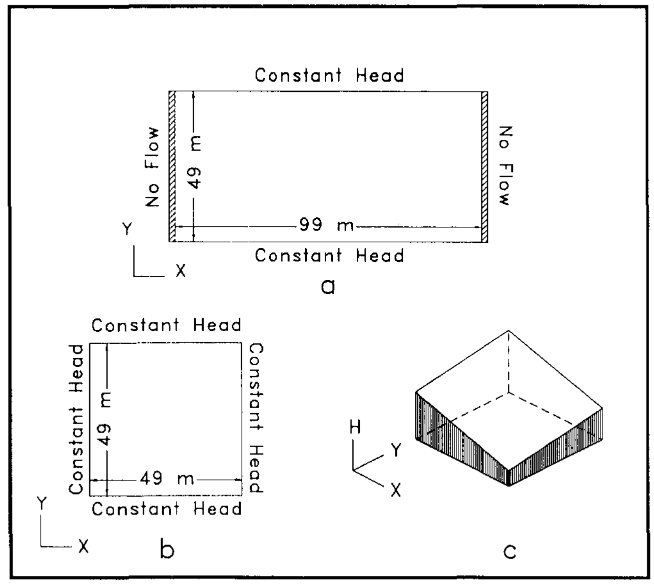

Fig. 3. Simulation domain. a. Domain used for Figures 5-8. b. Domain used for Figures 9-18. c. Method of specifying hydraulic head along the boundaries of the domain shown in panel b to produce a regional gradient at any orientation to the grid axes.

of 0.33. The finite-element grids have a 1 m $\times$ 1 m discretization, except in a few cases where 0.5 m discretization near the funnels was necessary to describe a particular funnel configuration. Figure 3a shows the system simulated to generate the results shown in Figures 5-8, although only a portion of the domain is shown in some figures. The direction of the regional hydraulic gradient in this domain is parallel to the Y axis. The results presented in Figures 9-18 were simulated using the domain shown in Figure 3b. Hydraulic head was specified along all four boundaries, Figure 3c, so the hydraulic gradient could be oriented at any direction relative to the grid axes.

The model simulates steady-state flow fields, so the effects of variation in the direction of the regional hydraulic gradient cannot be evaluated in a single simulation. Instead, this effect was evaluated by superimposing the results of several simulations with boundary conditions that cause the regional hydraulic gradient to be oriented at various directions relative to the funnel-and-gate system.

The simulated aquifers have isotropic hydraulic conductivity, so ground-water flow directions and the direction of the steepest hydraulic head decline coincide. In anisotropic systems, flow directions are generally not in the direction of the steepest hydraulic head decline, so caution must be used in extrapolating the results presented here to anisotropic aquifers.

The symbols and nomenclature used for describing funnel-and-gate systems are illustrated in Figure 4. The *relative discharge* through the gate of a funnel-and-gate system is presented on Figures 6-8. The relative discharge is the proportion of the water in the streamtube intersected by a funnel-and-gate system that flows through the gate instead of around the ends of the funnel. It is calculated by normalizing the discharge through the gate by the discharge through a section with width W_{funnel} located at the upstream face of the gate under the same hydraulic conditions except that the funnel-and-gate system is absent.

The capture zone of a funnel-and-gate system is analogous to the capture zone of an extraction well, and is defined as the region through which water flows before passing through the gate. In this paper, the capture zone is taken to be the area upstream of the gate bounded by the streamlines that intersect the left and right edges of the upstream face of the gate. The capture zone is represented as a hatched or stippled area. Simulations presented later illustrate the effects of funnel-and-gate geometry on the discharge through the gate, which affects residence time, and on the size and shape of the capture zone.

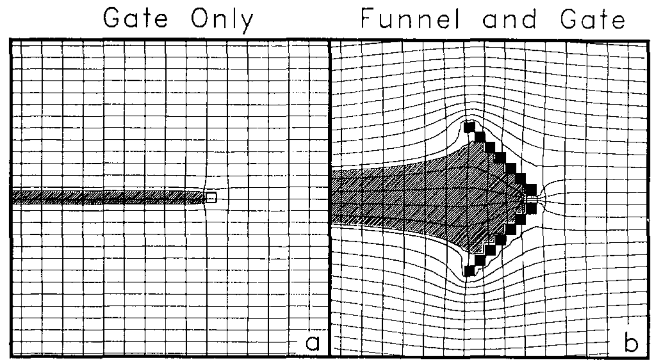

Fig. 5. General effect of funnel-and-gate systems. a. Gate without a funnel, and capture zone (hatched). b. Funnel-and-gate system, and capture zone.

Results and Discussion

General

Several typical effects of a funnel-and-gate system on ground-water flow systems are illustrated in Figure 5. Figure 5a shows an aquifer that has a 1 m × 1 m gate whose hydraulic conductivity is 10 times that of the aquifer. The capture zone extends upstream (to the left) of the gate, and is slightly wider than the gate since the higher hydraulic conductivity of the gate causes minor focusing of flow. In Figure 5b, cutoff walls have been added to both sides of the gate. This substantially increases the discharge through the gate, reflected by the larger number of streamtubes that pass through the gate, and consequently causes a wider capture zone. However, note that some streamtubes are deflected around the ends of the cutoff walls, so the capture zone is not as wide as the funnel.

There are two reasons for installing a cutoff wall funnel in addition to an in situ reactor. First, it increases the amount of water that flows through the gate, which makes the capture zone wider. Beyond the local influence of the funnel, the width of the capture zone is proportional to the discharge through the gate. Second, addition of a funnel allows the shape of the capture zone close to the funnel and the location of the capture zone relative to the gate to be controlled to some degree.

Two conflicting factors must be considered in evaluating funnel-and-gate configurations. On one hand, the discharge through a gate should be maximized so that the capture zone is as wide as possible. On the other hand, the residence time of contaminated ground water in the gate should be as long as possible, so that contaminant concentrations are attenuated more. Residence time and discharge are inversely related, so the desire for a large capture zone must be balanced against the requirement for greater attenuation.

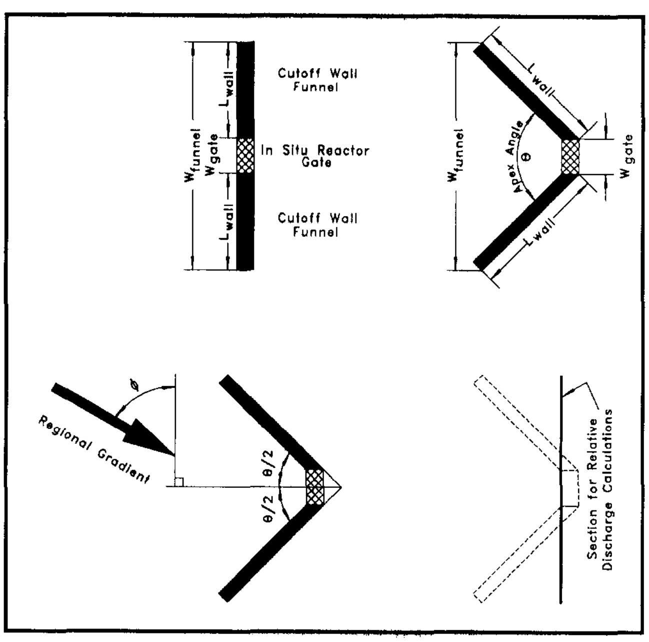

Fig. 4. Symbols and nomenclature.

Effect of Funnel Width

The effect of the width of a funnel with an apex angle of 180 degrees (a straight wall) perpendicular to the regional hydraulic gradient on the discharge through the gate is illustrated in Figure 6.

Figures 6a-c show simulations of funnels 7, 21, and 61 m wide. As the funnel width increases, the discharge through the gate increases and the capture zone becomes wider. The discharge does not increase proportionally with funnel width (Figure 6d). In contrast, the discharge of water through the streamtube intersected by the funnel increases proportionally with funnel width, so the relative discharge through the gate decreases dramatically with increasing funnel width. In other words, the fraction of water that passes through the gate decreases and the fraction deflected around the ends of the funnel increases as funnel width increases.

Effect of Gate Width

Figure 7 shows a 21-m wide funnel, with gate widths of 1, 3, and 9 meters, and the absolute and relative discharge as a function of gate width. As the gate becomes wider relative to the funnel, the absolute and relative discharge and the width of the capture zone all increase. Hence, a gate that is as wide as practical is desirable.

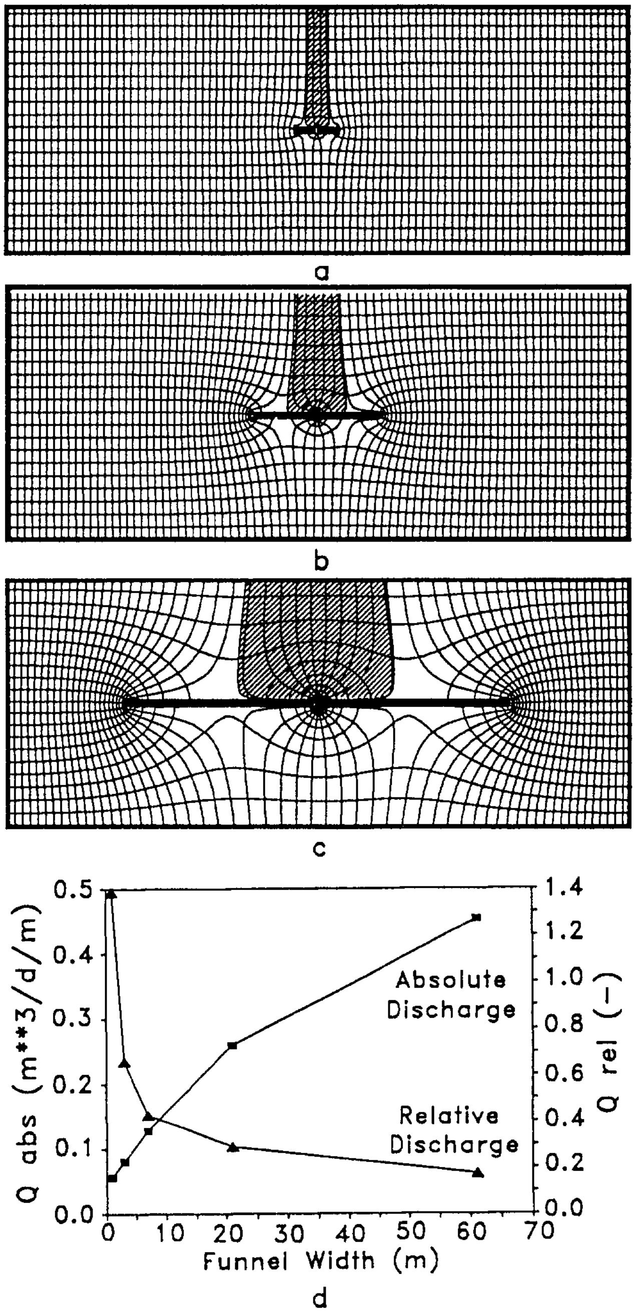

Fig. 6. Effect of funnel width with constant 1-m gate width. a. Funnel width 7 m. b. Funnel width 21 m. c. Funnel width 61 m. d. Discharge as a function of funnel width.

Effect of Gate Hydraulic Conductivity

Figure 8 is a plot of the discharge through the gate of a funnel-and-gate system with a 180-degree apex, and a funnel width of 21 meters. The hydraulic conductivity of the gate was varied from 0.1 to 100 times that of the aquifer. The discharge through the gate increases with increasing hydraulic conductivity, but there is relatively little increase for conductivities greater than 10 times that of the aquifer. The practical implication is that while designers should strive to make the gate hydraulic conductivity as high as possible, very high values are not required to make the system work properly. This is fortunate, in that high hydraulic conductivity porous media generally have large grain size and hence low surface area to mass ratios. Reaction rates for many in situ reaction media would be expected to be proportional to surface area, so slower reaction rates would probably be an adverse side effect of placing a very high hydraulic conductivity medium in the gate.

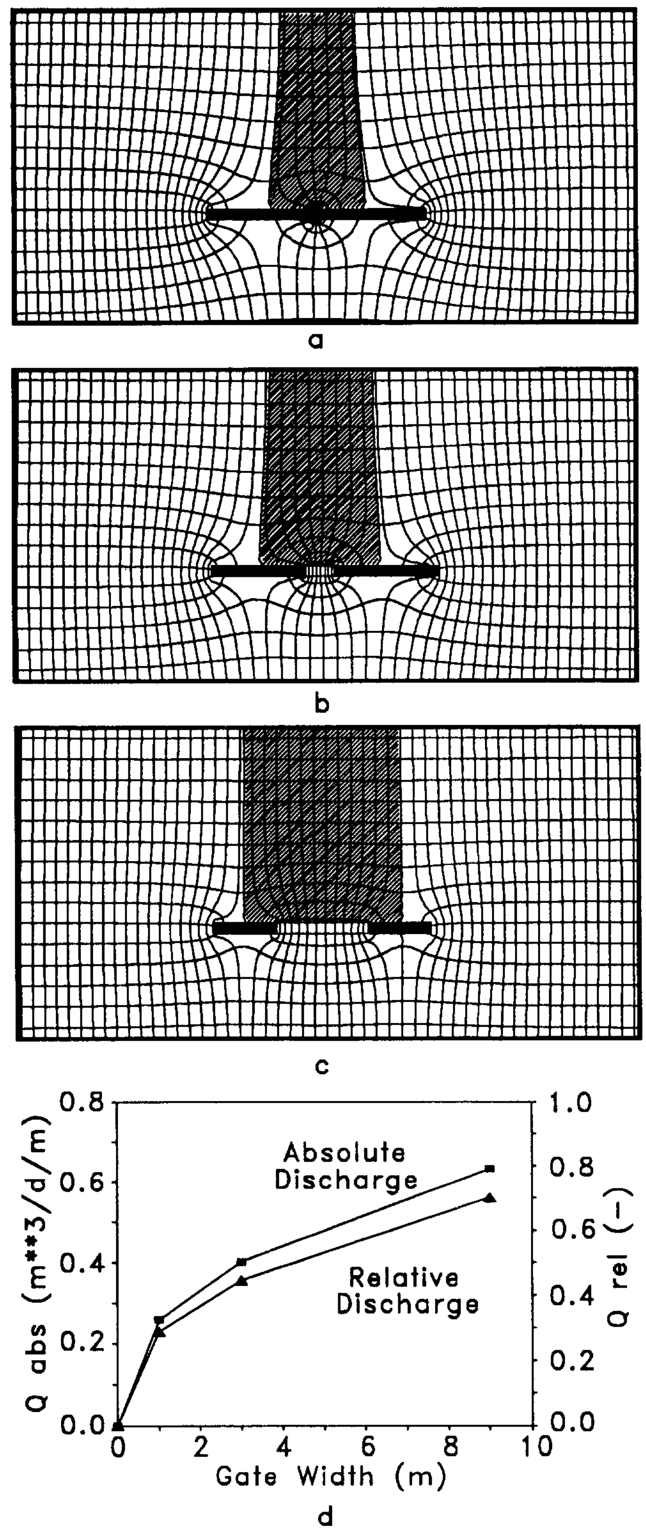

Fig. 7. Effect of gate width with constant 21-m funnel width. a. Gate width 1 m. b. Gate width 3 m. c. Gate width 9 m. d. Discharge as a function of gate width.

Effect of Funnel Apex Angle and Orientation to the Regional Gradient on Discharge Through the Gate

The effects of funnel apex angle and orientation to the regional gradient are illustrated in Figures 9 and 10. All funnels in these simulations have the same length of wall, 10 m per side, and thus the funnel width decreases as the apex angle is farther from 180 degrees. As was shown in Figure 6, the discharge through the gate of a straight funnel-and-gate system perpendicular to the regional gradient is related to the width of the funnel. In the general case where the funnel is not perpendicular to the regional gradient, the funnel width projected perpendicular to the regional gradient is related to both the apex angle and the orientation to the hydraulic gradient. Using the symbols defined on Figure 4, the width of a funnel with apex angle theta and wall length L_{wall} is:

$$W_{funnel} = W_{gate} + 2L_{wall}\sin(\text{theta}/2)$$

For constant wall length, the funnel width is maximum for a straight wall (theta = 180 degrees) and decreases as theta becomes farther from 180 degrees. The width of the funnel projected perpendicular to the regional gradient is:

$$W_{funnel\ perpendicular} = W_{funnel}\sin(\text{phi})$$

The projected width is maximum for phi = 90 degrees, i.e. for funnels perpendicular to the regional gradient.

Figure 9 shows the effect of the apex angle on the discharge through the gate, for various orientations of the funnel to the regional gradient. For all orientations to the regional gradient, the maximum discharge occurs at an apex angle of 180 degrees. There is little effect of apex angle between 127 and 233 degrees, but the discharge drops rapidly for apex angles beyond this range. This indicates that the most efficient configuration is a straight funnel, but apex angles that are close to 180 degrees are only slightly less efficient.

Figure 10 shows the same data plotted with respect to the angle to the regional gradient. For all apex angles, the maximum discharge occurs when the funnel is perpendicular to the regional gradient. For a funnel with a given apex angle, the discharge through the gate when the funnel is not perpendicular to the regional gradient is the product of the sine of the angle to the regional gradient and the discharge through the gate of the funnel when it is perpendicular to the regional gradient. This relationship holds for symmetric funnels, but not necessarily for unsymmetric funnels.

Note that the curves in Figure 10 do not cross, which indicates that a symmetric funnel configuration that is more effective than another at one angle to the regional gradient is more effective at all other angles. Also note that the curves are fairly flat between 60 and 90 degrees. Although the maximum discharge occurs when the funnel is perpendicular to the regional gradient, the dicharge decreases less than 15 percent for orientations as much as 30 degrees from perpendicular.

The features illustrated in Figures 9 and 10 offer considerable flexibility in designing funnel-and-gate systems. Discharge through the gate for a given length of cutoff wall can be approximately maximized by using apex angles of about 180 +/− 50 degrees, and by orienting the funnel within 30 degrees of perpendicular to the regional hydraulic gradient.

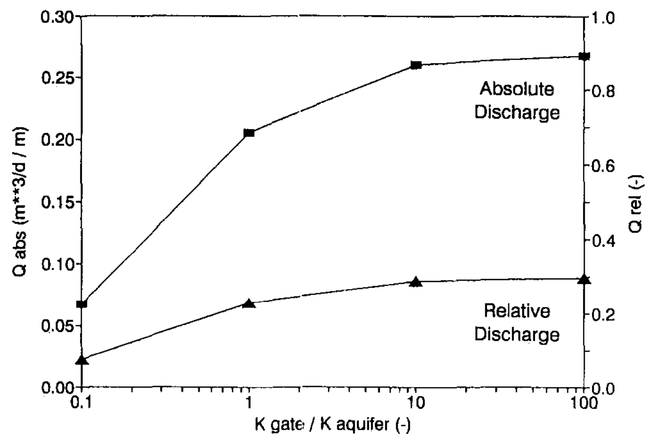

Fig. 8. Effect of gate hydraulic conductivity on discharge through the gate.

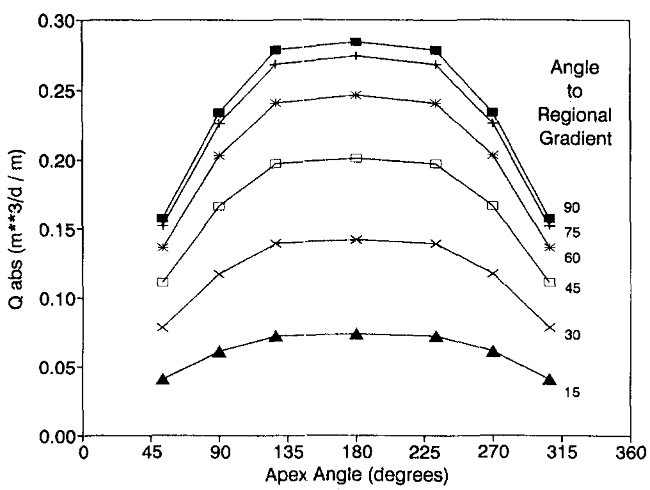

Fig. 9. Effect of funnel apex angle on discharge through the gate.

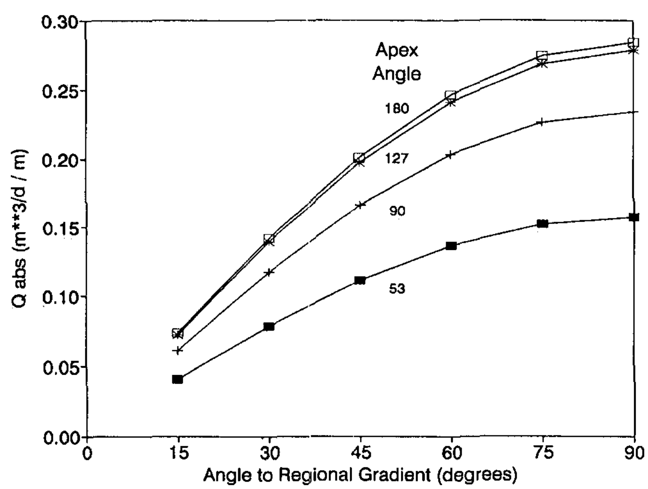

Fig. 10. Effect of funnel orientation on discharge through the gate.

Effect of Funnel Configuration and Orientation to the Regional Gradient on the Capture Zone

One goal of designing a funnel-and-gate system is to select the configuration that produces the greatest discharge per length of cutoff wall in the funnel. The width of the capture zone beyond the immediate vicinity of the funnel is proportional to the discharge through the gate, hence maximizing the discharge also maximizes capture zone width. Much of the expense of constructing a funnel is proportional to the length of cutoff wall installed, thus cost can be minimized by using the configuration that generates the maximum discharge per length of cutoff wall. The configuration that produces the greatest discharge per length of cutoff wall is a funnel with a 180-degree apex oriented perpendicular to the regional gradient (Figures 9 and 10).

At many sites, it may not be feasible to construct a funnel-and-gate system with this configuration due to access restrictions such as existing infrastructure or property boundaries. In addition, in some cases the goal might be something other than maximizing the capture zone width, as discussed below. Therefore, the effects of funnel geometry and orientation to the regional gradient on the size and shape of the capture zone are illustrated in the following figures. To facilitate modeling, the funnel-and-gate systems shown in these figures were fixed and the direction of the regional gradient was varied.

Figure 11 illustrates the relationship between ground-water plumes and funnel-and-gate capture zones. The squares are contaminant source zones, the stippled areas are ground-water plumes, and the cross-hatched area in each panel is the capture zone of the funnel-and-gate system. In Figure 11a the funnel is perpendicular to the regional gradient. The plume from the upper contaminant source zone bypasses the funnel-and-gate system. The lower source lies in the capture zone, so its plume intersects the gate and is remediated. In Figure 11b, the funnel is oriented 60 degrees to the regional gradient. Now the upper contaminant source zone lies in the capture zone and its plume travels through the gate and is remediated while the plume from the lower source bypasses the funnel-and-gate. This illustrates that plumes generated by contaminant sources that are in a capture zone travel through a gate, while plumes generated by contaminant sources that are outside of a capture zone bypass the gate. Capture zones but not plumes are shown for clarity in the following diagrams.

Funnel-and-gate geometry and orientation to the regional gradient affect the size and shape of the capture zone in the immediate vicinity of a funnel, in addition to affecting the width of the capture zone beyond the immediate vicinity of the funnel. If a contaminant source zone is close to a funnel, then it could be advantageous to select a configuration that maximizes the size of the capture zone near the funnel, even though this does not necessarily maximize the width of the capture zone far from the funnel. Figure 12 shows the capture zones for a 180-degree funnel and a 90-degree funnel at 30, 60, and 90 degrees to the regional gradient. Both funnels have the same width, so the V-shaped funnel requires a greater length of cutoff wall and would be more expensive. The shapes of the capture zones immediately upstream of the gates are quite different in the two cases, although the widths are comparable well upstream of the funnel.

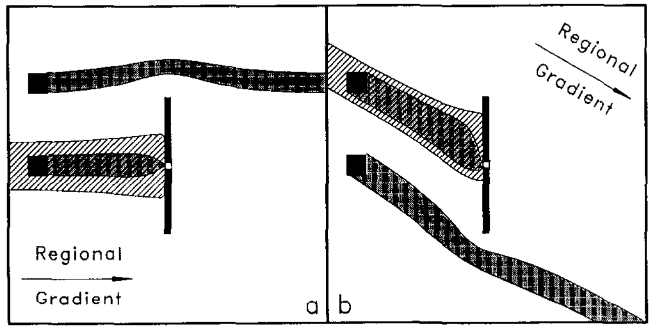

Fig. 11. Effect of the direction of the regional hydraulic gradient on ground-water plumes and capture zones.

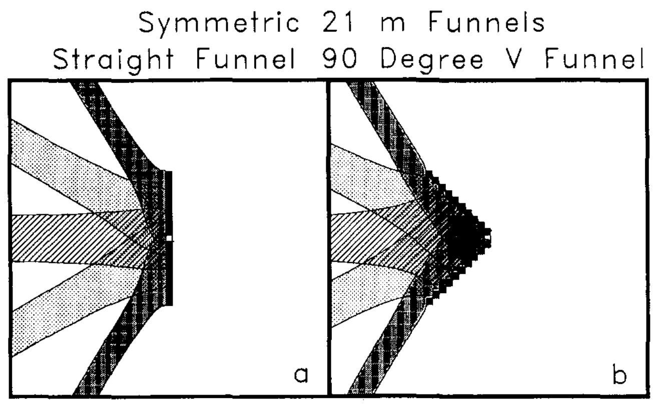

Fig. 12. Effect of orientation relative to the regional hydraulic gradient on capture zones of symmetric funnels.

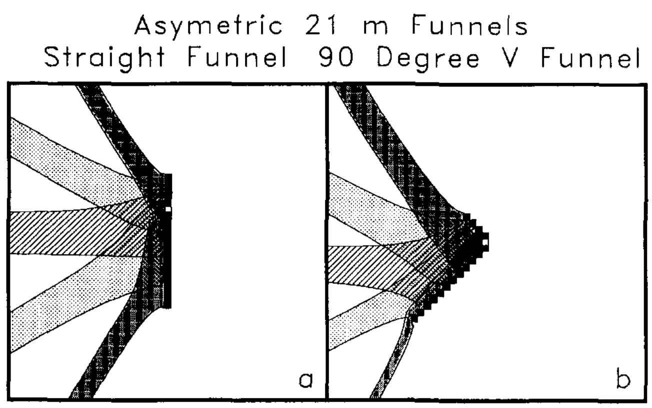

Fig. 13. Effect of orientation to the regional hydraulic gradient on capture zones of asymmetric funnels.

The capture zones of two asymmetric funnels are shown in Figure 13. In Figure 13a the gate is not centered in a 180-degree funnel, and the sides of the funnel have different lengths in Figure 13b. The capture zones are markedly off center from the gate for all orientations to the regional gradient. Also note that the capture zones for a given angle to the regional gradient, one clockwise and the other counterclockwise, are not mirror images of each other as they are for symmetric funnels. These features can be used by funnel designers to adjust the location of the capture zone in simulations where the gate cannot be constructed directly downgradient of the contaminant source zone due to access restrictions.

Ground-water flow directions fluctuate over time due to natural variations in recharge and discharge and anthropogenic effects such as changes in pumping rates. Rivett et al. (1992) and Farrell et al. (1993) report an annual variation in the ground-water flow direction at Canadian Forces Base Borden, Ontario, of approximately 30 degrees. Kerfoot and Horsley (1988) assumed a 60-degree annual variation in ground-water flow direction for simulating septic system plumes on Cape Cod. As flow directions fluctuate, the capture zone of a funnel-and-gate system, or an extraction well for that matter, also changes. Figures 11-13 illustrate that capture zones swing around as the regional gradient and ground-water flow directions fluctuate. Hence a contaminant source zone that is in the capture zone under some flow conditions could be outside of the capture zone under other conditions (Figure 11). Thus, it is important to consider a reasonable range of flow directions while designing funnel-and-gate systems.

Figure 14 shows capture zones for several funnel-and-gate systems in flow systems where the direction of the regional gradient fluctuates 30 degrees. The funnels are oriented perpendicular to the mean gradient direction. The hatched areas are the capture zones when the gradient is perpendicular to the funnel, and the stippled areas are the capture zones when the regional gradient is +/- 15 degrees from perpendicular. The dark, roughly triangular area immediately upstream of each gate is the region that falls within the capture zone throughout this 30-degree fluctuation in flow direction, and is called the *composite capture zone.* Contaminants that originate in the composite capture zone travel through the gate if the regional gradient varies no more than +/- 15 degrees from perpendicular, while contaminants that fall outside of this area do not travel through the gate under some conditions in this 30-degree range. Figure 14 shows V-shaped funnels with various apex angles. The area of the composite capture zone, from largest to smallest, is for funnels with apex angles of 127 degrees, 90 degrees, 180 degrees, and 53 degrees. Although the 180-degree funnel produces the widest capture zone for any single flow direction, it does not produce the largest composite capture zone if flow directions fluctuate.

U-shaped funnels with extensions that project upstream are shown in Figure 15. All of these configurations have the same length of cutoff wall in the funnel, so funnels with longer extensions are narrower. Two-meter extensions do not have a significant effect on the size of the composite capture zone compared to the funnel without extensions, 5-meter extensions generate the largest composite capture zone of the configurations show, and 8-meter extensions reduce the size of the composite capture zone.

The size and shape of the capture zone can also be modified by using multiple gates (Figure 16). The single-gate funnel (Figure 16a) is the same one shown in previous figures. A funnel with two gates approximately at the third points is shown in Figure 16b, while the gates are at the ends

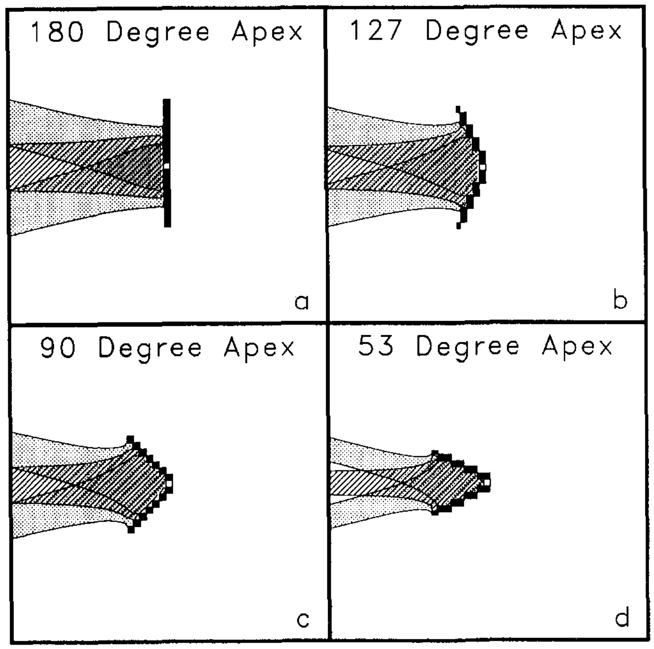

Fig. 14. Effect of 30-degree fluctuation in the direction of the regional hydraulic gradient on the capture zone of V-shaped funnels with two 10-m walls. The hatched area is the capture zone when the regional gradient is perpendicular to the funnel, and the stippled areas are the capture zones when the regional gradient is +/- 15 degrees from perpendicular to the funnel.

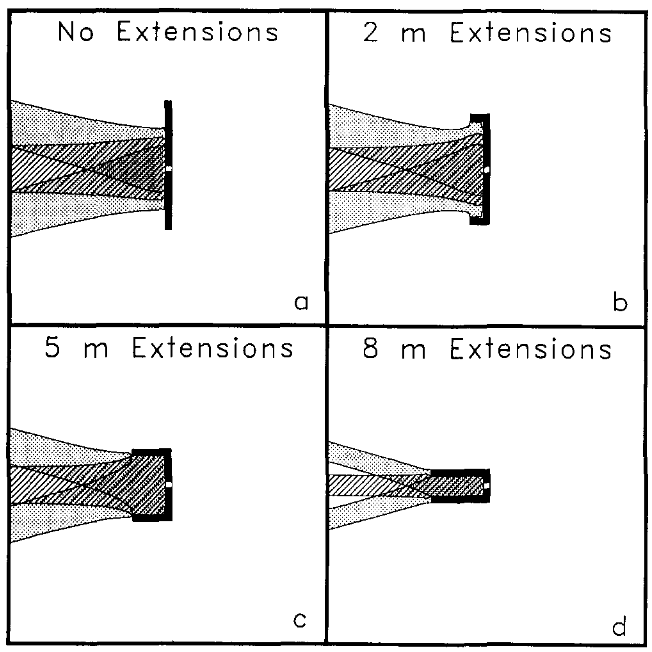

Fig. 15. Effect of 30-degree fluctuation in the direction of the regional hydraulic gradient on the capture zone of U-shaped funnels with a total wall length of 20 m. The hatched area is the capture zone when the regional gradient is perpendicular to the funnel, and the stippled areas are the capture zones when the regional gradient is +/- 15 degrees from perpendicular to the funnel.

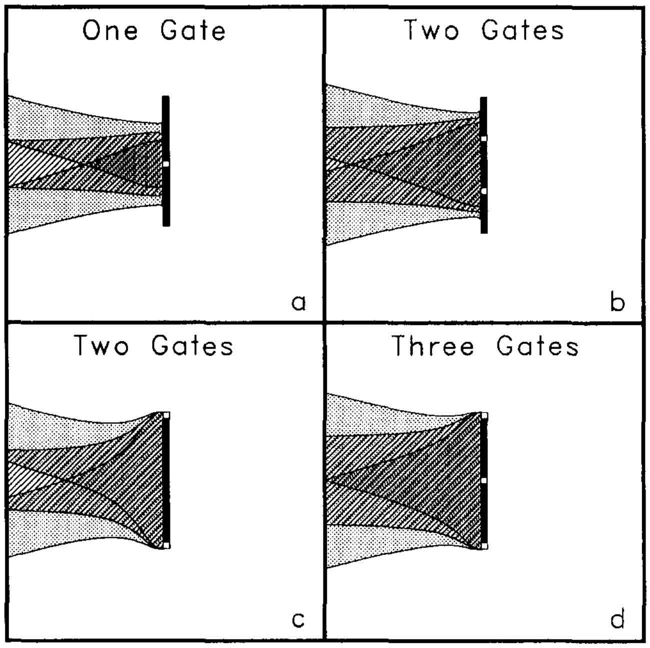

Fig. 16. Effect of 30-degree fluctuation in the direction of the regional hydraulic gradient on the capture zone of funnels with multiple gates. The hatched area is the capture zone when the regional gradient is perpendicular to the funnel, and the stippled areas are the capture zones when the regional gradient is +/- 15 degrees from perpendicular to the funnel.

of the funnel in Figure 16c. Gates are located at both ends and the middle of the funnel in Figure 16d. Multiple gates produce composite capture zones that are substantially larger than those generated by single gates. There is little difference in the size of the composite capture zone for a 30-degree variation in the regional gradient for the two dual gate configurations, but the composite capture zones have quite different shapes. Triple gates produce the largest composite capture zone of any configuration simulated. It is likely that a system that consists of many alternating gates and lengths of cutoff wall would produce the largest composite capture zone.

Retention Time

An important factor to consider while designing a funnel-and-gate system is the relationship between the residence time of contaminated ground water in the gate and the rate of the contaminant degradation reactions that occur in the gate. The mean retention time in the gate can be calculated by dividing the pore volume of the gate by the discharge through the gate. The discharge through the gate plotted on Figures 6-10 is for a one-meter vertical thickness of gate filled with a porous medium that has a porosity of 0.33. The systems simulated have discharges of approximately 0.1 to 0.7 m^3/d per meter vertical thickness of gate, and residence times of approximately 0.5 to 3.3 days.

The attenuation in concentration for first-order reactions with various half-lives is shown in Figure 17. If several orders of magnitude reduction in concentration are to be achieved in the systems that have retention times similar to the ones described here, then reactions with half-lives on the order of tenths of a day or less are required. Greater concentration ratios and slower reaction rates (i.e. longer reaction half-lives) require longer retention times.

For degradation processes that proceed by first-order reactions, the retention time necessary for reducing the concentration a given amount can be calculated using:

$$N_{1/2} = [\ln(C_{effluent}/C_{influent})]/\ln(1/2)$$

where $C_{effluent}$ is the concentration at the effluent, or downstream, side of the reactor; $C_{influent}$ is the concentration at the influent, or upstream, side of the reactor; and $N_{1/2}$ is the number of half-lives required.

As an illustrative example, we will calculate the residence time in an in situ reactor required for decreasing the concentration of two compounds with different reaction half-lives. Assume that hexachloroethane (HCA) enters a reactor at a concentration of 1000 μg/l, and the desired concentration at the downstream side of the reactor is 5 μg/l. The half-life observed by Gillham and O'Hannesin (1992) for HCA degradation in the presence of a particular porous medium that causes dehalogenation is 0.22 hours, or 0.0092 days. Substituting the appropriate values yields $N_{1/2} = 7.6$, indicating that a residence time of 7.6 half-lives would be necessary to decrease the concentration the specified amount. The required residence time in this case would be 0.07 days, or 1.7 hours.

Next, assume that the compound of interest is trichloroethylene (TCE) instead of HCA. The half-life of TCE degradation observed by Gillham and O'Hannesin (1992) is 13.6 hours, or 0.567 days. Decreasing the concentration of TCE from 1000 μg/l to 5 μg/l would again require 7.6 half-lives. However, since the half-life is longer, the required residence time is 4.3 days.

Greater attenuation can be achieved by either faster reaction rates or longer retention times. In some cases it may be possible to increase the reaction rate by increasing the surface area of the reactive material or using a higher proportion of reactive material in a reactive porous medium. Alternatively, longer retention times can be obtained by decreasing the discharge through a gate, which causes a

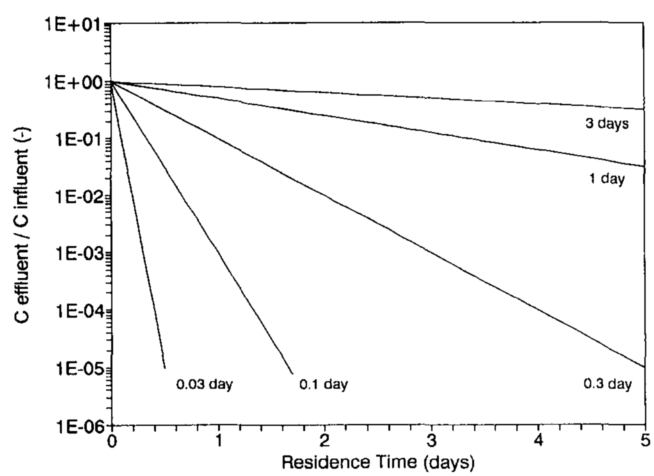

Fig. 17. Effect of residence time and reaction half-life on concentration decrease in the gate.

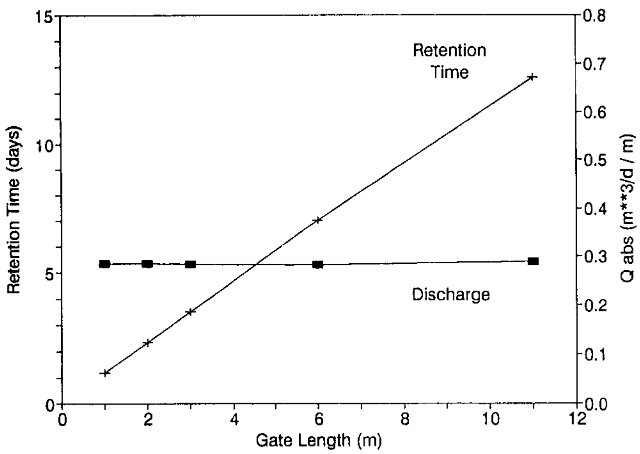

Fig. 18. Effect of gate length on discharge and retention time.

corresponding reduction in the size of the capture zone, or by increasing the pore volume of the gate. One way of increasing the pore volume of the gate while having only a minor effect on the discharge is to make the gate longer in the direction of flow through the gate, similar to the multiple reactor configuration shown in Figure 2. Figure 18 shows the discharge through the gate and retention time as a function of gate length. Gate length has a minor effect on discharge through the gate, so retention time increases almost linearly with gate length. The residence time required to attenuate concentrations by a specified amount can be achieved by making the gate as long as necessary.

A second application of long gates is for treating a plume that contains a mixture of contaminants. Several different types of in situ reactors could be placed in series, with each reactor treating a different class of contaminant (Figure 2b). For example, a series of in situ reactors might be used at an electroplating facility where a plume contains dissolved chlorinated hydrocarbons used for cleaning, and metals such as chromium from spent plating solutions. One reactor could treat the halocarbons using the metallic sand described by Gillham and O'Hannesin (1992) and the other could precipitate metals using the reactive sand described by Blowes and Ptacek (1992). Another example is a plume that contains chlorinated hydrocarbons such as trichloroethylene and solutes leached from petroleum products such as benzene, toluene, and the xylenes (BTX). The first reactor would be aerobic to enhance microbial degradation of BTX, and the second reactor would be anaerobic, with abiotic degradation using the metallic sand of Gillham and O'Hannesin (1992).

An established approach for isolating a contaminant source zone is to surround it with cutoff walls and pumping water from the interior of the enclosure so that ground water flows into, not out of, the enclosure. This approach provides effective containment of a contaminant source zone, but requires that a pump-and-treat system be operated indefinitely.

A similar approach that does not require operation of a pump-and-treat system is based on the funnel-and-gate system. The contaminant source zone is surrounded by cutoff walls, except that there is a gap filled with an in situ reactor in the downstream wall (Figure 2). The upstream wall deflects clean ground water around the contaminant source zone and reduces the discharge of ground water through the contaminant source zone. The walls substantially reduce the amount of water that comes into contact with the contaminant source zone but does not reduce it to zero. Water that enters the cell consists of precipitation that falls on the ground surface inside the cell and infiltrates, ground water that flows up through the bottom of the cell, and ground water that flows through the cutoff walls. Little water should flow through the walls if they were constructed properly. Virtually all of the water that enters the cell exist via the gate. The discharge through the gate is much smaller than it would be without an enclosure since most of the ground water that would flow through the contaminant source zone is deflected by the upstream cutoff wall. This configuration yields the greatest retention time for a given length of cutoff wall, and generates a capture zone that is insensitive to variation in ground-water flow direction.

Summary and Conclusions

Two-dimensional flow modeling of funnel-and-gate systems in a homogeneous, isotropic aquifer shows that the width of the capture zone produced by a funnel-and-gate system is proportional to the discharge through the gate. The discharge through the gate can be increased by increasing the width, length, and hydraulic conductivity of the gate, and the width of the funnel. For a given length of cutoff wall, the most efficient configuration in an isotropic aquifer is a funnel with sides 180 degrees apart, oriented perpendicular to the regional hydraulic gradient. However, other configurations have a larger capture zone in the immediate vicinity of the funnel. In settings where the direction of the regional hydraulic gradient fluctuates, the area that falls in the capture zone throughout the range of flow direction variation is strongly dependent on funnel configuration. Shapes other than a 180-degree funnel produce a larger composite capture zone throughout the range of flow direction variation.

Balance between maximizing the size of the capture zone for a gate and maximizing the retention time of contaminated ground water in the gate must be achieved. In general, capture zone size and retention time are inversely related. However, residence time can be easily increased without substantially affecting the capture zone by making gates longer in the direction parallel to flow. Alternatively, long residence times can be achieved by completely surrounding a contaminant source zone with cutoff walls, except for a gap that contains an in situ reactor in the downstream wall.

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