Optimum Hydraulic Conductivity to Limit Contaminant Flux Through Cutoff Walls

by J. F. Devlin and B. L. Parker[a]

Abstract

Cutoff walls are becoming increasingly attractive options for the control of solute migration from long-term sources of contamination. The main advantage of low permeability enclosures is that they restrict advective transport of solutes away from the source. However, with high concentration source zones surrounded by cutoff walls, there exists the potential for notable mass fluxes outward due to *diffusive transport*. This paper shows, through the use of the steady-state flux equations, that there is an optimal range of hydraulic conductivities for barrier materials which permit the outward diffusive flux to be counter balanced by an inward advective and dispersive flux. This concept of designing optimum contaminant containment using an inward advective flux to counter the outward diffusive flux is valid for sealable joint sheet pile walls, bentonite-slurry walls and clay liners, but not synthetic membrane materials with extremely low hydraulic conductivities. The effective diffusion coefficient for the common chlorinated organic solvents such as TCE in water-saturated clayey materials is approximately 1×10^{-6} cm^2/sec, resulting in an optimum hydraulic conductivity ranging from 1×10^{-6} to 1×10^{-8} cm/sec. This range in hydraulic conductivity is within the range of common barrier materials but not the lowest achievable. The steady-state concentration profile in a slurry cutoff wall can result in a substantial amount of contaminant mass stored within the wall which will need to be considered over the long term or dealt with during site remediation. Large inward advective fluxes reduce the total chemical mass stored within the low permeability barrier material.

Introduction

Pump and treat has traditionally been the basis for groundwater remediation at most contaminated sites. However, this approach often requires many years before contaminant concentrations in the aquifer fall permanently below cleanup standards. This inevitably leads to large volumes of ground water being pumped which require treatment at considerable expense, particularly when residual or pooled organic liquids are present as a subsurface "source zone" in the aquifer (Mackay and Cherry, 1989). One approach to reducing the volume of water pumped, while maintaining contaminant capture at the source area, is to surround the source with a cutoff wall of low hydraulic conductivity material. This prevents ground water from flowing through the source zone and might be of benefit to in situ remediation efforts within the source zone by enhancing the hydraulic control. Various materials have been used for containment of this sort, including synthetic and clay liners, clay slurry walls, and various types of steel sheet piling.

The main reason for surrounding a subsurface source zone with a cutoff wall is to prevent or minimize contaminant transport away from the source, i.e., to limit the advective flux of contaminants. It is generally believed that this is accomplished by creating cutoff walls having as low a value of hydraulic conductivity as possible. However, due to high concentrations of contaminants within the cutoff wall enclosure, diffusive fluxes that result from contaminant concentration gradients across the wall also need to be considered. The existence of diffusive fluxes through clay barriers such as cutoff walls, landfill liners, and caps has been established by several authors (Gray and Weber, 1984; Shackelford, 1988 and 1990; Mott and Weber, 1991; and Vita, 1994), who indicate that an outward flux due to diffusion can take place even when hydraulic gradients drive flow inward. Mott and Weber (1992) proposed the addition of fly ash to barriers to increase sorption and retard diffusion of low molecular weight organic compounds. However, this measure only affects the transit time of the contaminant front through the barrier, not the steady-state flux after breakthrough is complete.

Shackelford (1989) and Vita (1994) discuss opposing advective and diffusive fluxes through containment barriers in terms of barrier performance and design. In this paper, we take the analysis of diffusion against advection a step further by proposing to manipulate the inward advective flux to limit or avoid the outward diffusive flux. Opposing advective and diffusive fluxes across a barrier are illustrated in Figure 1. This diagram represents the conditions for a containment system where a lower hydraulic head is maintained inside a cutoff-wall enclosure where a high concentration source zone is contained which results in an outward diffusive flux. The direction of the two opposing fluxes is controlled by the respective gradients or driving forces. However, it is the relative magnitude of these fluxes which ultimately controls the amount of leakage through such barriers. The objective of this paper is to show that there is an optimum range for the hydraulic conductivity of the wall which, given other system parameters such as a specified rate of pumping within an isolated zone or a given hydraulic gradient across the cutoff wall, will result in an advective flux inward that will counter the diffusive flux outward. This balancing of fluxes could theoretically result in complete containment. Thus, the hydraulic conductivity of the barrier material is an important design parameter that can be used to achieve the desired degree of containment.

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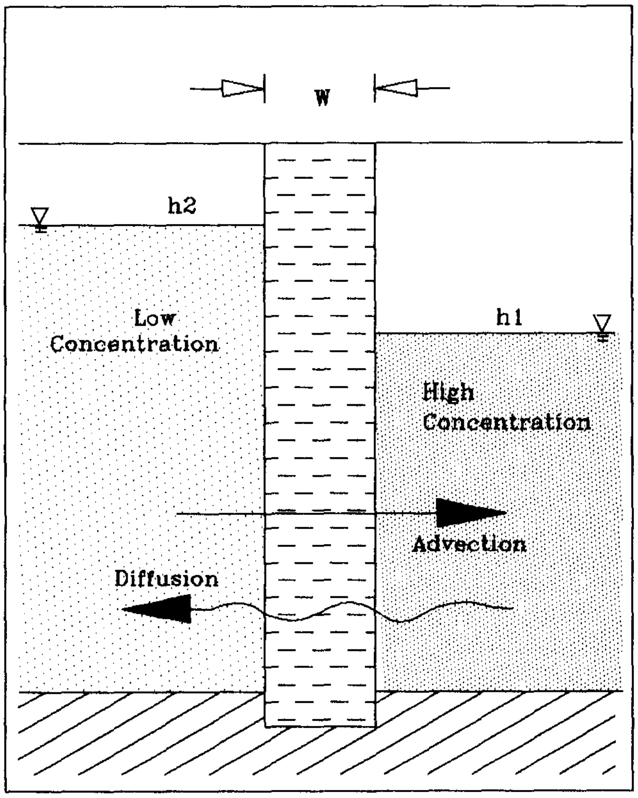

Fig. 1. Conceptualization of advective and diffusive fluxes in opposite directions across a cutoff wall.

The Optimal K Range

Consider a source zone pumped at some minimal rate, Q_o. With no low permeability enclosure isolating the source zone, the hydraulic capture provided by the minimal Q_o is insufficient to prevent advection of contaminants away from the site (case A, Figure 2). On the other hand, the installation of a very low permeability barrier around the site diverts ground-water flow away from the source zone causing advection through the source to be negligible. Under these conditions, pumping at Q_o inside the enclosure establishes a hydraulic capture zone across the entire enclosure. However, because the low permeability severely restricts the flow of water through the barrier, there is very little inward advective flux. Outward contaminant flux due to diffusion then takes place at a rate controlled only by the outward concentration gradient across the barrier (case B, Figure 2).

The two cases above illustrate that contaminants may escape from the source zone because either the enclosure permeability is too low to attain a sufficient inward advective flux or the permeability of the enclosure wall is too high, allowing outward advection in parts of the enclosure. Fortunately, the mechanisms of escape are different in these two extreme cases. By selecting an appropriate, intermediate value of hydraulic conductivity for the barrier, it is possible to design a system in which the two mechanisms operate against one another. Sufficient inward advective flux is thus permitted through the barrier to offset the outward diffusive flux (case C, Figure 2).

The effect of barrier hydraulic conductivity on contaminant flux is summarized conceptually in Figure 2. The total flux

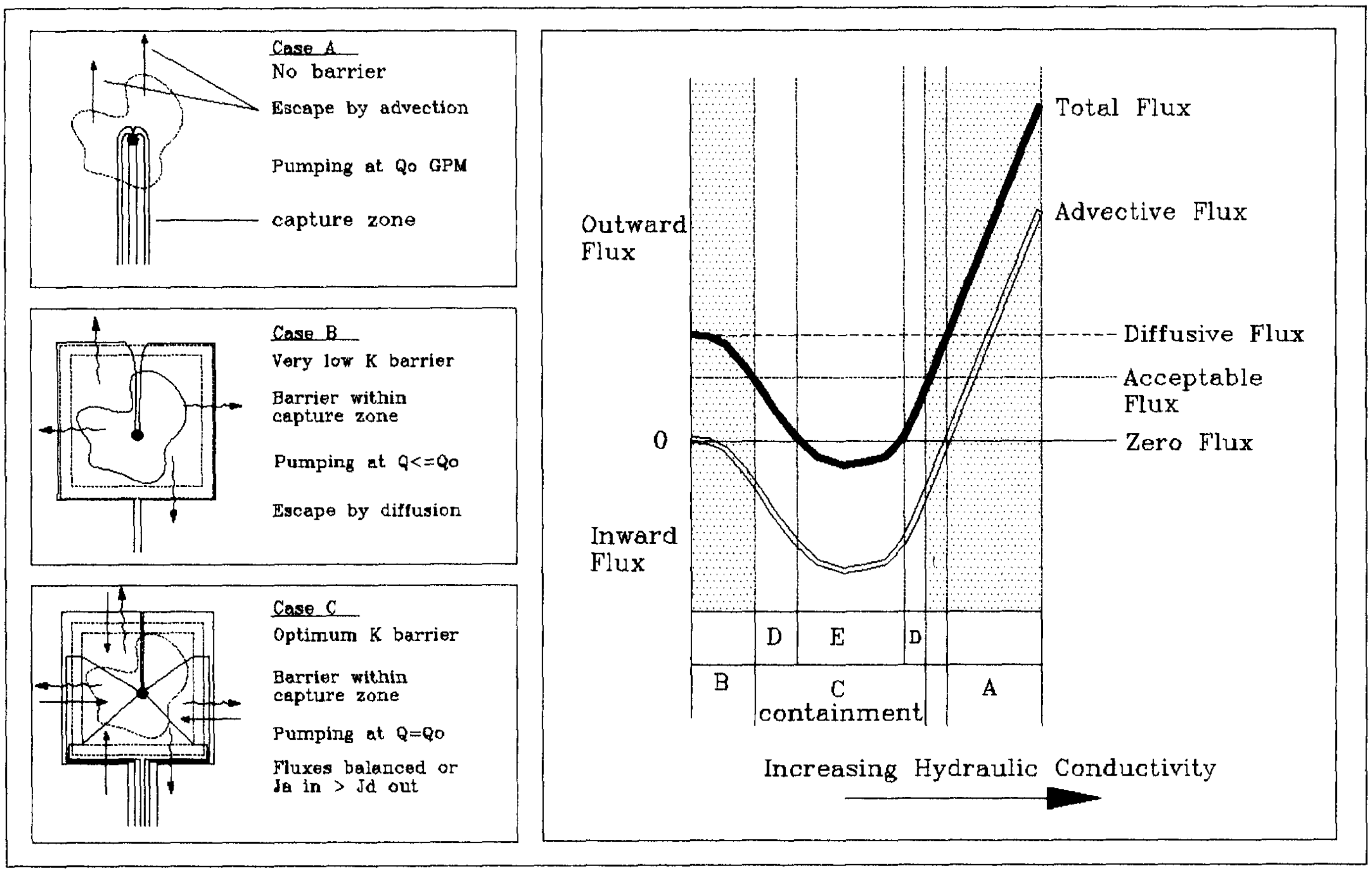

Fig. 2. Schematic representations of cases a, b, and c and a conceptual graph illustrating the relationship between contaminant flux and barrier wall hydraulic conductivity (K). The optimal range in K for containment is indicated, assuming a constant pumping rate is maintained in the source area.

consists of the sum of the advective and diffusive fluxes. An acceptable flux is defined as the maximum outward contaminant flux permissible in order to achieve a specified ground-water quality objective outside the wall. The shaded regions of the graph represent conditions under which contaminant mass is escaping the source area. The three cases described above are indicated as regions A, B, and C in the graph, respectively. The optimal K range for the barrier wall is in the zone over which containment is realized. Containment (region C) is considered to have been achieved when the total flux is either inward (region E) or outward below the acceptable limit (region D). The latter condition reinforces an issue mentioned earlier: within regions D and most of B, the advective flux is inward, though the total flux is outward, due to diffusion. Thus, inward gradients are necessary but are not, by themselves, a guarantee of complete containment.

Contaminant Fluxes in Porous Media Barriers

As discussed above, the two chief mechanisms for contaminant transport in porous media are advection and diffusion. Advective transport dominates in cases where the ground-water velocity is relatively high while diffusive transport dominates in cases where there is no flow, or where the flow rate is very low (Perkins and Johnson, 1963). In this paper, the term advective flux will refer to the purely advective component plus the mechanical dispersion flux of a solute as given by,

$$J_a = Cq - \phi D_m \frac{\partial C}{\partial x} \qquad D_m = \alpha \frac{q}{\phi} \tag{1}$$

where J_a = advective flux $[M/(L^2t]$, C = contaminant concentration (M/L^3), q = Darcy flux (L/t), D_m = mechanical dispersion coefficient (L^2/t), α = dispersivity (L), and ϕ is the porosity of the saturated porous medium. The magnitude of the advective flux can be controlled by changing the hydraulic conductivity of the medium or the driving force (the hydraulic gradient). The practical way to minimize advection through an isolated volume is to minimize the hydraulic conductivity of the surrounding barrier walls. This is evident from Darcy's law (for steady-state flow across the barrier).

$$q = -Ki \qquad i = \frac{(h_2 - h_1)}{w} \tag{2}$$

where K = hydraulic conductivity (L/t), i = gradient across the wall (dimensionless), w = cutoff wall thickness (L), h_2 = hydraulic head outside cutoff wall (L), and h_1 = hydraulic head inside cutoff wall (L). This reasoning forms the basis of the existing guidelines for cutoff wall permeabilities. The State of California requires that cutoff walls at waste disposal sites be constructed with hydraulic conductivities not more than 1×10^{-6} cm/s. Where such regulations do not exist, it is common practice to adopt the U.S. EPA requirement for soil based landfill liners, which specifies a hydraulic conductivity of less than 1×10^{-7} cm/s (Starr et al., 1991; Johnson et al., 1989).

In clayey materials, where hydraulic conductivities are low, diffusion is the principal mechanism of solute transport (Goodall and Quigley, 1977, Johnson et al. 1989). At steady state, the diffusive flux in saturated clay is expressed by Fick's first law (Crank, 1975),

$$J_d = -\phi D_e \frac{\partial C}{\partial x} \qquad D_e = D_o \tau \tag{3}$$

where J_d = diffusive flux $[M/(L^2t)]$, D_e = effective diffusion coefficient (L^2/t), D_o = free solution diffusion coefficient (L^2/t), τ = apparent tortuosity (dimensionless), and x = distance from source (L). In addition to the "effective" and "free solution" diffusion coefficients defined above, a "reactive" diffusion coefficient may be defined as $D' = D_e/R$, where R is the retardation factor. The inclusion of R in the diffusion coefficient affects the transit time of the solute front through the barrier, not the steady-state diffusive flux. Retardation also affects the storage capacity of the wall, a point which will be revisited later.

The effective diffusion coefficient is a function of the porous medium and the solute. Consequently, as one might expect, it varies over one to two orders of magnitude. Table 1 lists some species and their reported effective diffusion coefficients. Most of the values in Table 1 apply to diffusion in natural clay deposits. However, the properties of the voids of natural clays and consolidated soil-bentonite backfill mixtures, which are used in cutoff wall construction, are likely to be similar (Mott and Weber, 1991). It seems reasonable to assume that the diffusion coefficients for solutes in these saturated media would also be similar. For the purposes of this analysis, the nonpolar organic compounds are of greatest interest, so D_e values of 1×10^{-6} and 1×10^{-8} cm^2/s were used for the calculations which follow.

The apparent tortuosity, τ, may be simply defined as the ratio of the effective diffusion coefficient to the free solution diffusion coefficient. It refers to a constant between 0 and 1 which accounts for the effect of the porous medium on diffusion. For the purposes of this paper, the effective diffusion coefficient does not include the retardation factor which accounts for solute partitioning to solids or the porous medium porosity which accounts for the reduction in the cross-sectional surface area available for diffusive flux. Freeze and Cherry (1979) state that the magnitude of τ ranges from 0.01 to 0.5 depending on the porous medium. For the clay till deposits studied by Johnson et al. (1989), τ was estimated to be between 0.20 and 0.33. Shackelford and Daniel (1991) estimated τ to be 0.24 for lufkin clay and between 0.24 and 0.53 for kaolinite.

Typical values for effective porosity of clays are in the range 0.33 to 0.52 and are often equal to or well approximated by the total porosity (Illgenfritz et al., 1988; Johnson et al., 1989; Van Rees et al., 1991); 0.40 is considered to be a generally representative value and is used in all calculations presented here.

The general equation used to describe the total, steady-state flux of contaminants in a porous medium (J_T) due to advection, mechanical dispersion, and diffusion with the concentration and hydraulic gradients in the same direction is generally written as:

$$J_T = C\,q - \phi\, D_m \frac{\partial C}{\partial x} - \phi\, D_e \frac{\partial C}{\partial x} \tag{4}$$

For the system depicted in Figure 1, with the hydraulic gradient in the opposite direction to the concentration gradient, the sign for the diffusive flux term changes relative to the advective and dispersive flux terms as presented in equation (5).

Table 1. Effective Diffusion Coefficients, Calculated or Assumed, for Various Species in Previous Studies

Species	D_e *(cm²/s)*	*Porous medium*	*Reference*
Tritium	1.1×10^{-5} to 2.3×10^{-5}	Littoral sediments	Van Rees et al., 1991
Chloride	5×10^{-6}	Clay till, natural	Johnson et al., 1989
Chloride and sodium	1×10^{-6} to 6×10^{-6}	Clay liner, natural	Quigley and Rowe, 1987
Nonionic solutes	9×10^{-9} to 5×10^{-7}	Clay liner, natural	Ilgenfritz et al., 1988
Hydrophobic organics	2.9×10^{-6} to 3.5×10^{-6}	Clay till, natural	Myrand et al., 1992
Hydrophobic organics	3.2×10^{-6} to 8.8×10^{-6}	Clay till, natural	Johnson et al., 1989
Hydrophobic organics	2.4×10^{-6} to 2.8×10^{-6}	Bentonite mixtures	Mott and Weber, 1991

$$J_T = C\,q - \phi\,D_m \frac{\partial C}{\partial x} + \phi\,D_e \frac{\partial C}{\partial x} \qquad (5)$$

In order to achieve complete containment, as defined above, the outward diffusive flux must be balanced by an inward advective flux. This is done mathematically by setting the total flux J_T equal to zero and rearranging equation (5):

$$-\phi\,D_e \frac{dC}{dx} = C\,q - \phi\,(\alpha v)\frac{dC}{dx} \qquad (6)$$

where v = the average linear ground-water velocity (L/t) ($v = q/\phi$). Equation (6) rearranges to,

$$\frac{dC}{C} = \frac{v dx}{[(\alpha v) - D_e]} \qquad (7)$$

integrating both sides yields,

$$C = C_o e^{[vx/(\alpha v - D_e)]} \qquad (8)$$

where C_o = solute concentration inside the wall (M/L^3). and C = solute concentration at the outside edge of the cutoff wall (M/L^3). Equation (8) is only useful over the range $0 < v < D_e/\alpha$. This corresponds to regions B and D in Figure 2. At $v < 0$, advection and diffusion are operating in the same direction (A in Figure 2). At $v > D_e/\alpha$ advection is predominant and no diffusion into the cutoff wall takes place (E in Figure 2). At $v = D/\alpha$ the fluxes are balanced and the total flux through the barrier is zero. This corresponds to the line dividing regions D and E in Figure 2.

Equation (8) can be rearranged several ways to provide relations which can be used in cutoff wall design and can provide insights into cutoff wall performance. For example, letting w be the thickness of the cutoff wall (set $w = |\Delta x|$), it is possible to calculate the thickness which would be necessary to prevent breakthrough of a contaminant at some performance standard C/C_o,

$$w = \frac{\ln(C/C_o)\,(\alpha v - D_e)}{v} \qquad (9)$$

Since K is related to v through Darcy's Law,

$$v = \frac{q}{\phi} = -\frac{K(h_2 - h_1)}{\phi w} \qquad (10)$$

Equation (8) relates K to a steady-state concentration profile through a cutoff wall where advective and diffusive fluxes are balanced. Rearranging equation (8) and combining it with equation (10), it is possible to calculate the gradient $i = [h_2 - h_1)/w]$ required across a cutoff wall of thickness w and hydraulic conductivity K to overcome the diffusive flux of the solute (as defined for the conditions presented in Figure 1),

$$i = -\frac{\phi\,D_e \ln(C/C_o)}{K[w - \alpha \ln(C/C_o)]} \qquad (11)$$

The hydraulic gradient i will limit C/C_o at the outside edge of the cutoff wall to some performance standard.

Estimating the Lower Limits of Hydraulic Conductivity for Porous Media Cutoff Walls

The equations above were used to calculate a family of curves relating the steady-state gradient across a hypothetical cutoff wall 1 m thick, the hydraulic conductivity of the wall, and the normalized concentrations at the outside edge of the cutoff wall. The calculations have been performed for two cases: (a) $D_e = 1 \times 10^{-8}$ cm²/s (Figure 3), and (b) $D_e = 1 \times 10^{-6}$ cm²/s (Figure 4).

To illustrate the use of Figures 3 and 4, a practical example is helpful. Consider the case where a contaminant, such as trichloroethene (TCE), exists throughout the source area of a spill site in a saturated aquifer 4 m thick at a concentration near its solubility (1,100 mg/l). Suppose that the cutoff wall thickness is 1 m and the maximum allowable concentration of TCE outside the source area is 0.005 mg/l. The relative concentration at the outside face of the cutoff wall (C/C_o) is therefore limited to $0.005/1100 = 4.5 \times 10^{-6}$. According to Figure 3, case (a), the outward diffusive flux may be counter balanced by an inward advective flux for a K value of 1×10^{-6} cm/s (the upper regulatory limit) by maintaining a gradient across the wall of 4.6×10^{-4}. If this gradient is held constant but the K of the barrier is reduced to 1×10^{-7} cm/s, the outward flux of contaminants would increase due to diffusion and the relative concentration at outer edge of the cutoff wall would increase to about 0.3, at steady state, four orders of magnitude above the limit. To limit the concentration at the outside face of the wall to 0.005 mg/l, the gradient would need to be 4.6×10^{-3}. It is worth noting that these calculations provide the concentration at the outside face of the cutoff wall and do not evaluate the resultant concentration within the outside aquifer itself.

If the hydraulic conductivity of the wall is reduced to 1×10^{-10} cm/s, the gradient must be maintained at 4.6 to prevent the outer edge concentration from rising above the limit. Since the aquifer is 4 meters deep and the wall is only 1 meter thick, this gradient cannot be achieved.

The infeasibility of achieving large enough gradients to counter the diffusion flux is demonstrated more strongly using case (b) where $D_e = 1 \times 10^{-6}$ cm^2/s. With higher diffusion coefficients, diffusive fluxes are larger, and larger advective fluxes are required to prevent the solute from escaping. The effective diffusion coefficients for the common chlorinated organic solvents in saturated clayey materials are approximately 1×10^{-6} cm^2/s. Therefore the results presented in Figure 4 [case (b)] are most relevant for this class of contaminants (Parker et al. 1994). For example, a 1-m thick wall with a K of 1×10^{-6} cm/s only contains the TCE if a gradient of 4.6×10^{-2} is maintained. However, for hydraulic conductivity values less than 1×10^{-8} cm/s, gradients greatly exceeding 10 are required.

Further analysis of Figure 4 reveals that a gradient of 1, which is considered reasonable and achievable in most cases, is sufficient to contain TCE, for a case (b) scenario, when the hydraulic conductivity of the cutoff wall is 5×10^{-8} cm/s or greater. The most common type of wall used to contain source zones is the standard soil-bentonite slurry wall. These walls are generally constructed to be 0.75-1.0 m thick and can have a hydraulic conductivity of 1×10^{-5} to 1×10^{-10} cm/s, depending on how much bentonite is added to the slurry. The calculations presented in this paper show that the optimum hydraulic conductivity for slurry-type cutoff walls is not the lowest value achievable, if the desire is to minimize the outward flux of contaminants. Thus, the hydraulic conductivity of the barrier material can be an important design parameter for achieving the desired level of containment and an intermediate value of hydraulic conductivity for barrier materials can result in the lowest outward flux.

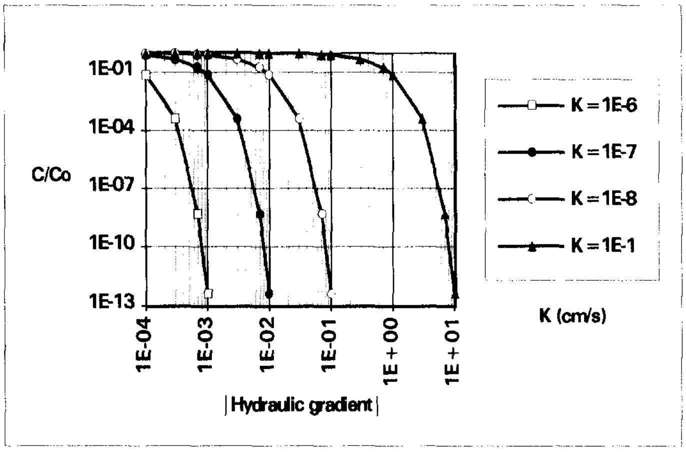

Fig. 3. The dependence of relative concentration at the outer edge of a cutoff wall on the gradient across the wall and the hydraulic conductivity of the wall. The curves were calculated assuming $D_e = 1 \times 10^{-8}$ cm^2/s and the wall thickness, w, = 1 m.

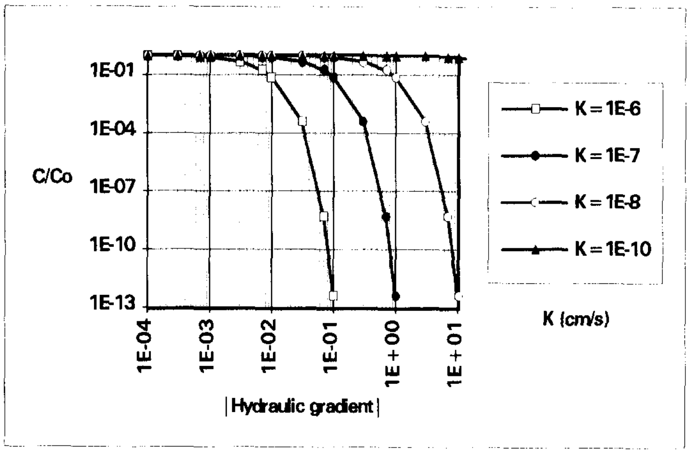

Fig. 4. The dependence of relative concentration at the outer edge of a cutoff wall on the gradient across the wall and the hydraulic conductivity of the wall. The curves were calculated assuming $D_e = 1 \times 10^{-6}$ cm^2/s and the wall thickness, w, = 1 m.

The equations and examples above inherently assume that there is no physicochemical alteration of the clay barrier due to interactions with the chemicals being contained. The reader should be aware that under some conditions these kinds of interactions are possible, and may enhance contaminant migration through a barrier. A review of clay-chemical interactions is beyond the scope of this paper, but further information may be obtained from Middleton and Cherry (1994) and Shackelford (1994) who summarize the status of research findings regarding various waste/leachate and clay permeability tests.

Estimating the Solute Mass Stored in a Cutoff Wall at Steady State

If the ultimate goal of a remedial effort is to remove the maximum amount of contaminant possible from the subsurface, it is important to consider that part of the total mass which has diffused into the cutoff wall. Contaminant mass in the cutoff wall can later diffuse out, extending cleanup times. The less permeable the cutoff wall is, the more dependent the recovery of solute mass from the wall will be on the diffusion rate.

The mass stored in the water phase of a cutoff wall, after a steady-state profile has developed, may be calculated by integrating equation (8) over the wall thickness and accounting for the porosity,

$$\begin{aligned} M &= A\phi \int_0^w C_o e^{[vx/(\alpha v - D_e)]}\, dx \\ M &= \frac{A\phi C_o(\alpha v - D_e)}{v} \left(e^{[vw/(\alpha v - D_e)]} - 1\right) \end{aligned} \tag{12}$$

where A = the total area of the cutoff wall (L^2). This relationship assumes a uniform profile throughout the wall, and is only defined over the useful range of equation (8), $0 < v < D_e/\alpha$. If sorption takes place, additional mass resides on the solid phase. Assuming unit wall height and length (set A = 1), and uniform equilibrium sorption according to a linear isotherm, this quantity may be calculated from,

$$\begin{aligned} \text{Mass on solids} &= (1 - \phi)\, \rho_s \int_0^w C_s dx \\ &= \rho_b Kd \int_0^w C_w dx \end{aligned} \tag{13}$$

where ρ_s = dry solid phase density (M/L^3), ρ_b = dry bulk density (M/L^3), Kd = partition coefficient of the contaminant between the water and solid phases (L^3/M), C_s = concentration of contaminant on the solid phase (M/M), and C_w = concentration of the contaminant in the water (M/L^3). Taking this into account, a more general form of equation (12) may be derived:

$$\text{Mass total} = \text{Mass}_{\text{water}} + \text{Mass}_{\text{solids}}$$

$$= \phi \int_0^w C_w\,dx + \rho_b Kd \int_0^w C_w dx \tag{14}$$

$$= \phi \int_0^w C_w dx[1 + (\rho_b/\phi)\,Kd]$$

$$= R\phi \int_0^w C_w dx$$

which, when the integral is solved, and wall area is no longer restricted, becomes:

$$M = \frac{AR\phi C_o(\alpha - D_e)}{v}\left(e^{[vw/(\alpha v - D_e)]} - 1\right) \tag{15}$$

The equation indicates that as advection is restricted, an overall higher, steady-state concentration profile develops, hence more mass is present in the wall (Figure 5). This also permits a higher concentration on the outside of the containment system and into the ground-water flow system. Figure 5 illustrates the relationship between the hydraulic gradient across a barrier and the contaminant mass stored in the barrier at steady state. The maximum hydraulic gradient driving flow inward, [(ho-h3)/w], corresponds to the least mass stored in the barrier (see the shaded area below line C3-Co). As the hydraulic gradient is reduced, [ho-h1)/w], the amount of stored mass in the barrier increases due to outward diffusion (see shaded region below line C1-Co).

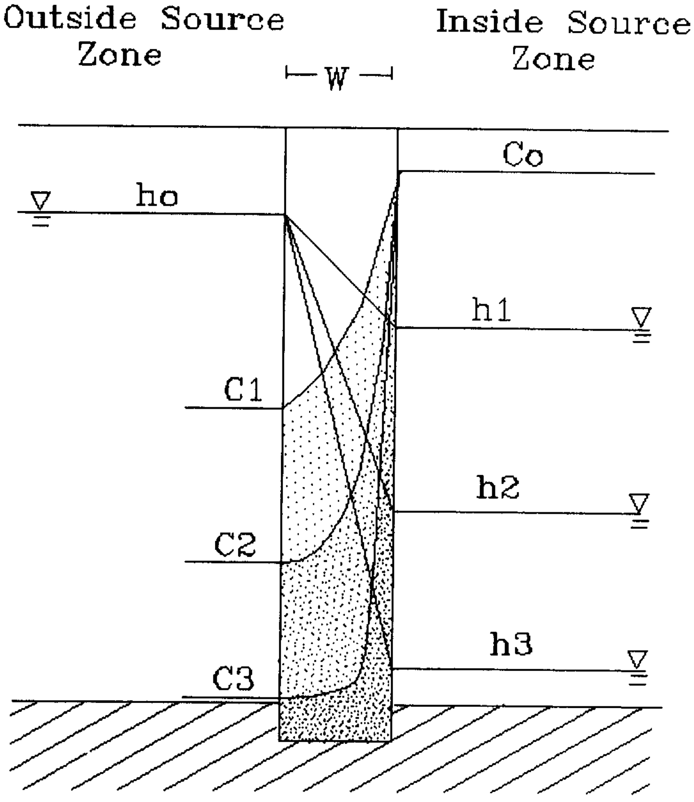

Fig. 5. A conceptual representation of the steady-state concentration profiles in a cutoff wall and the hydraulic gradients under which they were produced. Profile Co-C1 corresponds to gradient (ho-h1)/w; profile Co-C2 corresponds to gradient (ho-h2)/w, etc. The relative amounts of mass stored in the wall are indicated by the shaded areas. The largest amounts of stored mass correspond to the lowest gradients and the highest concentration profiles.

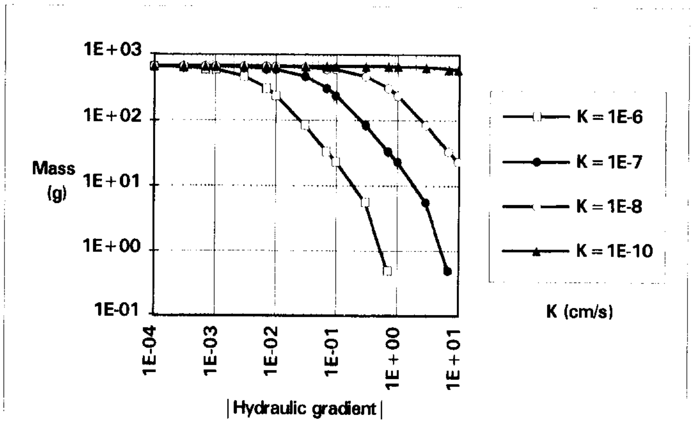

Fig. 6. The dependence of solute mass stored in the cutoff wall on the gradient across the wall and the hydraulic conductivity of the wall. The curves were calculated assuming Co = 1,100 mg/l, $D_e = 1 \times 10^{-6}$ cm^2/s and the wall thickness, w, = 1 m.

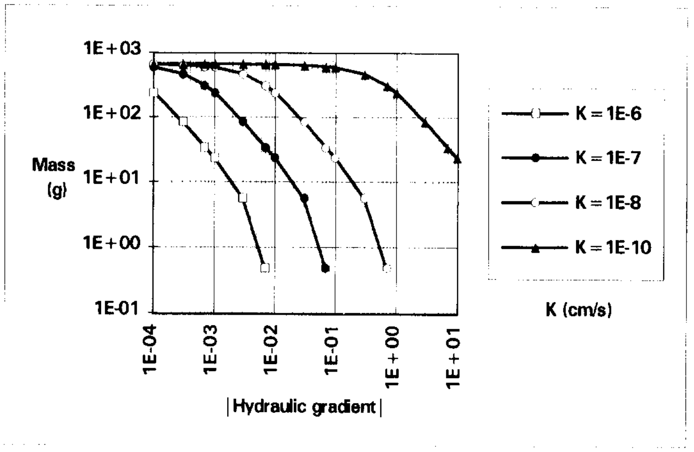

Fig. 7. The dependence of solute mass stored in the cutoff wall on the gradient across the wall and the hydraulic conductivity of the wall. The curves were calculated assuming Co = 1,100 mg/l, $D_e = 1 \times 10^{-8}$ cm^2/s and the wall thickness, w, = 1 m.

Figures 6 and 7 were produced on the basis of equation (15). Referring once again to the TCE example and assuming TCE has a retardation factor of 1.5 and an effective diffusion coefficient of 1×10^{-6} cm^2/s, Figure 6 indicates that the mass of TCE stored in a cutoff wall with $K = 1 \times 10^{-6}$ cm/s and a hydraulic gradient of 4.6×10^{-4} [case (b)], is about 620 grams per square meter of wall area. This is equivalent to 0.4 liters of TCE per cubic meter of cutoff wall for the 1 meter thick cutoff wall scenario. If the gradient is increased to 4.6×10^{-2}, the mass stored is reduced to about 54 g/m^2 of wall area. Higher gradients reduce the mass stored even further. When the hydraulic conductivity of the wall is very small ($K = 1 \times 10^{-10}$ cm/s for example) a gradient as large as 5 fails to substantially limit the mass stored. Figure 7 shows that by reducing the diffusion coefficient from 10^{-6} to 10^{-8} cm^2/s, the mass stored in the barrier is reduced from 620 g/m^2 to 50 g/m^2 of wall, when $K = 1 \times 10^{-6}$ cm/s and $i = 4.6 \times 10^{-4}$.

Implications for Other Barrier Materials

In addition to clay, high-density polyethylene (HPDE) is a material used in cutoff walls and liners. HPDE is thought to be highly effective for waste and chemical containment due to its extremely low hydraulic conductivity (1×10^{-13} cm/sec), which renders it practically impermeable to ground-water flow except for leaks due to imperfect seams, rips, or tears created during emplacement (Vita, 1994). HPDE, like most plastics, is porous at the microscopic scale. Diffusion coefficients for various polymer membranes can be obtained from the chemical engineering literature and typically range from 1×10^{-8} to 1×10^{-10} cm^2/s (Hines and Maddox, 1985). The sheets of HDPE are thin (2 to 6 millimeters thick) and therefore, concentration gradients from the inside to the outside face of an enclosure are two to three orders of magnitude larger than those across a slurry wall. Inward advective fluxes across HDPE membranes, for diffusive flux control, cannot be established since HDPE is practically impermeable to ground-water flow. As a result, these kinds of barriers are especially susceptible to contaminant leakage due to diffusion.

A new type of barrier for creating enclosures around source zones is sealable joint steel sheet piles (SJSP) (Starr et al., 1991). SJSP are made with joints that can be sealed with a polymer grout, cement grout, or bentonite slurry, which makes the bulk hydraulic conductivity of the barriers much less than that of conventional steel sheet piling. The only significant porous zones along the face of a SJSP enclosure are the joints through which solutes can diffuse. The magnitudes of the parameters affecting diffusive fluxes through the sealed sheet pile joints are presented below using example calculations for a square containment structure enclosing a 10 m by 10 m area extending 6 m in depth in a saturated porous medium. For this example, the sheet pile enclosure has 80 sealed joints along the 40-m perimeter. The cross-sectional width of the joints is assumed to be 0.5 cm. Therefore, the cross-sectional area over which diffusion can take place in the SJSP cell is a factor of 100 less than an equivalent sized slurry wall. However, the concentration gradient across the sealed joint is larger by a factor of 10, assuming the effective length of the path through the joint is approximately 10 cm. As with slurry walls, it may be desirable to design an inward advective flux to control an outward diffusive flux through the sealed joints in SJSP cutoff walls. Therefore, joint sealants can be selected to provide optimum containment by balancing the advective and diffusive fluxes similar to the slurry wall scenario previously discussed. However, the total mass flux leaving the containment zone through SJSP is much less than that for slurry walls or HDPE walls due to reduction in surface area. Also, mass storage within the SJSP wall is substantially reduced.

Plume Geometry Associated with Cutoff Walls Leaking Contaminants by Diffusion

If the diffusion of solutes through the cutoff wall material is not prevented by establishing adequate inward advection, contamination will eventually migrate through the barrier and into the surrounding ground water where it follows the ground-water flow paths. This effect was demonstrated using the particle tracking program FLOWPATH by Franz and Guiger (1990) (Figure 8). Particles were released around the perimeter of the low permeability wall and tracked to steady state. The resulting advective plume is seen to be extremely narrow and might be mistaken for a leak in the barrier wall. In addition, since the streamtubes immediately next to the barrier receive the majority of solute diffusing from the cutoff wall, the resulting contaminant plume could contain unacceptably high concentrations of solute in spite of the fact that the leakage rate is diffusion controlled.

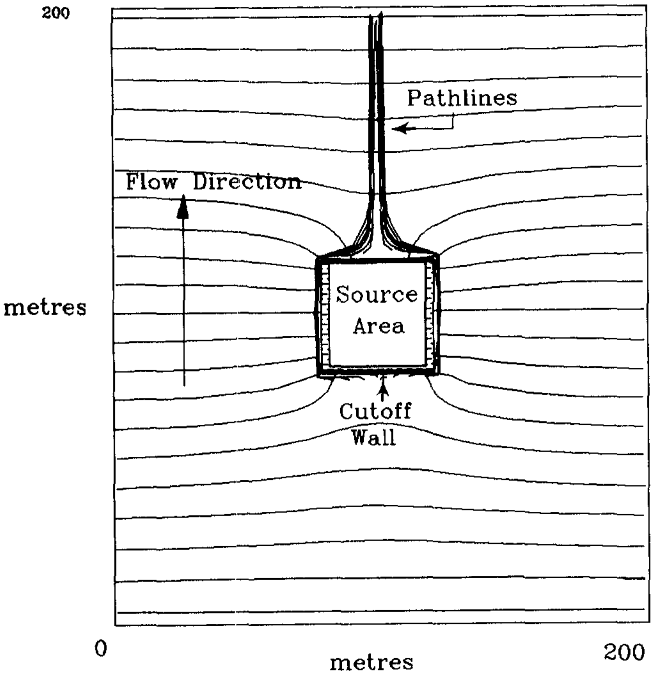

Fig. 8. Simulated equipotentials and particle paths for a steady-state plume produced by solute leakage from the entire perimeter of a cutoff wall.

Summary and Conclusions

Placement of low permeability enclosures around source zones is becoming a common remedial action at ground-water contamination sites. These enclosures are intended to limit or prevent contaminant flux from the source zones. However, in standard design procedures the goal is to limit the advective flux only. Our analysis indicates that the diffusive flux must also be considered given the nature of high concentration source zones. The escape of contaminants from enclosures is not prevented or even minimized by achieving exceptionally low hydraulic conductivities.

This work has shown that, for a given pumping rate within an enclosure, there exists an optimal value of hydraulic conductivity for the surrounding barrier walls where outward diffusive fluxes can be balanced by inward advection and dispersion. Hydraulic conductivity is a critical design parameter for optimizing the cutoff wall to achieve the desired degree of containment. If an enclosure is installed with a permeability which is too low, solutes will eventually diffuse through the walls and create a plume that may have unacceptably high contaminant concentrations. This is likely to happen when HDPE or other plastic membranes are used in the cutoff wall construction. Thus, the optimum hydraulic conductivity may not be the lowest hydraulic conductivity attainable.

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