&EPA Pump-and-Treat Ground-Water Remediation

A Guide for Decision Makers and Practitioners

1. Introduction to Pump-and-Treat Remediation

Pump-and-treat is one of the most widely used ground-water remediation technologies. Conventional pump-and-treat methods involve pumping contaminated water to the surface for treatment. This guide, however, uses the term pump and treat in a broad sense to include any system where withdrawal from or injection into ground water is part of a remediation strategy. Variations and enhancements of conventional pump and treat include hydraulic fracturing as well as chemical and biological enhancements. The pump-and-treat remediation approach is used at about three-quarters of the Superfund sites where ground water is contaminated and at most sites where cleanup is required by the Resource Conservation and Recovery Act (RCRA) and state laws [National Research Council (NRC), 1994]. Although the effectiveness of pump-and-treat systems has been called into question (Sidebar 1), after two decades of use, this approach remains a necessary component of most ground-water remediation efforts and is appropriate for both restoration and plume containment.

This guide provides an introduction to pump-and-treat ground-water remediation by addressing the following questions:

- When is pump and treat an appropriate remediation approach?

- What is involved in "smart" application of the pump-and-treat approach?

- What are tailing and rebound, and how can they be anticipated?

- What are the recommended methods for meeting the challenges of effective hydraulic containment?

- How can the design and operation of a pump-and-treat system be optimized and its performance measured?

- When should variations and alternatives to conventional pump-and-treat methods be used?

By presenting the basic concepts of pump-and-treat technology, this guide provides decision-makers with a foundation for evaluating the appropriateness of conventional or innovative approaches. An in-depth understanding of hydrogeology and ground-water engineering is required, however, to design and operate a pump-and-treat system for ground-water remediation. Readers seeking more information on specific topics covered in this booklet should refer to the U.S. Environmental Protection Agency (EPA) documents listed at the end of this guide (Section 9).

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Sidebar 1
Changing Expectations for the Pump-and-Treat Approach

Pump-and-treat systems for remediating ground water came into wide use in the early to mid-1980s. By the early 1990s, evaluations by EPA (Keely, 1989; U.S. EPA, 1989; Haley et al., 1991) and others (Freeze and Cherry, 1989; Mackay and Cherry, 1989) called into the question the performance of pump-and-treat systems. The general "failure" of the pump-and-treat approach was identified as its inability to achieve "restoration" (i.e., reduction of contaminants to levels required by health-based standards) in 5 to 10 years, as anticipated in the design phase of projects. Although a variety of factors contributed to this shortcoming, tailing and rebound (Section 4) represented the major barrier to achieving remediation goals. Pump-and-treat systems were criticized more pointedly by Travis and Doty (1990), who asserted as a "simple fact" that "contaminated aquifers cannot be restored through pumping and treating."

Expectations for the effectiveness of pump-and-treat technology, however, may have been too high. Ground-water scientists and engineers generally agree that complete aquifer restoration is an unrealistic goal for many, if not most, contaminated sites. Nonetheless, further experience with pump-and-treat systems indicates that full restoration at some sites with relatively simple characteristics is possible; moreover, at many sites, full restoration of ground-water quality can be achieved for part of a site (NRC, 1994). For example, Bartow and Davenport (1995), in a review of 37 applications of pump-and-treat systems in Santa Clara Valley, California, found that one site had achieved maximum contaminant levels (MCLs) for all contaminants and about one-third achieved, or were near, MCLs for one or more parameters. Bartow and Davenport's conclusion that pump-and-treat systems had significantly reduced the mass of volatile organic contaminants (VOCs) in the region's ground water indicates how expectations regarding the technology have changed.

Combining the pump-and-treat approach with *in situ* bioremediation (see Section 7.4) provides further opportunities for improving the effectiveness of ground-water cleanup. For example, Marquis (1995) suggested that in situ bioremediation used with the pump-and-treat approach should always be considered as an option for remediation of sand and gravel aquifers contaminated with biodegradable organic compounds, especially volatile aromatic and polyaromatic hydrocarbons.

2. Appropriate Use of Pump-and-Treat Technology

Pump-and-treat systems are used primarily to accomplish the following:

- *Hydraulic containment*. To control the movement of contaminated ground water, preventing the continued expansion of the contaminated zone. Figure 1 illustrates three major configurations for accomplishing hydraulic containment: (1) a pumping well alone, (2) a subsurface drain combined with a pump well, and (3) a well within a barrier wall system.

- *Treatment*. To reduce the dissolved contaminant concentrations in ground water sufficiently that the aquifer complies with cleanup standards or the treated water withdrawn from the aquifer can be put to beneficial use.

Although hydraulic containment and cleanup can represent separate goals, more typically, remediation efforts are undertaken to achieve a combination of both. For example, if restoration is not feasible, the primary objective might be containment. In contrast, where a contaminated well is used for drinking water but the contaminant source has not been identified, treatment at the wellhead might allow continued use of the water even though the aquifer remains contaminated.
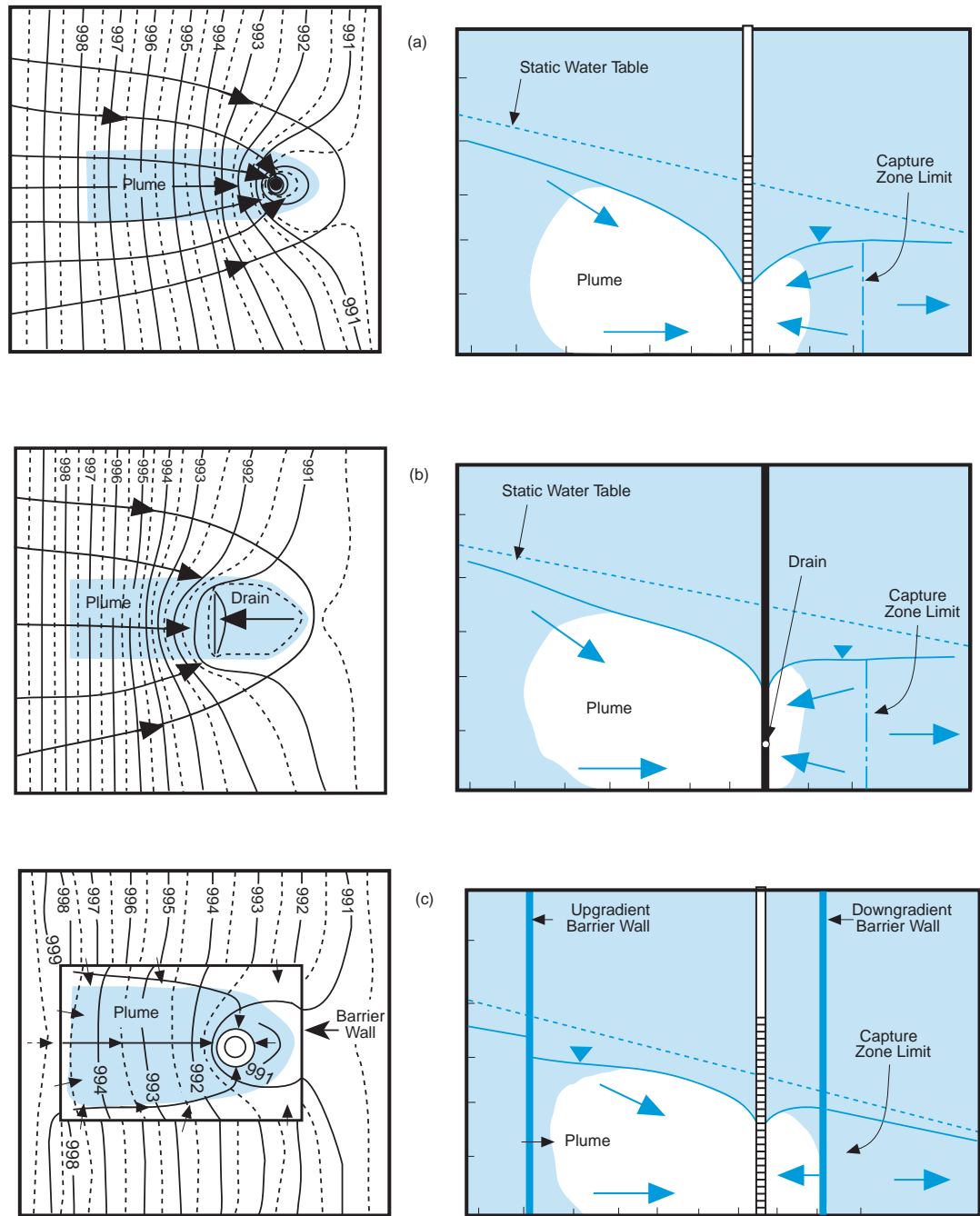
Figure 1.
Examples of hydraulic containment in a plan view and cross section using pump-and-treat technology: (a) pump well, (b) drain, and (c) well within a barrier wall system (after Cohen et al., 1994)

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3. Smart Pump-and-Treat Techniques

A fundamental component of any ground-water remediation effort using the pump-and-treat approach is contaminant removal or control. Thus, effective remediation of ground water using pump-and-treat technology requires knowledge of contaminants and site characteristics. Additionally, the remediation plan should call for implementation of dynamic system management based on a statement of realistic objectives (Hoffman, 1993).

3.1. Contaminant Removal/Control

Any ground-water cleanup effort will be undermined unless inorganic and organic contaminant sources are identified, located, and eliminated, or at least controlled, to prevent further contamination of the aquifer. Toxic inorganic substances may serve as a continuing source of contamination through mechanisms such as dissolution and desorption. At many contaminated sites, organic liquids are a major contributor to ground-water contamination. Figure 2 illustrates four common types of contaminant plumes, each characterized by the liquid's density relative to water and the degree to which the liquid mixes with water. Even when the organic liquid resides exclusively in the *vadose zone* (i.e., the area between the ground surface and the water table) it can serve as a source of ground-water contamination. In such situations, contamination occurs when percolating water comes in contact with the liquid (sometimes called *product*) or its vapors and carries dissolved

material to the ground water. Vapors also might migrate to the water table and contaminate ground water without infiltration.

Source removal is the most effective way to prevent further contamination. Where inorganic or organic contaminants are confined to the vadose zone, removal is usually the preferred option. When removal is not feasible, as is often the case with dense non-aqueous phase liquids (DNAPLs) residing below the water table, containment is an essential initial step in remediation. In some situations, containment can be achieved through capping, which prevents or reduces infiltration of rainfall through the contaminated soil. Capping can be ineffective if water table fluctuations occur within the zone of contamination or when NAPL vapors are present.

3.2. Thorough Site Characterization

Comprehensive characterization of the contaminated site serves two major functions:

- Accurately assessing the types, extent, and forms of contamination in the subsurface increases the likelihood of achieving treatment goals. This requires an understanding of the physical phases in which contaminants exist (mainly sorbed and aqueous phases for inorganic contaminants, and sorbed, NAPL, aqueous, and gaseous phases for organic liquids) and quantification of the distribution between the phases. Indeed, inadequate site characterization has undermined some pump-
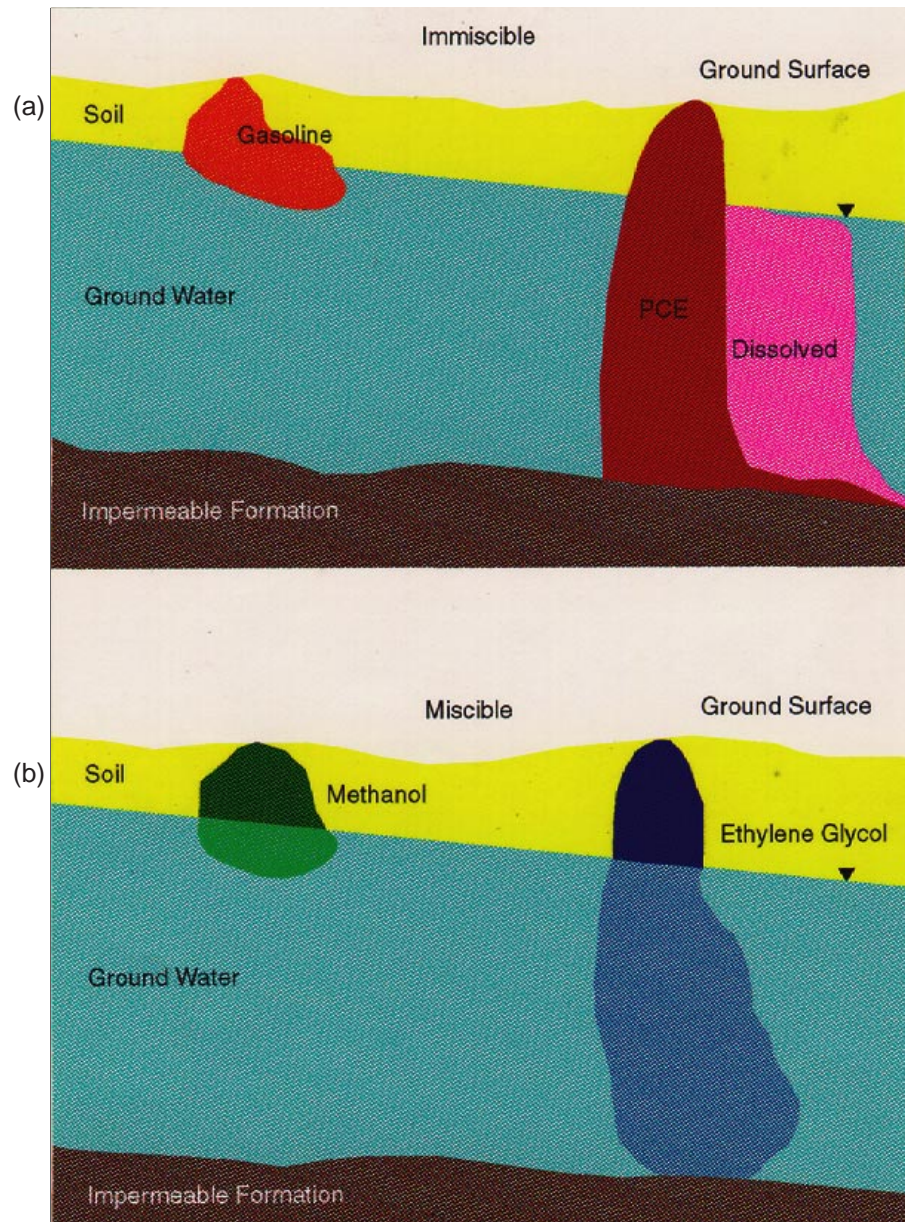
Figure 2.
Contaminant plumes as a function of density and miscibility with ground water: (a) light liquids (gasoline and methanol) create contaminant plumes that tend to flow in the upper portions of an aquifer; (b) dense liquids (perchloro-ethylene [PCE] and ethylene glycol) create a plume that contaminates the full thickness of an aquifer (adapted from Gorelick et al., 1993).

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and-treat efforts; for instance, when after a few years greater quantities of contaminants had been removed than were identified in the initial site assessment.

- A thorough, three-dimensional characterization of subsurface soils and hydrogeology, including particle-size distribution, sorption characteristics, and hydraulic conductivity, provides a firm basis for appropriate placement of pump-and-treat wells. Such information is also required for evaluating the extent to which tailing and rebound may present problems at a site (Section 4).

Three-dimensional characterization techniques include primarily indirect observations, using surface and borehole geophysical instruments and cone-penetration measurements, and direct sampling of soil and ground water. Important advances in soil sampling technology have been made relatively recently, such as continuous samplers used with a hollow-stem auger (Figure 3) and smaller continuous-core, direct-push equipment that also can be used to collect ground-water samples without installing wells (Figure 4). Vibratory drilling methods are another innovative technique for collecting soil cores and ground-water samples. Additionally, sensitive borehole flow meters that allow measurement of vertical changes in hydraulic conductivity in a borehole represent an important recent development. These techniques allow subsurface mapping to be generated with a level of detail that generally would be prohibitively expensive using conventional drilling and sampling methods. Figure 5 presents a conceptual diagram of trichloroethene (TCE) contamination at a complex site (Sidebar 2) developed from extensive use of direct-push sampling techniques.

Moreover, if sufficient data are obtained, the interpretation of subsurface data can be enhanced greatly by performing two- and three-dimensional computer modeling of the subsurface. Figure 6 shows a conceptual model of a site developed by combining contour visualization of a contaminant plume of benzene with subsurface lithologic logs (Sidebar 3). EPA's SITE3D software, being developed by the National Risk Management Laboratory's Subsurface Protection and Remediation Division, allows three-dimensional visualization of contaminant plumes (Figure 7). Statistical software developed by EPA such as Geo-EAS and GEOPACK for geostatistical analysis and contouring of ground-water contaminant data and GRITS/STAT for analysis of contaminant concentrations are among the many computer-based tools available for analyzing subsurface data.

3.3. Dynamic Management of the Well Extraction Field

To be effective, pump-and-treat efforts must go beyond initial site characterization, using information gathered after remediation operations are under way to manage the well extraction field dynamically. For instance, information collected while drilling and installing extraction wells, operating pumping wells, and tracking changes in water levels in monitoring wells (Section 6.4) and contaminant concentrations in observation wells can refine the portrayal of the site.

Dynamic management of the well extraction field based on more comprehensive information can provide both economic and environmental benefits. In general, additional information about the site and the pump-and-treat effort allows operators to make informed decisions about the efficient use of remediation resources. More specifically, this flexible site management approach may facilitate greater success in hydraulic containment (Section 5). Ultimately, the time required to achieve cleanup goals might be minimized.

Figure 3. This hollow-stem auger is fitted with a 5-foot sampling tube that collects a continuous core as the auger advances, allowing detailed and accurate observation of subsurface lithology. When drilling is completed, a monitoring well also can be installed.
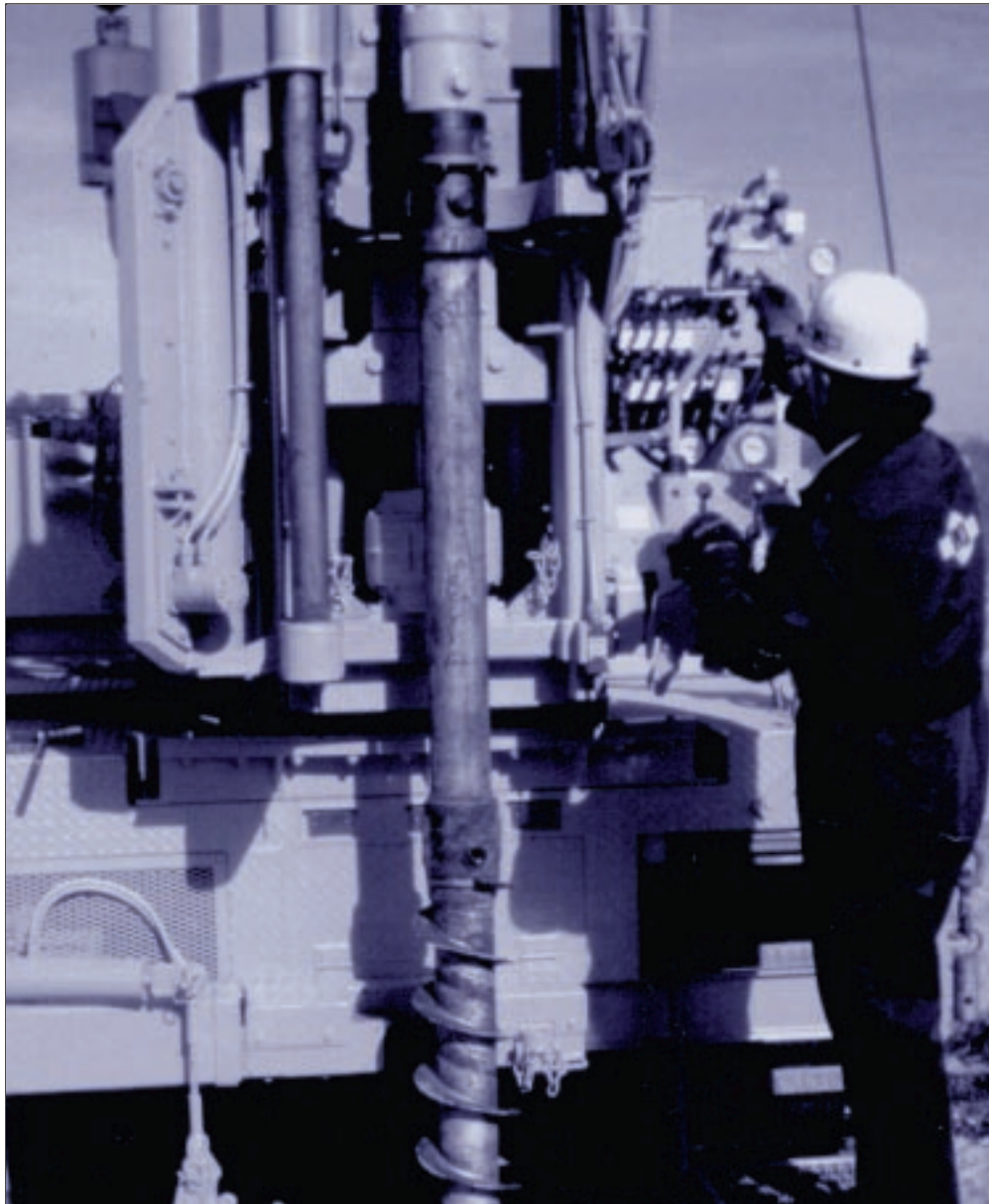
Figure 4. Hydraulic or vibratory direct-push rigs can be installed on vans, small trucks, all-terrain vehicles, or trailers and allow collection of continuous soil cores and depth-specific ground-water samples for detailed subsurface mapping if contaminants are generally confined to depths of less than 15 meters. (Photo courtesy of Geoprobe Systems.)

A key component of the dynamic management approach is the effective design and operation of the pump-and-treat system. The following techniques can be useful in this regard:

- Using capture zone analysis, optimization modeling, and data obtained from monitoring the effects of initial extraction wells to identify the best locations for wells (Section 6.1).

- Phasing the construction of extraction and monitoring wells so that information obtained from operation of the initial wells informs decisions about siting subsequent wells (Section 6.2).

- Phasing pumping rates and the operation of individual wells to enhance containment, avoid stagnation zones (Section 5.2.3), and
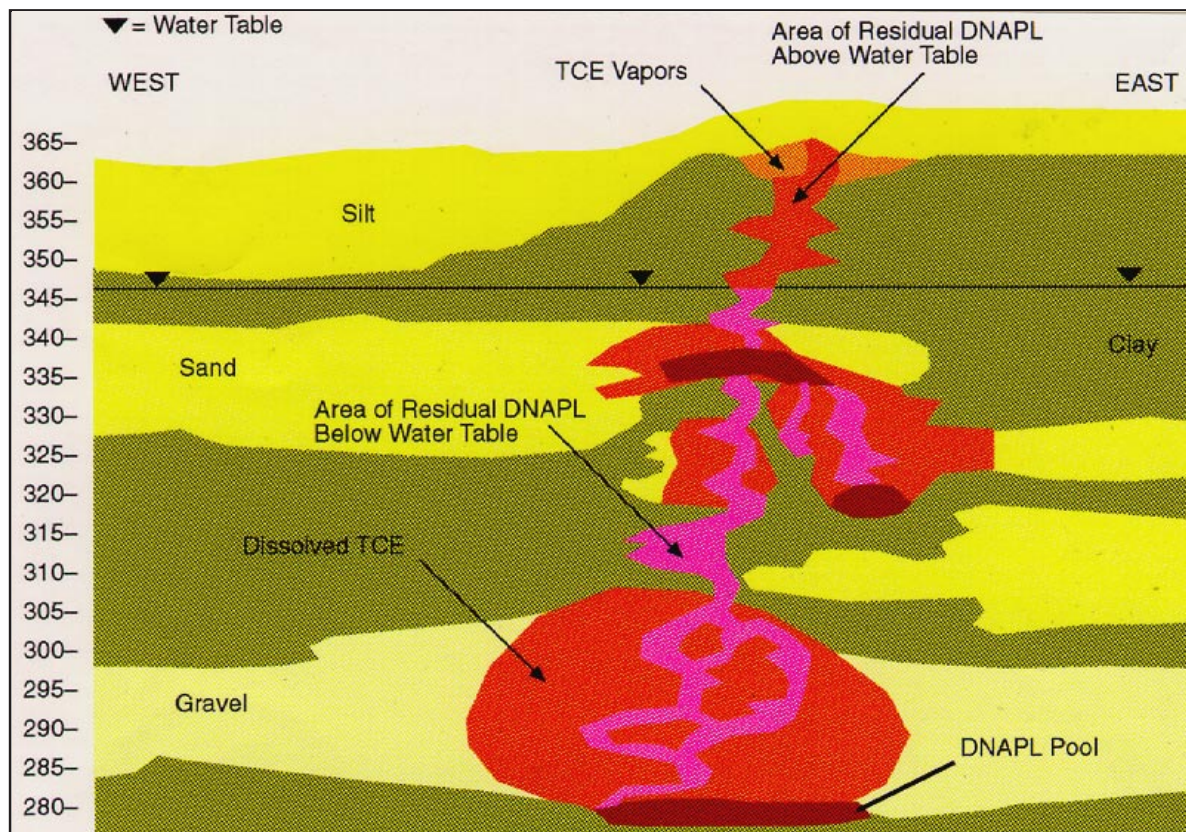
Figure 5. Conceptual diagram of DNAPL (TCE) based on soil and ground-water sampling in a heterogeneous sand and gravel aquifer. The extreme difficulty in cleaning up this site, which includes five distinct forms of TCE (vapors and residual product in the vadose zone; pooled, residual, and dissolved product in the ground water) led to modification of the pump-and-treat system for hydraulic containment rather than restoration (adapted from Clausen and Solomon, 1994).

ensure removal of the most contaminated ground water first (Section 6.3).

3.4. Realistic Cleanup Goals

Unrealistic expectations for the pump-and-treat approach can lead to disappointments in system performance (Sidebar 1). Indeed, a cleanup goal that is realistic for one site may not be reasonable elsewhere. The Committee on Ground Water Cleanup Alternatives of the National Academy of Sciences (NRC, 1994) has identified three major classes of sites based on hydrogeology (Sidebar 2) and contaminant chemistry (see Table 1):

- *Class A*. Sites where full cleanup to health-based standards should be feasible using current technology. Such sites include homogeneous single- and multiple-layer aquifers involving mobile, dissolved contaminants.

Sidebar 2
Major Types of Hydrogeologic Settings

The Committee on Ground Water Cleanup Alternatives of the National Academy of Sciences has defined three major hydrogeologic settings for evaluating the technical feasibility of ground-water cleanup based on the degree of uniformity of the aquifer material and layering (Table 1).

- *Homogeneous* aquifers consist of materials that do not vary significantly in their water-transmitting properties. Contaminant movement in homogeneous aquifers is largely a function of the hydraulic conductivity of the aquifer. For example, a homogeneous aquifer might comprise permeable, well-sorted sands or gravels.

- *Heterogeneous* aquifers consist of materials that vary in their water-transmitting properties laterally, vertically, or in both directions. Contaminants in heterogeneous aquifers move preferentially in the high-permeability zones, resulting in more rapid transport than would be expected based on the average hydraulic conductivity of the aquifer. A sand aquifer with lenses of silts and clays is an example of a heterogeneous aquifer.

- *Fractured* aquifers typically consist of low-permeability rock where most ground-water flow is in joints and fractures.

Single-layered aquifers are less complex than *multiple-layered* aquifers, which are separated by less-permeable strata, because the possibility of cross contamination between aquifers by either upward or downward movement becomes a consideration. Note that the term aquifer is used in this guide in a broad sense to include any area within the saturated zone where the presence of ground-water contamination is of sufficient concern to require remediation. Figure 2 illustrates a homogenous, single-layer aquifer. Figure 15c (described in Section 4.2.5) illustrates a two-layered homogenous aquifer. Figure 5 illustrates a multiple-layered heterogeneous aquifer. The challenge of ground-water cleanup increases along with aquifer complexity because of difficulties in delineating contaminant sources and pathways and the increased likelihood of tailing and rebound effects (Section 4).

- *Class B*. Sites where the technical feasibility of complete cleanup is likely to be uncertain. This class includes a wide range of hydrogeologic settings and contaminant types that do not fall into classes A or C.
- *Class C*. Sites where full cleanup of the source areas to health-based standards is not likely to be technically feasible. Such sites include fractured-rock aquifers contaminated by free-product light nonaqueous phase liquids (LNAPL) or DNAPL and single- or multiple-layered heterogeneous aquifers contaminated by a free-product DNAPL (Sidebar 4).

Typically, preliminary ground-water cleanup efforts at contaminated sites are focused on standards established for drinking water, such as federal or state maximum contaminant levels

Figure 6. GEOS computer screen showing organic contaminant plume in relation to subsurface stratigraphy (see text for discussion).

(MCLs) or nonzero MCL goals (MCLGs). EPA has established procedures, however, by which efforts can target alternative goals at Superfund and RCRA sites using alternate concentration limits (ACLs) where ground-water discharges into nearby surface water (U.S. EPA, 1988) or demonstrating the technical impracticality (TI) of ground-water cleanup (U.S. EPA, 1993; Feldman and Campbell, 1994). At DNAPL sites where the TI of ground-water cleanup has been demonstrated, the remedial strategy might call for

removal of as much of the DNAPL as is feasible, containment of the remaining DNAPL, and treatment of the aqueous contaminant plume outside the containment area. Consequently, even at Class C and Class B sites where restoration is not feasible, application of some form of the pump-and-treat approach may be required either to help contain the contaminant source and aqueous-phase plume or to clean up the contaminated ground water outside the containment area.

Sidebar 3
Computer Graphics as a Site Characterization Tool

Computer visualization can help focus attention on the types of additional information needed when characterizing a site before initiating a remediation effort. For example, in Figure 6 the contoured benzene data, collected from the sand/gravel #1 aquifer (yellow in the cross section in the upper right) shows two areas of high concentration (i.e., MW-5 and MW-7). Does this represent a contaminant plume from a single source, or does it indicate two contaminant plumes from separate sources? An examination of the cross section (upper right of center) indicates that sand/gravel #1 aquifer at MW-7 has the lower "high" concentration of benzene, suggesting that the two plumes might be related.

The cross section also shows, however, that the aquifer is quite thin between the two monitoring wells. Indeed, examination of monitoring well MP-10, which lies near the cross section (see lower center log) reveals that the aquifer is missing at this point. This suggests the absence of a concentration gradient between the two wells, indicating that two different sources may be involved.

Further analysis of the spatial distribution of the sand/gravel #1 aquifer, including flow directions as indicated by potentiometric heads, and possibly additional sampling for benzene would be required to determine if one or two sources are contributing to the contamination.

This particular example also cautions against relying exclusively on computer-generated interpolations, which can suggest features that are not actually present (i.e., continuity of the aquifer between MW-5 and MW-7).
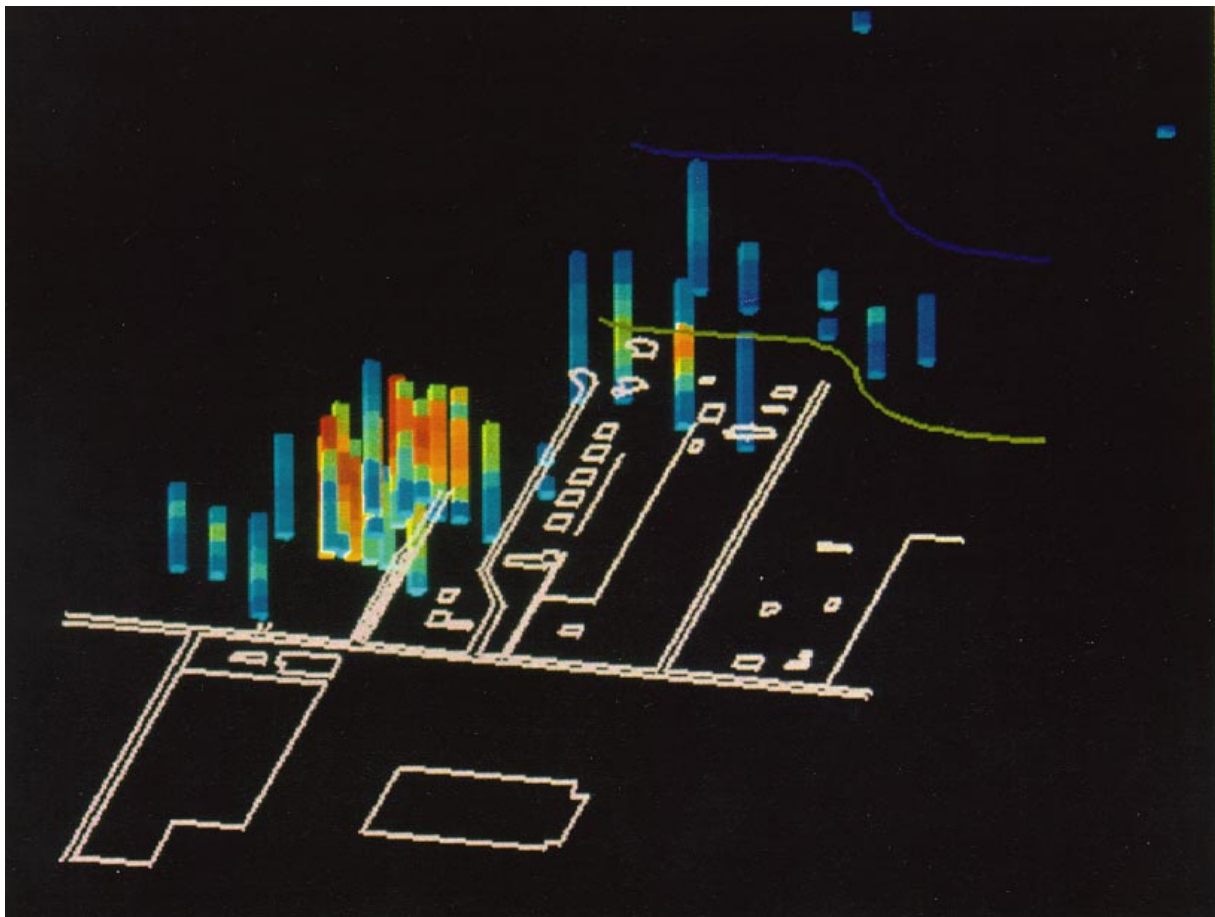
Figure 7. EPA's SITE3D software, under development at the Ada, Oklahoma, laboratory, helps visualize in three-dimensions a TCE contaminant plume at a Superfund Site. Yellows and reds indicate zone with highest concentrations of TCE in ground water.

Table 1. Categories of Sites for Technical Infeasibility Determinations (NRC, 1994)

| Hydrogeology	Contaminant Chemistry					
	Mobile Dissolved (degrades/ volatilizes)	Mobile, Dissolved	Strongly Sorbed, Dissolved (degrades/ volatilizes)	Strongly Sorbed, Dissolved	Separate Phase LNAPL	Separate Phase DNAPL
Homogeneous, single layer	A (1)	A (1-2)	B (2)	B (2-3)	B (2-3)	B (3)
Homogeneous, multiple layers	A (1)	A (1-2)	B (2)	B (2-3)	B (2-3)	B (3)
Heterogeneous, single layer	B (2)	B (2)	B (3)	B (3)	B (3)	C (4)
Heterogeneous, multiple layers	B (2)	B (2)	B (3)	B (3)	B (3)	C (4)
Fractured	B (3)	B (3)	B (3)	B (3)	C (4)	C (4)

Note: Shaded boxes at the left end (group A) represent types of sites for which cleanup of the full site to health-based standards should be feasible with current technology. Shaded boxes at the right end (group C) represent types of sites for which full cleanup of the source areas to health-based standards will likely be technically infeasible. The unshaded boxes in the middle (group B) represent sites for which the technical feasibility of complete cleanup is likely to be uncertain. The numerical ratings indicate the relative ease of cleanup, where 1 is easiest and 4 is most difficult.

Sidebar 4
The Effect of NAPL Phases on Ground-Water Contamination

The light (LNAPLs) and dense (DNAPLs) *immiscible* nonaqueous phase liquids shown in Figure 2 pose the most difficult problems for ground-water cleanup because of their complex interactions with water and solids in the subsurface. Figure 5 illustrates these complexities when trichloroethene (TCE), a DNAPL has moved through a heterogeneous, multiple-layered alluvial aquifer (at a site in Tennessee). Four distinct forms, or phases, of TCE are evident:

• The NAPL emits a *vapor* phase in the unsaturated zone that moves by diffusion. DNAPL vapors tend to sink until they reach impermeable layers (Figure 5) or the water table. Even if the NAPL does not reach the ground water, contamination can occur by dissolution of the vapors directly into the ground water or by water percolating through the unsaturated zone.

• *Residual* NAPL remains after the free product has moved through the subsurface by gravity or been displaced by water (Figure 8a and b). Residual NAPL exists as single- to complex-shaped blobs that fill

pore spaces (Figure 8b and 9). The amount of residual NAPL remaining in the subsurface depends on the subsurface material and the type of NAPL. *Residual saturation* in the unsaturated zone typically ranges from 10 to 20 percent of the subsurface volume and in the saturated zone generally ranges from 10 to 50 percent (Cohen and Mercer, 1993). Figure 5 differentiates residual TCE *above* and *below* the water table.

• *Free product* exists where most of the pore space is filled by the NAPL. It accumulates wherever a barrier prevents downward movement. LNAPLs, such as gasoline, tend to float on top of the water table, whereas DNAPLS tend to sink until they reach an impermeable layer (Figure 5).

• *Dissolved* NAPL forms the aqueous contaminant plume that moves in the direction of ground-water flow. The residual NAPL and free product can serve as a source of ground-water contamination as long as they remain in the subsurface.

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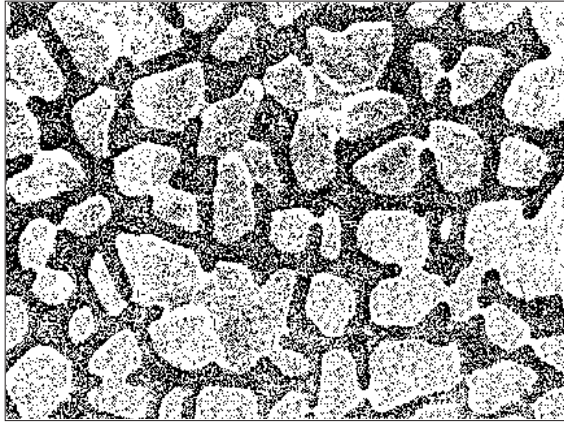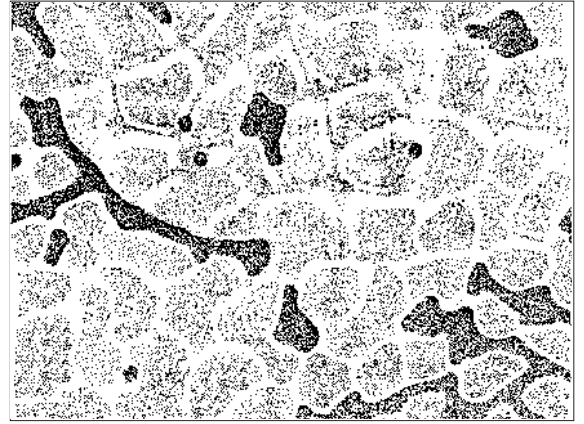
a   b

Figure 8. Dark NAPL (Soltrol) and water in a homogenous micromodel after (a) the displacement of water by NAPL and then (b) the displacement of NAPL by water, with NAPL at residual saturation (Wilson et al., 1990).
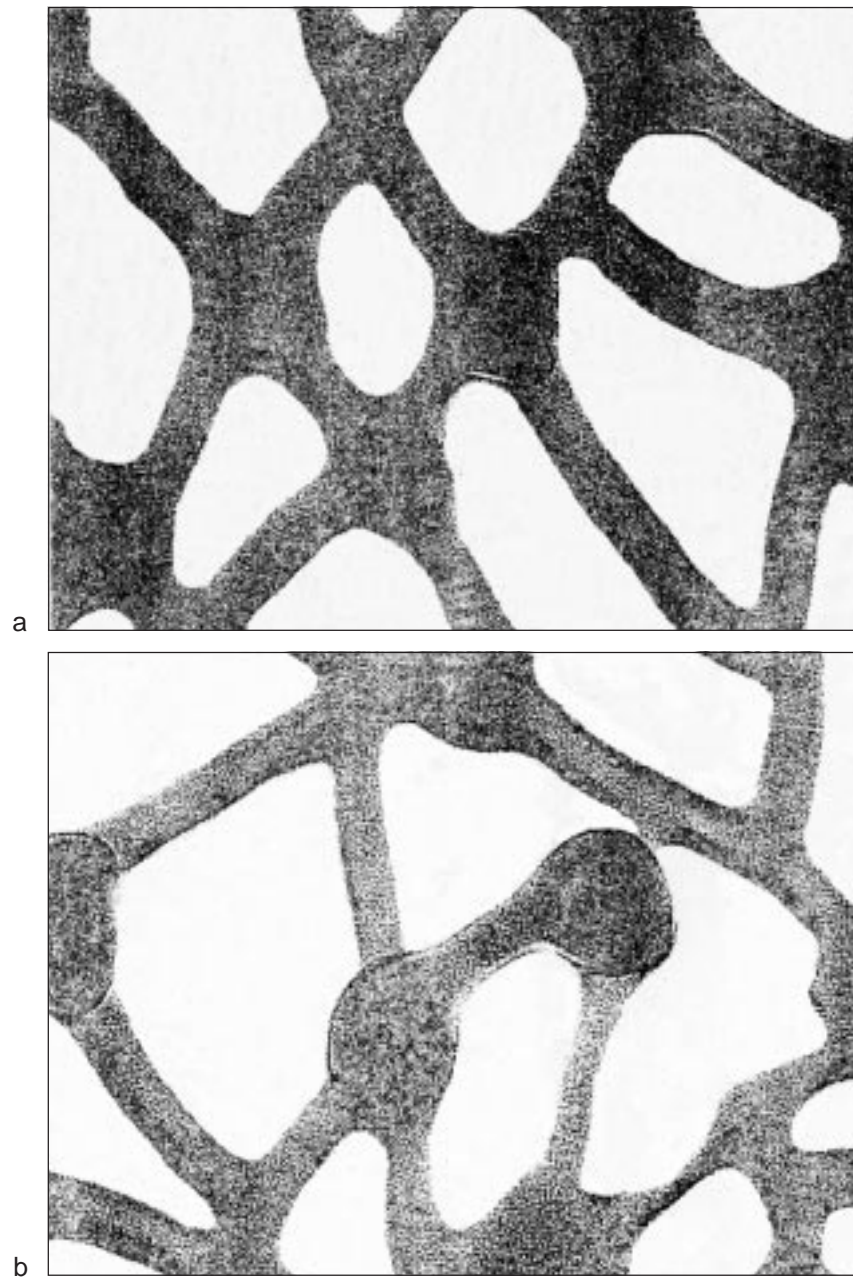
Figure 9.
Photomicrographs of (a) a single blob occupying one pore body, and (b) a doublet blob occupying two pore bodies and a pore throat (Wilson et al., 1990).

4.   Anticipating Tailing and Rebound Problems

The phenomena of tailing and rebound are commonly observed at pump-and-treat sites. *Tailing* refers to the progressively slower rate of decline in dissolved contaminant concentration with continued operation of a pump-and-treat system (Figure 10). *Rebound* is the fairly rapid increase in contaminant concentration that can occur after pumping has been discontinued. This increase may be followed by stabilization of the contaminant concentration at a somewhat lower level.

4.1.   Effects of Tailing and Rebound on Remediation Efforts

Tailing presents two main difficulties for ground-water restoration:

- *Longer treatment times*. Without tailing, contaminants theoretically could be removed by pumping a volume of water equivalent to the volume of the contaminant plume (Figure 10). The tailing effect, however, significantly increases the time pump-and-treat systems must be operated to achieve ground-water restoration goals. Indeed, pumping may need to be conducted for hundreds of years rather than tens of years.

- *Residual concentrations in excess of the cleanup standard*. When tailing occurs, often initially the decline in the rate of contaminant concentrations is fairly rapid, followed by a more gradual decline that eventually stabilizes at an apparent residual concentration level above the cleanup standard (Figure 10).

Rebound is most problematic when a pump-and-treat system attains the cleanup standard, but concentrations subsequently increase to a level that exceeds the standard.

4.2.   Contributing Factors

The degree to which tailing and rebound complicate remediation efforts at a site is a function of the physical and chemical characteristics of the contaminant being treated, the subsurface solids, and the ground water. Major factors and processes that contribute to tailing and rebound are discussed below.

4.2.1.   Non-Aqueous Phase Liquids

Although immiscible LNAPLs and DNAPLs tend to be relatively insoluble in water, unfortunately they often are sufficiently soluble to cause concentrations in ground water to exceed MCLs. Consequently, residual and pooled free-product NAPL will continue to contaminate ground water that makes sufficient contact to dissolve small amounts from the NAPL surface (Figure 11a). When ground water is moving slowly, contaminant concentrations can approach the solubility limit for the NAPL (Figure 11c). Although pump-and-treat systems increase ground-water velocity, causing an initial decrease in concentration, the decline in concentration will later tail off until the NAPL's rate of dissolution is in equilibrium with the velocity of the pumped ground water. If pumping stops, the ground-water velocity slows and concentrations can rebound, rapidly at first and then gradually reaching the equilibrium
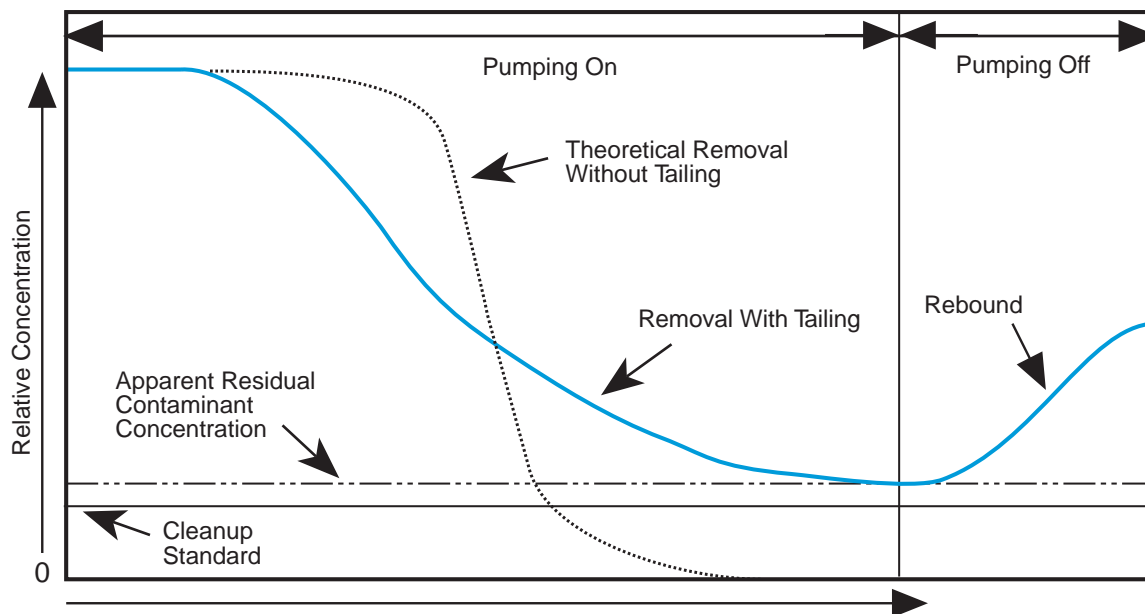
Figure 10. Concentration versus pumping duration or volume showing tailing and rebound effects (Cohen et al., 1994).

concentration (Figure 11c), unless pumping is resumed.

As shown in Table 1, DNAPL contamination in heterogeneous and fractured aquifers is the most intractable. The reasons for this are

- DNAPLs create an unstable wetting front in the subsurface, with fingers of more rapid vertical flow speeding the movement deeper into the saturated zone (Figure 12). (This also makes accurate delineation of zones of residual contamination extremely difficult in homogeneous aquifers.)

- If the volume of DNAPL exceeds the residual saturation capacity of the unsaturated and saturated zones, the DNAPL will reach lower permeability materials and form pools of free product (Figure 5).

- In heterogeneous aquifers, localized lenses of low-permeability strata may cause pools of free product to develop throughout the saturated zone (Figure 12). Low-permeability strata also may cause extensive lateral movement of the DNAPL. DNAPL pools are especially problematic because the contaminant will dissolve even more slowly than residual DNAPL. It may take tens of years to remove 1 cm of contaminant from a DNAPL pool (NRC, 1994).

4.2.2. Contaminant Desorption

The movement of many organic and inorganic contaminants in ground water is retarded by sorption processes that cause some of the dissolved contaminant to attach to solid surfaces. The amount of contaminant sorbed is a function of concentration, with sorption increasing as concentrations increase, and the sorption capacity
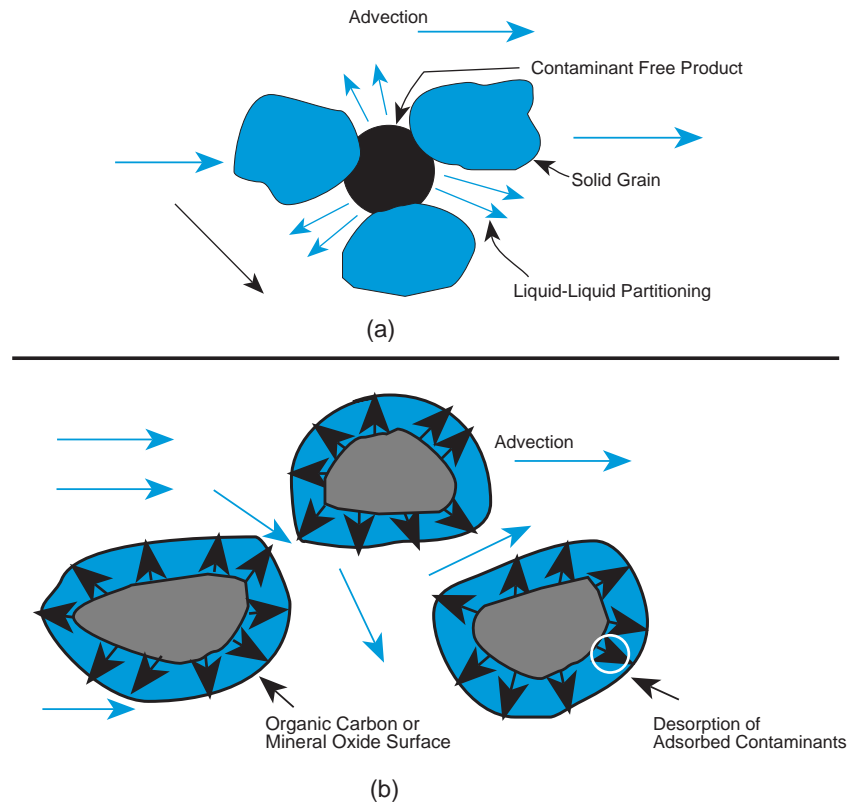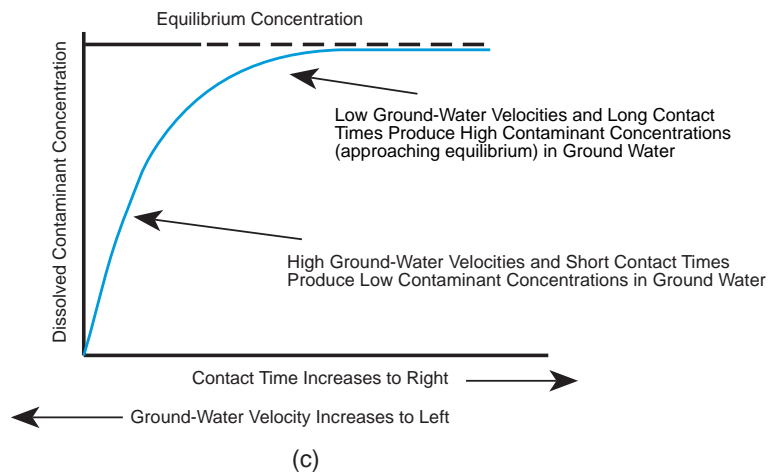
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Advection

Contaminant Free Product

Solid Grain

Liquid-Liquid Partitioning

(a)

Advection

Organic Carbon or
Mineral Oxide Surface

Desorption of
Adsorbed Contaminants

(b)

Figure 11.
Contaminants are mobilized
when ground water that is
undersaturated with a
contaminant comes in
contact with a NAPL (a) or
contaminant sorbed on an
organic carbon or mineral
surface (b). High ground-
water velocities and short
contact times will result in
low contaminant
concentrations, and low
velocities and long contact
times will result in high
contaminant concentrations
(c) (adapted from Gorelick et
al., 1993).

Equilibrium Concentration

Dissolved Contaminant Concentration

Low Ground-Water Velocities and Long Contact
Times Produce High Contaminant Concentrations
(approaching equilibrium) in Ground Water

High Ground-Water Velocities and Short Contact Times
Produce Low Contaminant Concentrations in Ground Water

Contact Time Increases to Right

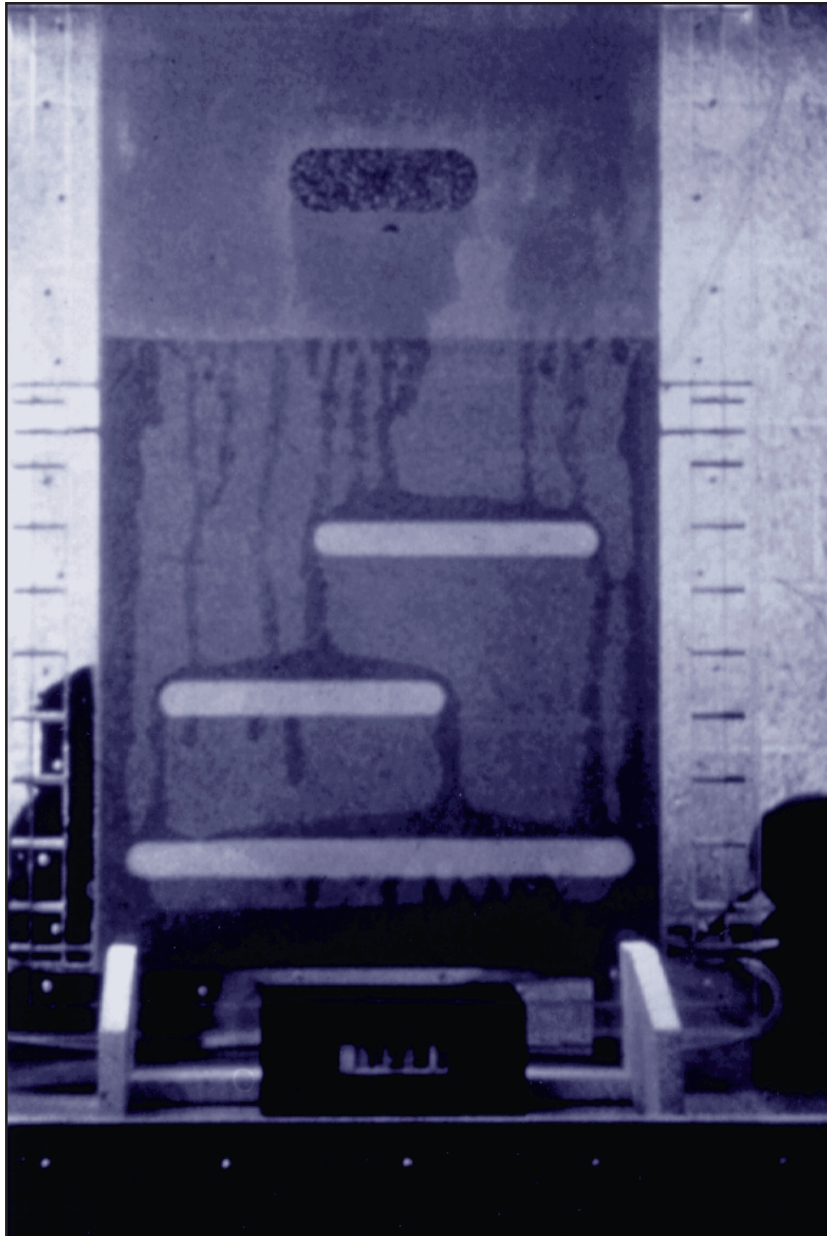Ground-Water Velocity Increases to Left

(c)

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Figure 12. Laboratory model of the transport of DNAPL contaminant through an aquifer with varying permeability; note the concentration of downward movement in fingers and the DNAPL pools above the low-permeability zones (the horizontal discs). (Source: U.S. EPA National Risk Management Research Laboratory.)

of the subsurface materials. Sorbed contaminants tend to concentrate on organic matter and clay-sized mineral oxide surfaces (Figure 11b). Sorption is a reversible process, however. Thus, as dissolved contaminant concentrations are reduced by pump-and-treat system operation, contaminants sorbed to subsurface media can desorb from the matrix into ground water. Contaminant concentrations resulting from sorption and desorption show a relationship to ground-water velocity and contact time similar to that of NAPLs (Figure 11c), causing the tailing of contaminant concentrations during pumping as well as rebound after pumping stops.

4.2.3.   Precipitate Dissolution

As with sorption-desorption reactions, precipitation-dissolution reactions are reversible. Thus, large quantities of inorganic contaminants, such as chromate in $BaCrO_4$, may be found with crystalline or amorphous precipitates in the subsurface (Palmer and Fish, 1992). Figure 13 illustrates a tailing curve where the contaminant concentration is controlled by solubility. In this situation, if pumping stops before the solid phase is depleted, rebound can occur.
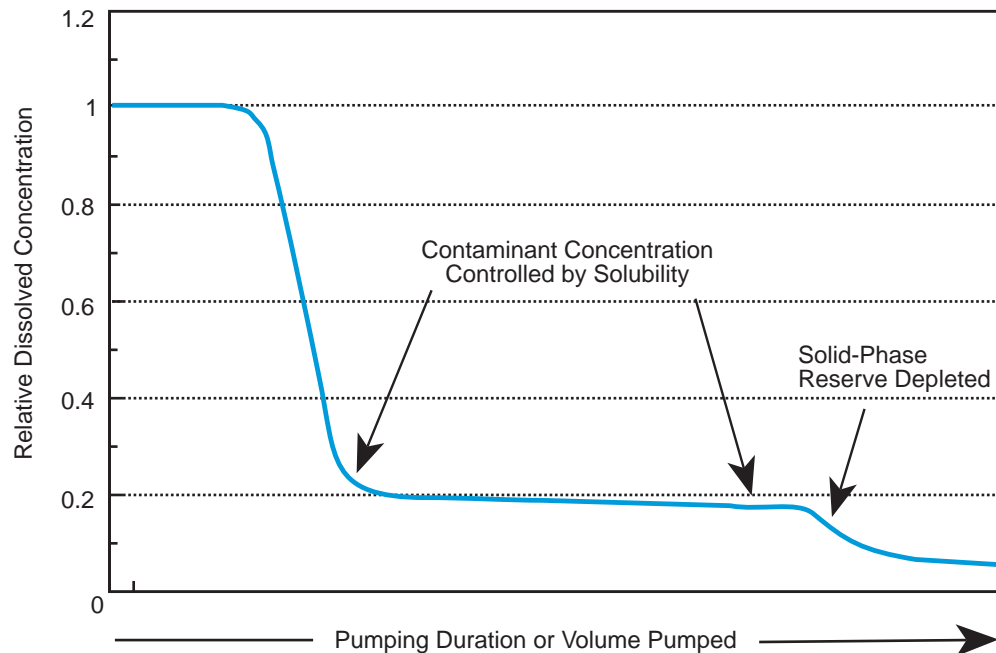

Figure 13. Dissolved contaminant concentration in ground water pumped from a recovery well versus time in a formation that contains a solid-phase contaminant precipitate (Palmer and Fish, 1992).

4.2.4.   Matrix Diffusion

As contaminants advance through relatively permeable pathways in heterogeneous media, concentration gradients cause diffusion of contaminant mass into the less permeable media (Gillham et al., 1984). Matrix diffusion is most likely to occur with dissolved contaminants that are not strongly sorbed, such as inorganic anions and some organic chemicals. During a pump-and-treat operation, dissolved contaminant concentrations in the relatively permeable zones are reduced by advective flushing, causing a reversal in the initial concentration gradient and slow diffusion of contaminants from the low to high permeability media. Figure 14, based on theoretical calculations of TCE concentrations in clay lenses of varying thickness, shows that diffusion is a slow process. For example, the figure indicates that the time required to reduce the concentration of TCE to 10 percent of the initial concentration would be 6 years for a clay lens 1 foot thick, 25 years for a clay lens 2 feet thick, and 100 years for a clay lens 4 feet thick. The significance of matrix diffusion increases as the length of time between contamination and cleanup increases. In heterogeneous aquifers, matrix diffusion contributions to tailing and rebound can be expected, as long as contaminants have been diffusing into less-permeable materials.

4.2.5.   Ground-Water Velocity Variation

Tailing and rebound also result from the variable travel times associated with different flow paths taken by contaminants to an extraction well (Figure 15a-c). Ground water at the edge of a capture zone created by a pumping well travels a greater distance under a lower hydraulic gradient
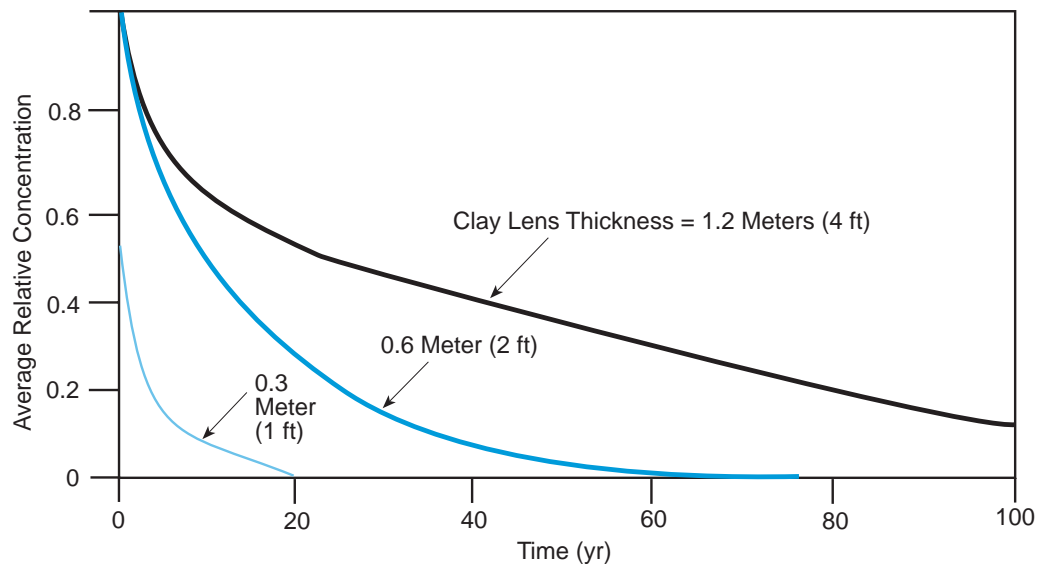

Figure 14. Changes in average relative trichloroethene (TCE) concentrations in clay lenses of varying thickness as a function of time (NRC, 1994).

(a)

Slow

Moderate

Fast   Moderate

(b)

Relative Dissolved Concentration

1.2
1.0
0.8
0.6
0.4
0.2
0

Tailing Due to
Different Travel
Times Along Flow
Paths to
Recovery Well

← Pumping Duration or Volume Pumped →

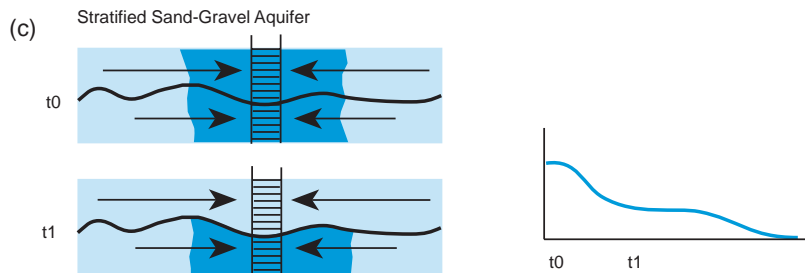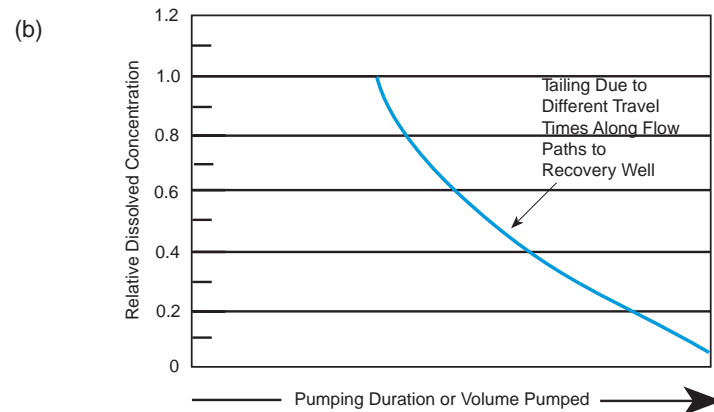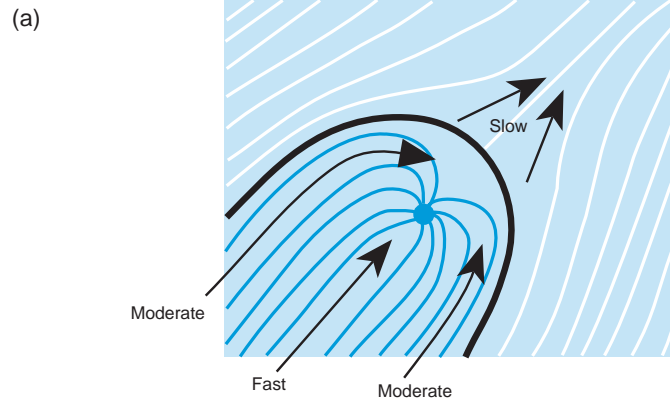(c)   Stratified Sand-Gravel Aquifer

t0

t1

t0   t1

Figure 15.
Tailing resulting from ground-water velocity variations: (a) horizontal variations in the velocity of ground water moving toward a pumping well (Keely, 1989) lead to (b) tailing as higher concentrations of ground water in slower pathlines mix with lower concentrations in faster pathlines (Palmer and Fish, 1992); (c) in a stratified sand and gravel aquifer, tailing occurs at t1 when clean water from the upper gravel strata mixes with still-contaminated ground water in the lower sand strata (Cohen et al., 1994).

than ground water closer to the center of the capture zone (Figure 15a). Additionally, contaminant-to-well travel time varies as a function of the hydraulic conductivity in heterogeneous aquifers (Figure 15c).

4.3. Assessing the Significance of Tailing and Rebound at a Site

Determining realistic objectives for a pump-and-treat system requires sufficient site characterization to define the complexity of the hydrogeologic setting (Sidebar 2) and the subsurface distribution of contaminants. Such information makes it possible for the system operator to assess whether conditions at the site will result in tailing and rebound and to evaluate the extent to which these conditions are likely to increase the time needed to attain health-based cleanup standards. The sorption characteristics of contaminants can be assessed using batch sorption tests with aquifer materials (Roy et al., 1992), although aquifer heterogeneity increases the difficulty of interpreting test results. For organics, the potential effects of sorption can be assessed based on a literature review of contaminant properties and on site-specific data on organic carbon in aquifer materials (Piwoni and Keely, 1990). Geochemical computer codes can be used to assess the potential for tailing and rebound effects from precipitation-dissolution reactions.

Assessing the potential for removal or containment of free product may be the first priority at NAPL-contaminated sites, followed by assessment of the extent of residual NAPL contamination. For DNAPLs, residual saturation may extend throughout the unsaturated and saturated zones (Figure 5). Typically, for LNAPLs most residual contamination is located in the vadose zone, but it may also extend to the depth of the seasonal low water table. As Figure 16 shows, pumping to remove free LNAPL product can cause residual NAPL to move deeper into the saturated zone. Consequently, when removing free-product LNAPL that is floating on the water table, steps should be taken to avoid or minimize movement of residual NAPL deeper into the saturated zone.

Berglund and Cvetkovic (1995) evaluated the relative importance of the degree of heterogeneity in hydraulic conductivity and mass transfer processes and concluded that the rate of mass transfer and the extent to which contaminants are sorbed on aquifer solids are the most important parameters that affect predicted cleanup time.
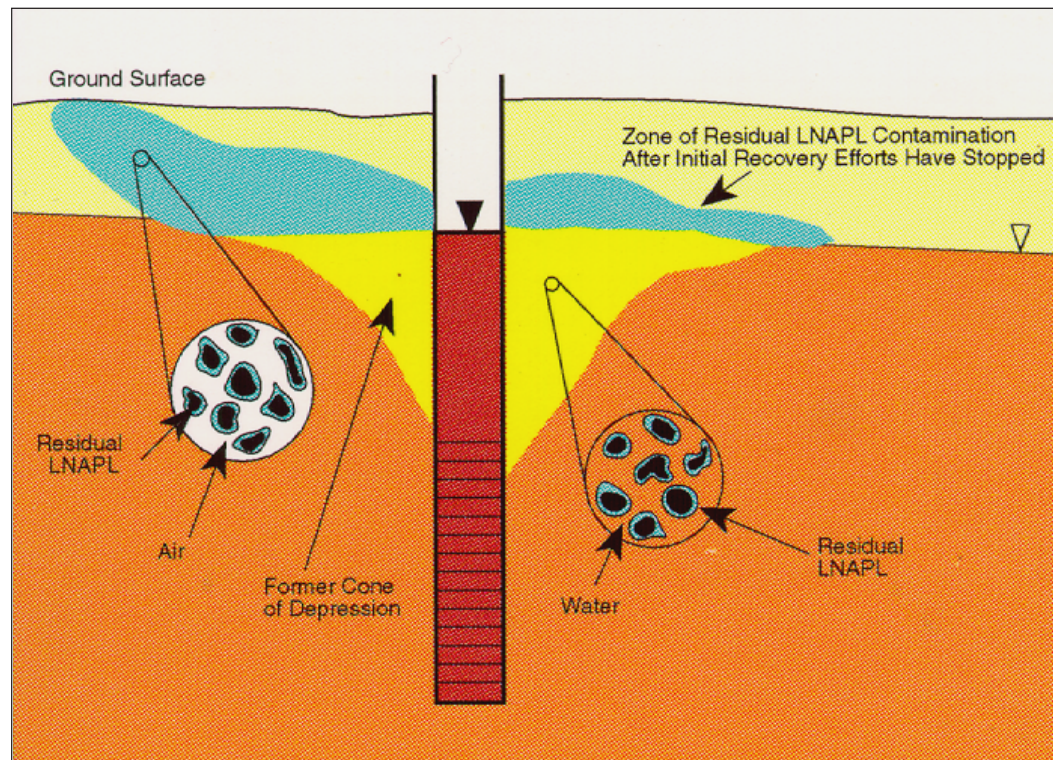
Figure 16. Zone of residuals created in former cone of depression after cessation of LNAPL recovery system (Gorelick et al., 1993).

5.   Effective Hydraulic Containment

Hydraulic containment is a design objective of nearly all pump-and-treat systems. Where restoration of an aquifer to health-based standards is the overall objective, the primary goal of containment must be to prevent farther spread of the contaminant plume during restoration efforts. Where NAPLs are present, containment using hydraulic and physical barriers might be the primary objective for cleanup efforts in the portion of the aquifer contaminated by free product and residual NAPL (Figures 1c and 17). In such situations a conventional pump-and-treat system might be used to restore the dissolved contaminant plume (Figure 17).

Effective hydraulic containment using pumping wells requires the creation of horizontal and vertical capture zones that draw all contaminated ground water to the wells (Section 5.1.1) or other hydraulic barriers (Sections 5.1.2 and 5.1.3). Failure to take aquifer anisotropy into account (Section 5.2.1) or limitations in the ability to create sufficient drawdown to establish capture zones (Section 5.2.2) may allow contaminants to escape from these systems. Additionally, stagnation zones created by pumping operations or the use of injection wells can reduce the effectiveness of cleanup efforts (Section 5.2.3). The monitoring of both hydraulic heads (Section 6.4.1) and ground-water quality (Section 6.4.2) can provide early indications that contaminants are not being contained.

5.1.   Ground-Water Barriers and Flow Control

Hydraulic containment can be accomplished by controlling the direction of ground-water flow with capture zones (Section 5.1.1) or pressure ridges (Section 5.1.2) or by using physical barriers (Section 5.1.3). Figure 17 illustrates a pump-and-treat system that uses all three types of hydraulic controls: (1) the contaminant source area is surrounded by a barrier wall, (2) extraction wells around the margins of the dissolved plume capture the contaminated ground water, and (3) treated ground water is reinjected to create a pressure ridge along the axis of the contaminant plume. Note that the pressure ridge in Figure 17 serves the function of increasing pore-volume exchange rates rather than functioning as a barrier. Barrier pressure ridge systems are created by placing injection wells along the perimeter of a contaminant plume.

5.1.1.   *Horizontal and Vertical Capture Zones*

Pumping wells provide hydraulic containment by creating a point of low hydraulic head to which nearby ground water flows. The portion of an aquifer where flow directions are toward a pumping well is called a *capture zone*. In an isotropic aquifer, where hydraulic conductivity is the same in all directions, ground-water flow is perpendicular to the hydraulic head contours, also called *equipotential lines* (Figure 18b).
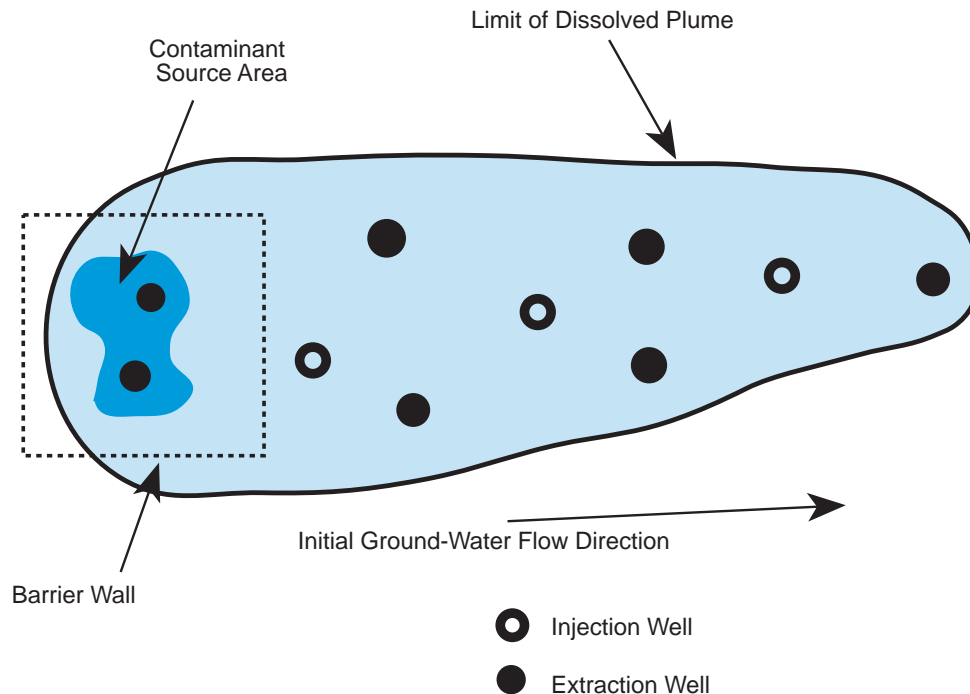
Figure 17. Plan view of a mixed containment-restoration strategy. A pump-and-treat system is used with barrier walls to contain the ground-water contamination source areas (e.g., where NAPL or waste may be present) and then collect and treat the dissolved contaminant plume (Cohen et al., 1994).

A pumping well creates a *zone of influence* where the potentiometric surface has been modified (Figure 18c). The capture zone is the portion of the zone of influence where ground water flows to the pumping well (Figure 18d). Figure 15a shows how a capture zone creates flow lines of varying velocity. The size and shape of a capture zone depend on the interaction of numerous factors, such as

- The hydraulic gradient and hydraulic conductivity of the aquifer.

- The extent to which the aquifer is heterogeneous (Sidebar 2) or anisotropic (Section 5.2.1).

- Whether the aquifer is confined or unconfined.

- The pumping rate and whether other pumping wells are operating.

- Whether the screened interval of the well fully or partially penetrates the aquifer.

When the screened portion of a pumping well fully penetrates an aquifer (Figure 1b), a two-dimensional analysis to delineate the horizontal

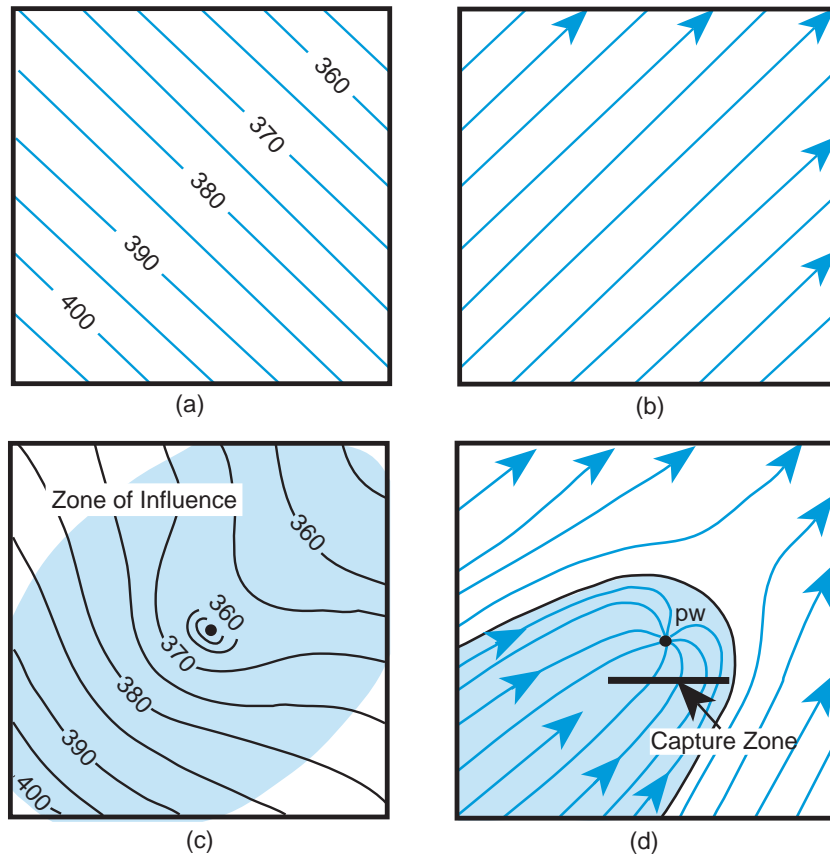**Figure 18.** In an isotropic aquifer, ground-water flow lines (b) are perpendicular to hydraulic head contours (a). Pumping causes drawdowns and a new steady-state potentiometric surface within the well's zone of influence (c). Following the modified hydraulic gradients, ground water within the shaded capture zone flows to the pumping well (d). (Cohen et al., 1994, adapted from Gorelick et al., 1993).

capture zone is usually sufficient. When a pumping well only partially penetrates an aquifer, however, vertical capture zone analysis also is required to determine whether the capture zone will contain a contaminant plume. Figure 19 shows a vertical capture zone for a partially penetrating well. If the contaminant plume extended to the base of the aquifer, some contaminants would bypass the well, despite the presence of apparent upward gradients. In stratified anisotropic media (Section 5.2.1), the vertical hydraulic control exerted by a partially penetrating well will be further diminished.

5.1.2. Pressure Ridge Systems

Pressure ridge systems are produced by injecting uncontaminated water into the subsurface through a line of injection wells located upgradient or downgradient of a contamination plume. The primary purpose of a pressure ridge is to increase the hydraulic gradient and hence the velocity of clean ground water moving into the plume, thereby increasing flow to the recovery wells, which serves to wash the aquifer. Upgradient pressure ridges also serve to divert the flow of uncontaminated ground water around the plume, and downgradient pressure ridges prevent further expansion of the contaminant plume. Typically, treated ground water from extraction

wells within a contaminant plume supply the upgradient or downgradient injection wells used to create a pressure ridge.

5.1.3. Physical Barriers

Physical barriers are constructed of low-permeability material and serve to keep fresh ground water from entering a contaminated aquifer zone. They also help prevent existing areas of contaminant from moving into an area of clean ground water or releasing additional contaminants to a dissolved contaminant plume. Most systems involving physical barriers also require ground-water extraction to ensure containment by maintaining a hydraulic gradient toward the contained area (see Figure 1c). The advantage of physical barriers is that the amount of ground water that must be extracted is greatly reduced compared to the amount when using hydrodynamic controls, as described in Sections 5.1.1 and 5.1.2. Major types of barriers include

- *Caps* (or covers), which are made of low-permeability material at the ground surface, can be constructed of native soils, clays, synthetic membranes, soil cement, bituminous concrete, or asphalt.

- *Slurry trench walls*, excavated at the proper location and to the desired depth while
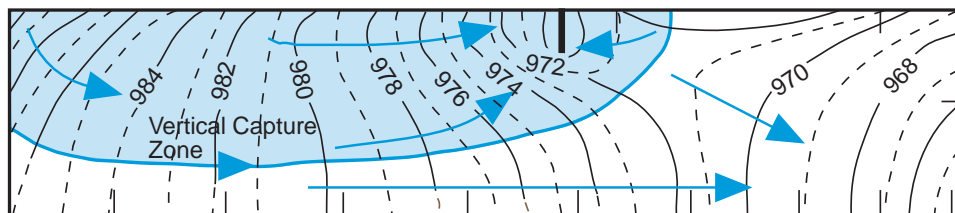

Figure 19. Cross section showing equipotential contours and the vertical capture zone associated with ground-water withdrawal from a partially penetrating well in isotropic media (Cohen et al., 1994).

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keeping the trench filled with a clay slurry, keep the trench sidewalls from collapsing and backfilling with soil bentonite, cement bentonite, or concrete mixtures.

- *Grout curtains* are created by injecting stabilizing materials under pressure into the subsurface to fill voids, cracks, fissures, or other openings in the subsurface. Grout also can be mixed with soil using larger augers.

- *Sheet piling cutoff walls* are constructed by driving sheet materials, usually steel, through unconsolidated materials with a pile driver or more specialized vibratory drivers.

Knox et al. (1984) provide further information on the design and construction of physical ground-water barriers.

5.2. Hydraulic Containment: Other Special Considerations

Certain site conditions can allow contaminants to escape from a hydraulic containment system if they are not characterized and anticipated.

5.2.1. Effects of Anisotropy

In *anisotropic* aquifers, hydraulic conductivity varies with direction. In flat-lying sedimentary aquifers, hydraulic conductivity is often higher in a horizontal than a vertical direction. In fractured rock and foliated metamorphic rocks, such as schist, the direction of maximum and minimum permeability is usually aligned parallel and perpendicular, respectively, to foliation or bedding plane fractures (Cohen et al., 1994). Where sedimentary strata and foliated media are inclined or dipping, significant horizontal anisotropy may be an aquifer characteristic. In anisotropic media, the flow of ground water, as well as contaminants moving with ground water, is usually not perpendicular to the hydraulic gradient.

Figure 20 illustrates how horizontal anisotropy in fractured rock can change the location of the

capture zone of a pumping well. In an aquifer that is assumed to be isotropic, the general direction of ground-water flow should be perpendicular to the hydraulic gradient (Figure 20a). If fractures cause hydraulic conductivity to be higher in a north-south rather than an east-west direction, however, the direction of ground-water flow will diverge from the direction of the hydraulic gradient (Figure 20b). In this example, siting a pumping well based only on the hydraulic gradient (Figure 20a) would result in its failure to capture any portion of a contaminant plume, except in the immediate vicinity of the well.

A contaminant plume that does not follow the hydraulic gradient may indicate that anisotropy is influencing the direction of ground-water flow. Aquifer heterogeneities, such as buried stream channels that have a different direction than the hydraulic gradient, also may allow the direction of contaminant travel to diverge from the hydraulic gradient. Computer programs, such as EPA's Well Head Protection Area (WHPA) code, can be useful for evaluating the potential effects of anisotropy on well capture zones. Figure 21 shows such a simulation for three pumping wells. In this case, with a vertical to horizontal anisotropy ratio of 10:1, the orientation of the capture zones shifts from northwest-southeast (isotropic) to east-west (anisotropic).

5.2.2. Drawdown Limitations

Under some conditions creating and maintaining an inward hydraulic gradient for a contaminant plume is problematic. In such situations, injection wells may be required to create pressure ridges (Section 5.1.2) or physical barriers may need to be installed (Section 5.1.3). Site conditions that might indicate the need for such measures include (Cohen et al., 1994)

- Limited saturated thickness of the aquifer

- Relatively high initial hydraulic gradient
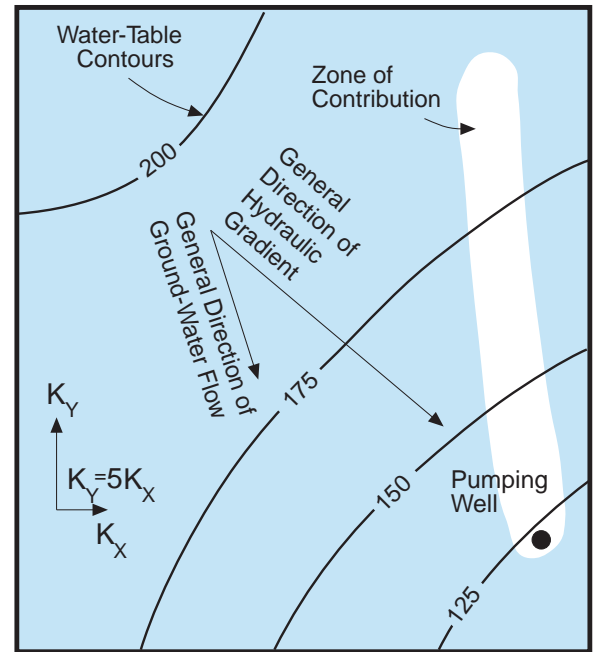
(a) Isotropic Aquifer
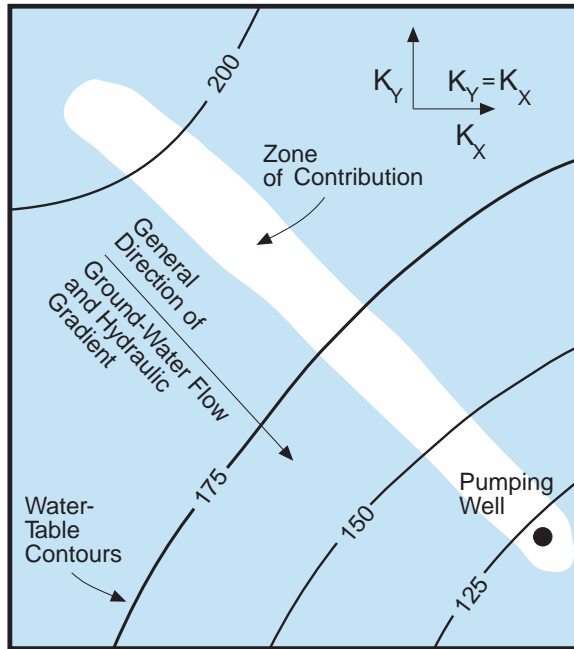
(b) Anisotropic Aquifer

Figure 20. Effect of fracture anisotropy on the orientation of the zone of contribution (capture zone) to a pumping well (Bradbury et al., 1991).

• Sloping aquifer base

• Very high aquifer permeability

• Low aquifer permeability

Where these conditions exist and hydraulic containment is planned, particular care should be taken during site characterization and pilot tests to assess drawdown limitations.

5.2.3. Stagnation Zones

Stagnation zones develop in areas where pump-and-treat operations create low hydraulic gradients and, consequently, low ground-water velocities. The stagnation zone associated with a single extraction well is likely to be located downgradient from the well (Figure 22a). A stagnation zone can develop upgradient from an injection well, however, and form in low-permeability zones, regardless of hydraulic gradient. When multiple extraction or injection wells are involved, a number of stagnation zones may develop (Figure 22b). Stagnation zones caused by low hydraulic gradients can be identified by measuring hydraulic gradients, tracer movement, and ground-water flow rates using downhole flowmeters and through modeling analysis. Stagnation zones within a contaminant plume can reduce the efficiency of a pump-and-treat system; thus, minimizing stagnation is an important objective of capture zone analysis and optimization modeling (Section 6.1).

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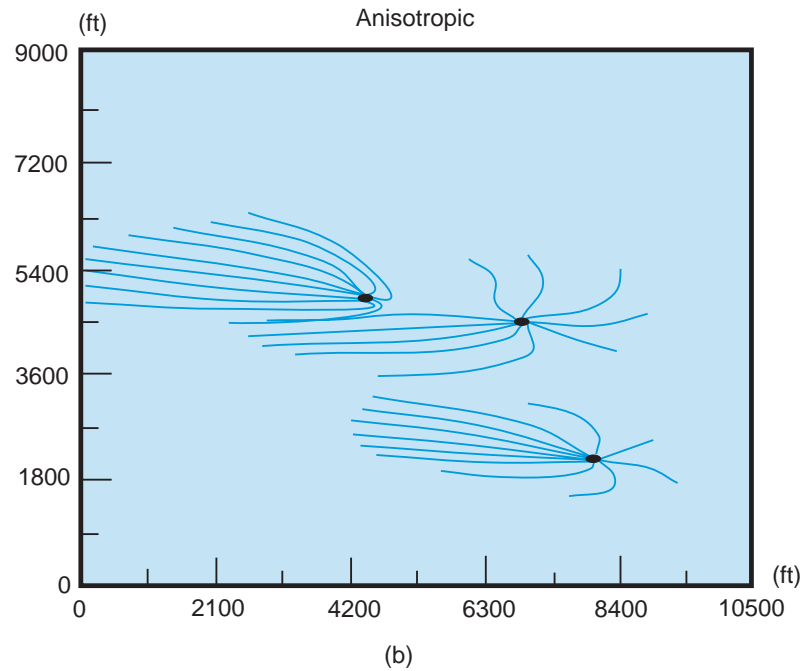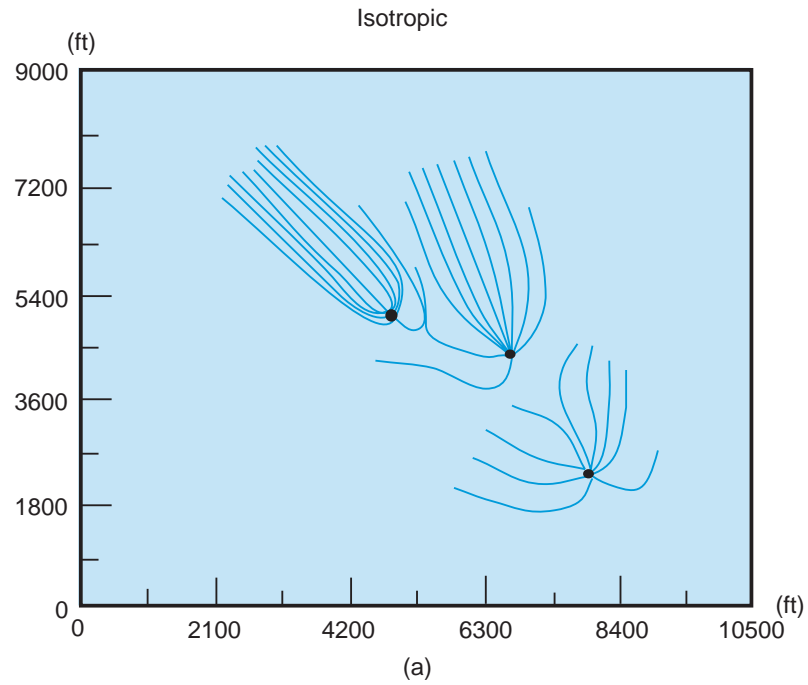**Figure 21.** Capture zone simulation of three pumping wells for an isotropic aquifer (a) and anisotropy ratio of 10:1 (b) using the EPA WHPA code.
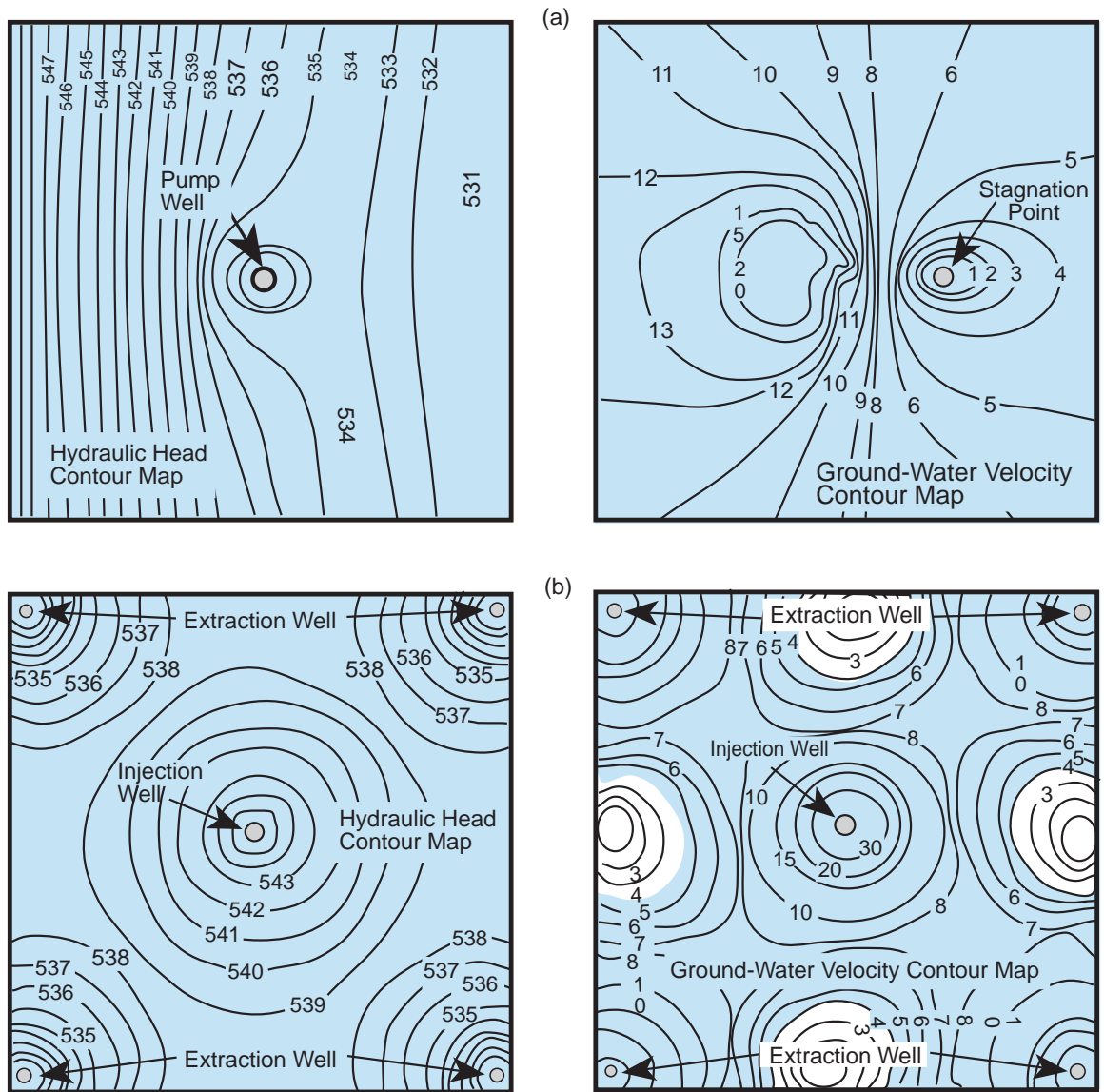
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Figure 22. Examples of stagnation zones (shaded where ground-water velocity is less than 4 L/T): (a) single pumping well and (b) four extraction wells with an injection well in the center (Cohen et al., 1994).

6. Pump-and-Treat System Design and Operation

The basic operating principle of a pump-and-treat system calls for locating a well (or wells) and then pumping at rates that cause all water in a contaminant plume to enter the well rather than continue traveling through the subsurface. Table 2 lists types of data required for evaluating the feasibility of using the pump-and-treat approach at a contaminated ground-water site and then designing an appropriate system. This section describes the key aspects of designing and operating a pump-and-treat system for optimal performance.

6.1. Capture Zone Analysis and Optimization Modeling

In recent years, numerous mathematical models have been developed or applied to compute capture zone, ground-water pathlines, and associated travel times to extraction wells or drains. For relatively simple hydrogeologic settings (homogeneous isotropic aquifers), analytical equations solved manually, using graphical techniques or computer codes based on analytical solutions, may be adequate. For more complex sites, numerical computer models may be required. These models provide insight to flow patterns generated by alternative pump-and-treat approaches and to the selection of monitoring points and frequency. The WHPA model (Blandford and Huyakorn, 1991) and Capture Zone Analytic Element Model (CZAEM) (Haitjema et al., 1994; Strack et al., 1994) developed by EPA are examples of relatively simple computer software based on analyti-

cal equations (WHPA) and the innovative analytic element method (CZAEM) that allows capture zone and ground-water pathline analysis. The numerical MODFLOW and MODPATH models developed by the U.S. Geological Survey are commonly used to model more complex hydrogeologic settings. Cohen et al. (1994) identify a number of computer codes of potential value for capture zone analysis. More detailed information about specific models and EPA guidance on the use of models are available in references on Ground-Water Modeling at the end of this guide (Section 9). Sidebar 5 summarizes the results of computer modeling performed to evaluate the effect of different hydrogeologic conditions on the effectiveness of different types of well patterns.

In addition, *optimization* programming methods are being used increasingly to improve pump-and-treat system design (Gorelick et al., 1993). As applied to the design of pumping systems, optimization involves defining an objective function, such as minimizing the sum of pumping rates from a number of wells. A set of restrictions, or *constraints*, specify various conditions, such as maximum pumping rates and minimum hydraulic heads at individual wells, that must be satisfied by the optimal solution alternative. Hydraulic containment of a contaminant plume usually requires only linear optimization methods, but when contaminant concentrations are specified as constraints, nonlinear methods are often required (Rogers et al., 1995). At the Lawrence Livermore

Table 2. Data Requirements for Pump-and-Treat Systems (Adapted from U.S. EPA, 1991)

Data Description	Purpose(s)	Source(s)/Method(s)
Hydraulic conductivities and storativities of subsurface materials	To determine feasibility of extracting ground water; applicability of pump-and-treat approach	Pumping test, slug tests, laboratory permeability tests
Contaminant concentrations and areal extent	To determine seriousness of the problem; existence of NAPL; applicability and evaluate effectiveness	Soil and water quality sampling data
Contaminant/soil properties (density, aqueous solubility, octanol-water/carbon partitioning coefficient, soil organic carbon content, sorption parameters)	To determine mobility properties; applicability of pump-and-treat approach	Published literature, laboratory tests
Types, thicknesses, and extent of saturated and unsaturated subsurface materials	To develop conceptual design; applicability/considerations for implementation	Hydrogeologic maps, surficial geology maps/reports, boring logs, geophysics
Depth to aquifer/water table	To select appropriate extraction system type; consideration for implementation	Hydrogeologic maps, observation wells, boring logs, piezometers
Ground-water flow direction and vertical/horizontal gradients	To determine proper well locations/spacing considerations for implementation	Water level data, potentiometric maps
Seasonal changes in ground-water elevation	To locate wells and screened intervals; considerations for implementation	Long-term water level monitoring
NAPL density/viscosity/solubility; residual saturation of vadose zone and saturated zone	To predict vertical distribution of contamination; consideration for implementation and evaluating effectiveness	Literature, laboratory measurements
Ground-water/surface water connection	To determine impacts of surface water	Seepage measurements, stream gaging
Precipitation/recharge	To calculate water balance; consideration for implementing and evaluating effectiveness	NOAA reports, local weather bureaus; onsite measurements
Locations, screen/open interval depths, and pumping rates of wells influenced by site	To determine impacts/interference; considerations for implementing and evaluating effectiveness	Well inventory, pumpage records

Sidebar 5

Computer Modeling of Well Patterns Versus Hydrogeologic Conditions

Satkin and Bedient (1988) used the U.S. Geological Survey MOC model to evaluate the effectiveness of seven different well patterns (Figure 23) for restoring contaminated ground water under eight generic hydrogeologic conditions. The hydrogeologic settings were defined as various combinations of three major factors: *maximum drawdown* (high > 10 ft; low < 5 ft), *hydraulic gradient* (high = 0.008; low = 0.0008), and *longitudinal dispersivity* (high = 30 ft; low = 10 ft). Because the contaminants were assumed to not interact with aquifer solids, tailing and rebound effects were not a consideration in the study. Major conclusions of the computer simulations include the following:

- Significant differences in cleanup time were observed using various well locations for a given well pattern.

- The three-spot, doublet, and double-cell well patterns are effective under low hydraulic gradient conditions. These well patterns minimize cleanup time, volume of water circulated, and volume of water treated.

- The three-spot well pattern performed better than any of the other well patterns studied under a high hydraulic gradient, high drawdown, and either a low or high dispersivity.

- None of the well patterns investigated was able to contain and clean up the contaminated plume in a setting with high gradient, low drawdown, and high dispersivity.

- The centerline well pattern is effective in achieving up to 99 percent contaminant reduction under both low and high gradient conditions, but it may present a water disposal problem.

- The five-spot well pattern was the least effective of the well patterns studied.
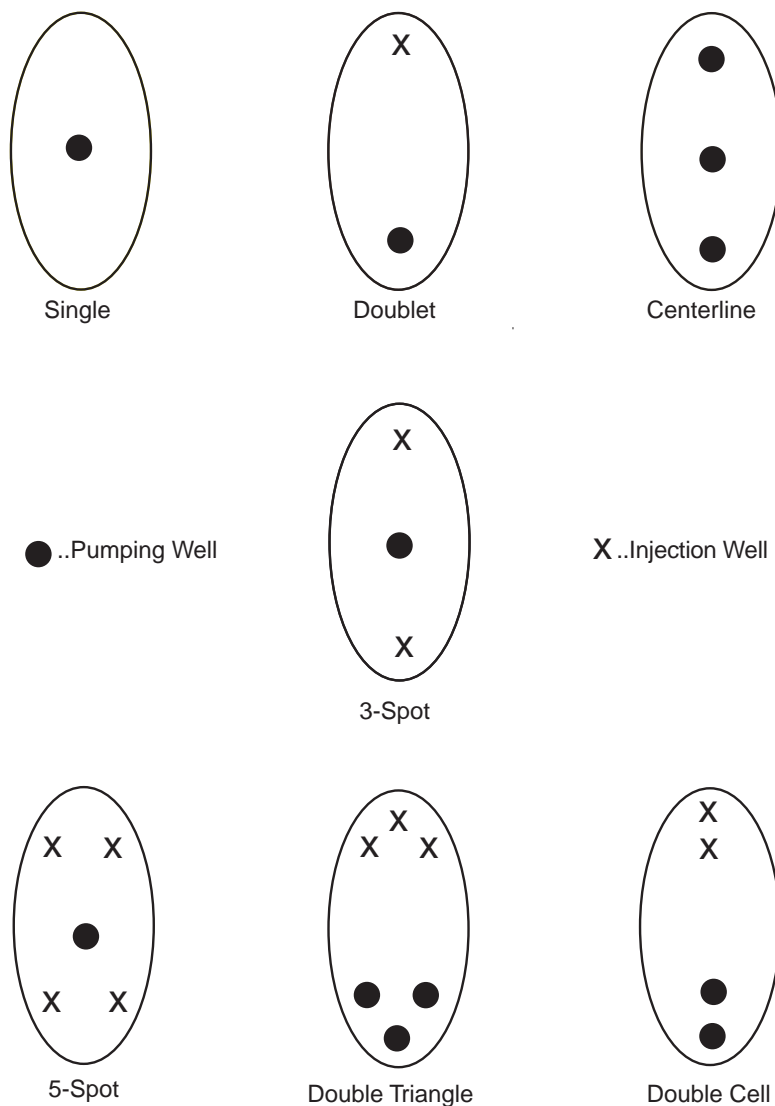
Figure 23.
Major types of
pumping/injection
well patterns
(Satkin and
Bedient, 1988).

National Laboratory (LLNL) site, Rogers et al. (1995) applied an innovative nonlinear optimization approach, using artificial neural networks and a genetic algorithm, to evaluate more than 4 million pumping patterns for the project's 28 extraction and injection wells. The three top-ranked patterns required 8 to 13 wells, with projected costs estimated at $41 to $53 million over the 50-year project life. Using these pumping patterns was estimated to cost from one-third to one-quarter the cost of using all 28 wells at an estimated cost of $155 million.

6.2. Efficient Pumping Operations

Removal of contaminated ground water should be a dynamic process that uses information on the response of the ground-water system to improve the efficiency of pumping operations (Section 3.3). Elements of efficient pumping operations can include

- *Combined plume containment and source remediation*, which can be achieved through the design of the initial pumping flow field. For example, at the LLNL site a line of extraction wells at the downgradient margins of the plume were established to prevent the movement of contaminants toward municipal water-supply wells, while other wells were located in the source areas where the contaminant concentrations were highest. This limited the area requiring remediation and maximized contaminant removal (Hoffman, 1993).

- *Phased construction of extraction wells*, which allows data on the monitored response of the aquifer to pumping operations to be used in siting subsequent wells.

- *Adaptive pumping*, which involves designing the well field such that extraction and injection can be varied to reduce zones of stagnation. Extraction wells can be periodically shut off, others turned on, and pumping rates varied to ensure that contaminant plumes are remediated at the fastest rate possible. Figure 24 illustrates stagnation zones that would develop at the LLNL site if a fixed pumping well configuration were used. With this approach, remediation at the site would take about 100 years (Figure 25). Computer modeling of adaptive pumping indicates that this technique should make it possible to reduce the time required for site cleanup to about 50 years (Figure 25). Further refinements in design might shorten the time even further (Hoffman, 1993).

- *Pulsed pumping*, which has the potential to increase the ratio of contaminant mass removed to ground-water volume where mass transfer limitations restrict dissolved contaminant concentrations. Figure 26 illustrates the concept of pulsed pumping. During the resting phase of pulse pumping, contaminant concentrations increase due to diffusion, desorption, and dissolution in slower moving ground water (Figure 11). Once pumping is resumed, ground water with a higher concentration of contaminants is removed, thus increasing mass removal during pumping. Special care must be taken to ensure that the hydraulic containment objective is met during pump rest periods. Bartow and Davenport (1995) have reported that about 19 percent of the pump-and-treat systems in Santa Clara Valley, California, use some form of pulsed pumping. A recent study by Harvey et al. (1994), however, on the effects of physical parameters (e.g., the mass transfer rate coefficient) concluded that pulsed pumping provides little if any advantage over continuous pumping at an average rate.
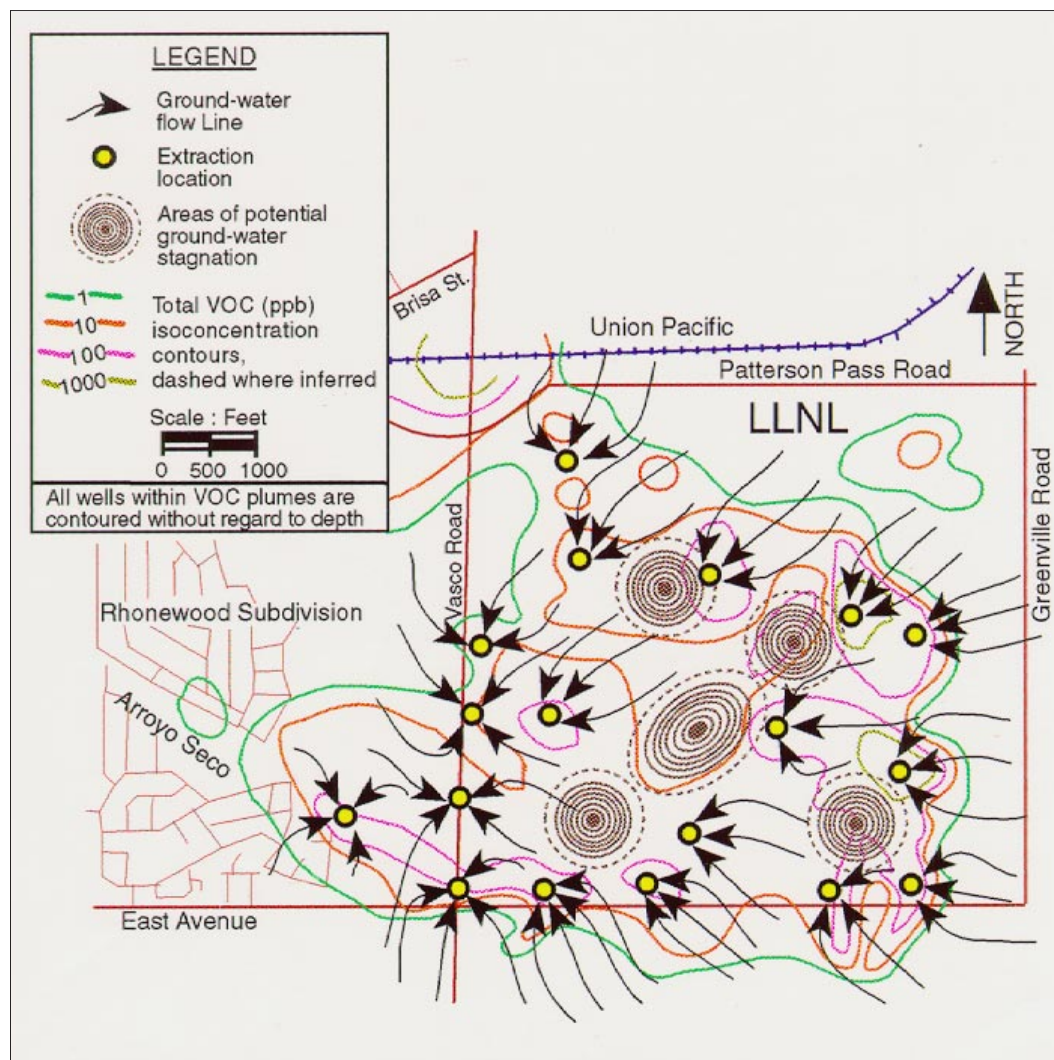
Figure 24. Ground-water flow line in the vicinity of conceptual pumping centers at Lawrence Livermore National Laboratory superimposed on an isoconcentration contour map and showing areas of potential stagnation (Cohen et al., 1994, after Hoffman, 1993).

Figure 25.
Effect of adaptive pumping on cleanup time at Lawrence Livermore National Laboratory Superfund site (Cohen et al., 1994, after Hoffman, 1993).
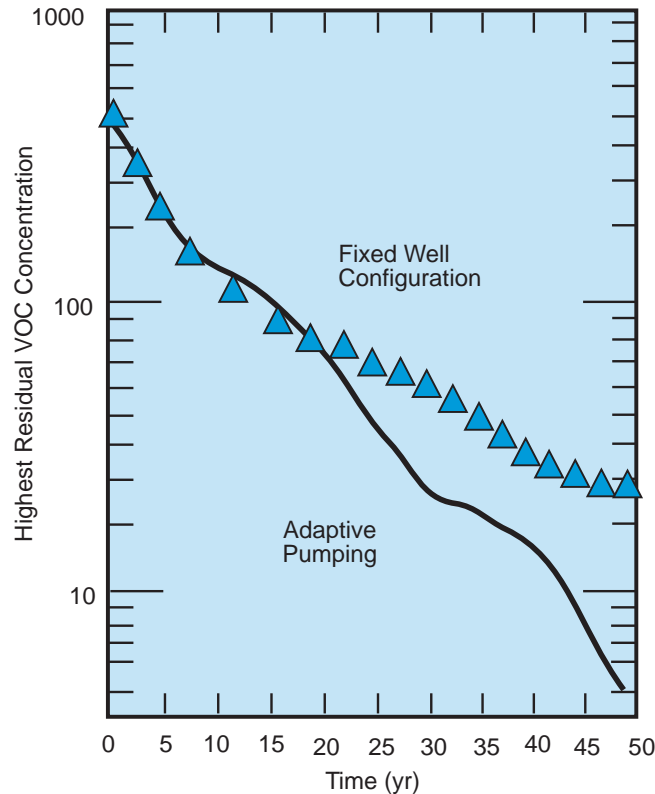
6.3. Treating Contaminated Ground Water

Once extraction wells have brought contaminated water to the surface, treatment is relatively straightforward, provided that appropriate methods have been selected and the capacity of the treatment facility is adequate. Table 3 summarizes the applicability of various treatment technologies to ground water contaminated by any of the major categories of inorganic and organic contaminants. U.S. EPA (1995) describes conventional technologies that have evolved from industrial wastewater treatment and that have been implemented at full scale for treatment of contaminated ground water. These methods fall into two main categories:

• *Biological*. Biological treatment methods use microorganisms to degrade organic compounds and materials into inorganic products. The methods may be applicable for treatment of ground water contaminated by organic compounds if concentrations are low enough and the biological processes are not inhibited. The best established biological treatment methods include (1) activated sludge systems, (2) a sequencing batch reactor, (3) powdered activated carbon in activated sludge (biophysical system), (4) rotating biological contactors, and (5) an aerobic fluidized bed biological reactor.
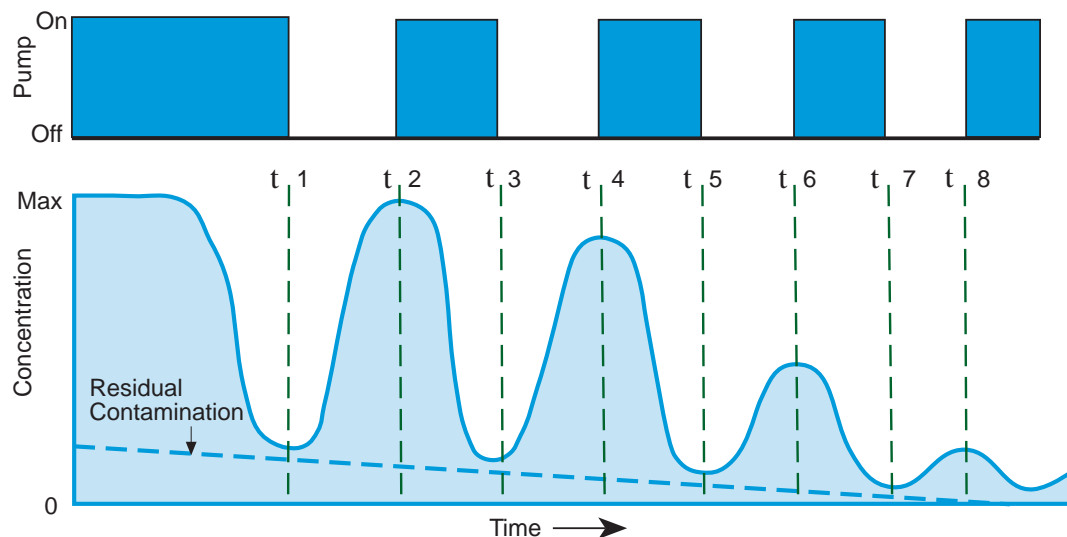
Figure 26.
The pulsed pumping concept (Cohen et al., 1994, after Keely, 1989).

- *Physical/Chemical*. Physical, chemical, or a combination of physical and chemical methods can be used to remove contaminants from ground water. The most commonly used methods include (1) air stripping, (2) activated carbon, (3) ion exchange, (4) reverse osmosis, (5) chemical precipitation of metals, (6) chemical oxidation, (7) chemically assisted clarification, (8) filtration, and (9) ultraviolet (UV) radiation oxidation.

Various emerging and innovative treatment technologies, such as electrochemical separation and wet air oxidation, are being tested. The EPA reference sources identified for ground-water treatment methods at the end of this guide (Section 9) provide additional information on established and innovative treatment technologies.

6.4.   Monitoring Performance

An appropriately designed monitoring program is essential for measuring the effectiveness of a pump-and-treat system in meeting hydraulic containment and aquifer restoration objectives. In general, *containment* monitoring involves (1) measuring hydraulic heads to determine if the pump-and-treat system creates inward gradients that prevent ground-water flow and dissolved contaminant migration across the containment zone boundary, and (2) ground-water quality monitoring to detect any contaminant movement or increase of contaminant mass across the containment zone boundary. Aquifer *restoration* monitoring mainly involves measurement of contaminant concentrations in pumping and observation wells to determine the rate and effectiveness of mass removal. Cohen et al. (1994) provide more detailed guidance on monitoring the performance of pump-and-treat systems.

6.4.1.   Hydraulic Head Monitoring for Containment

In general, the number of observation wells needed for monitoring inward hydraulic gradients in a containment area increases with site complexity and with decreasing gradients along the containment perimeter. Strategies for adequately monitoring inward gradients and hydraulic containment include (Cohen et al., 1994)

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- Measuring hydraulic heads in three dimensions using nested piezometers for detecting vertical gradients. As shown in Figure 19, partially penetrating wells may not create an adequate vertical capture zone. Where leaky confining layers separate aquifers, hydraulic gradients should be toward the contaminated zone. Figure 27 illustrates observations from a nest of piezometers at the Chem-Dyne Superfund site in Ohio. Water levels from the deep piezometer are consistently about a foot higher than in the intermediate and shallow piezometers, indicating an upward gradient.

- Monitoring water levels in observation wells intensively during system startup and equilibration to determine an appropriate measurement frequency. This may involve using pressure transducers and dataloggers to make near-continuous head measurements for a few days or weeks, then switching sequentially to daily, weekly, monthly, and possibly quarterly monitoring. Data collected during each phase should provide the justification for any subsequent decrease in monitoring frequency.

- Making relatively frequent hydraulic head measurements when the pumping rates or locations are modified, or when the system is significantly perturbed in a manner that has not been evaluated previously. Significant new perturbations can arise from, for example, unusual recharge, flooding, drought, and new offsite well pumping.

- Measuring hydraulic head as close to the same time as possible when monitoring inward hydraulic gradients or a potentiometric surface so that data are temporally consistent. This ensures that differences in ground-water elevation within a network represent spatial rather than temporal variations.

- Supplementing hydraulic head data with flow-path analysis using potentiometric maps or particle tracking computer codes. Figure 28 shows that ground water can flow between and beyond recovery wells even though hydraulic heads throughout the mapped aquifer are higher than the pumping level.

- Conducting an analysis to determine if containment is threatened or lost when hydraulic head data do not indicate a clear inward gradient. Rose diagrams can be prepared to display the variation over time of hydraulic gradient direction and magnitude based on data from at least three wells (Figure 29). Even when the time-averaged flow is toward the pump-and-treat system, containment can be compromised if contaminant escapes from the larger capture zone during transient events or if a net component of migration away from the pumping wells occurs over time.

6.4.2. Ground-Water Quality Monitoring for Containment

Monitor well locations and completion depths should be selected to provide a high probability of detecting containment system leaks in a timely manner. Consequently, monitor wells with relatively close spacing are usually located along or near the potential downgradient containment boundary. Ground-water quality sampling usually is performed less frequently than the measuring of hydraulic head because contaminant movement is a slower process. Because ground-water quality monitoring is more expensive than hydraulic head monitoring, designing a cost-effective monitoring plan requires special care. Strategies that may help reduce costs without compromising the integrity of the program include (Cohen et al., 1994)

Table 3. Applicability of Treatment Technologies to Contaminated Ground Water (U.S. EPA, 1991)

Contaminants	Neutralization	Precipitation	Coprecipitation/Coagulation	UV/Ozone	Chemical Oxidation	Reduction	Distillation	Air Stripping	Steam Stripping	Activated Carbon	Evaporation	Gravity Separation	Flotation	Membrane Separation*	Ion Exchange	Filtration	Biological	Electrochemical
Metals																		
Heavy metals	X	●	●	X	X	○	X	X	X	○	●	●	X	●	●	●	X	●
Hexavalent chromium	X	●	X	X	X	●	X	X	X	○	●	X	X	○	●	X	X	●
Arsenic	X	○	●	○	○	X	X	X	X	○	X	○	X	●	●	●	X	X
Mercury	X	●	●	X	X	●	X	X	X	●	X	○	X	○	●	●	X	X
Cyanide	X	X	X	●	●	X	X	X	X	X	●	X	X	●	●	X	○	○
Corrosives	●	●	X	X	X	X	○	X	X	X	X	X	X	X	X	X	X	X
Volatile organics	X	X	X	○	●	X	●	●	●	●	X	X	X	○	○	X	○	X
Ketones	X	X	X	○	●	X	●	●	●	X	X	X	X	X	X	X	●	X
Semivolatile organics	X	○	○	●	●	X	●	X	●	●	○	○	○	●	●	X	●	X
Pesticides	X	○	○	●	●	X	●	X	○	●	○	○	○	●	●	●	○	X
PCBs	X	●	●	●	●	X	●	X	X	●	●	●	●	●	●	●	○	X
Dioxins	X	●	●	●	○	X	●	X	X	●	●	●	●	●	●	●	○	X
Oil and grease/floating products	X	●	●	X	X	X	●	X	X	X	●	●	●	●	●	○	○	X

● Applicable   ○ Potentially Applicable   X Not Applicable

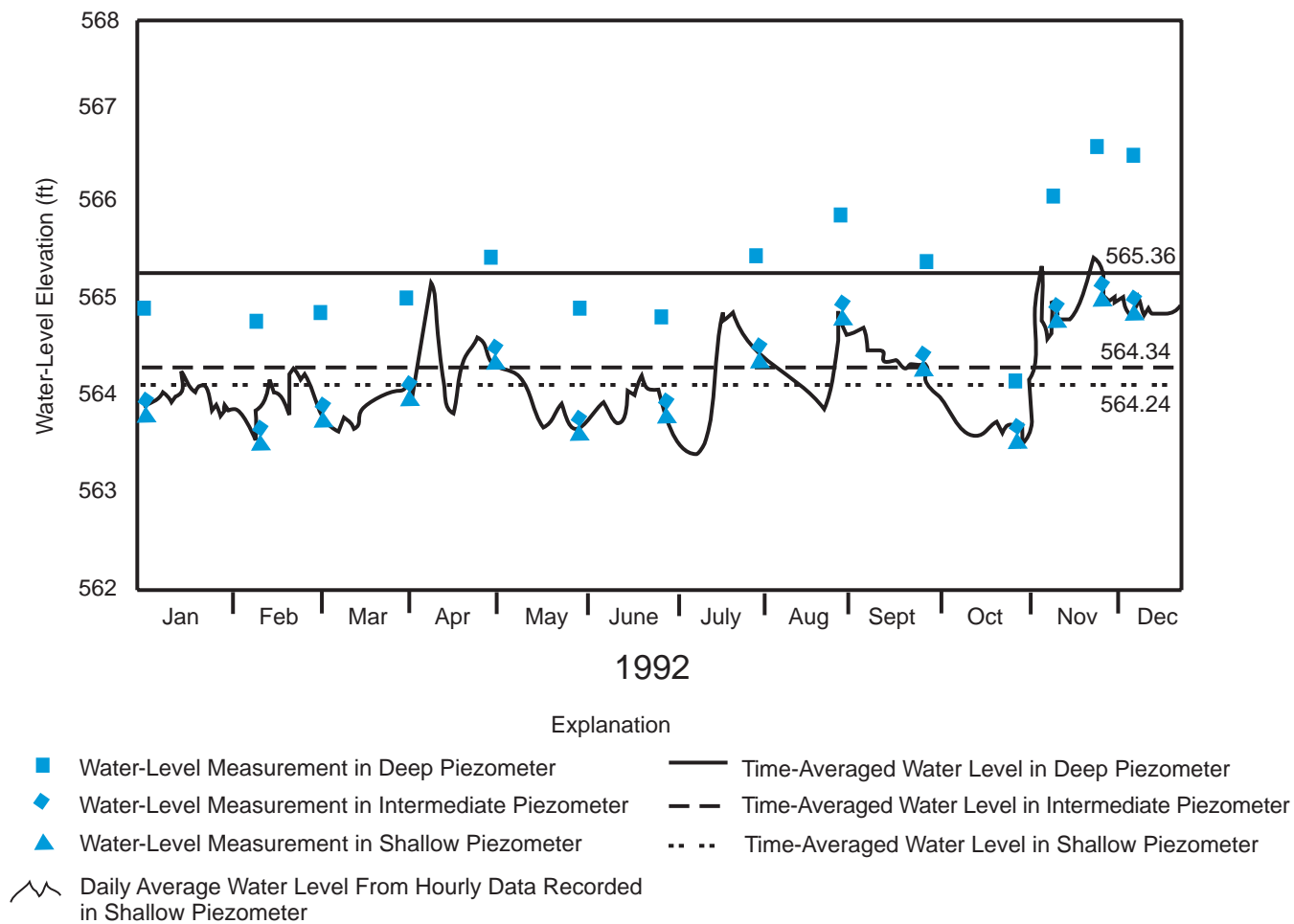*Technology includes several processes; reverse osmosis and ultrafiltration among others.

Figure 27. Nested piezometer hydrograph for 1992 at the Chem-Dyne Superfund site (Cohen et al., 1994, after Papadopulos & Associates, 1993).

Figure 28.
Ground-water flow between and beyond the extraction wells, resulting even though hydraulic heads throughout the mapped aquifer are higher than the pumping level (Cohen et al., 1994).
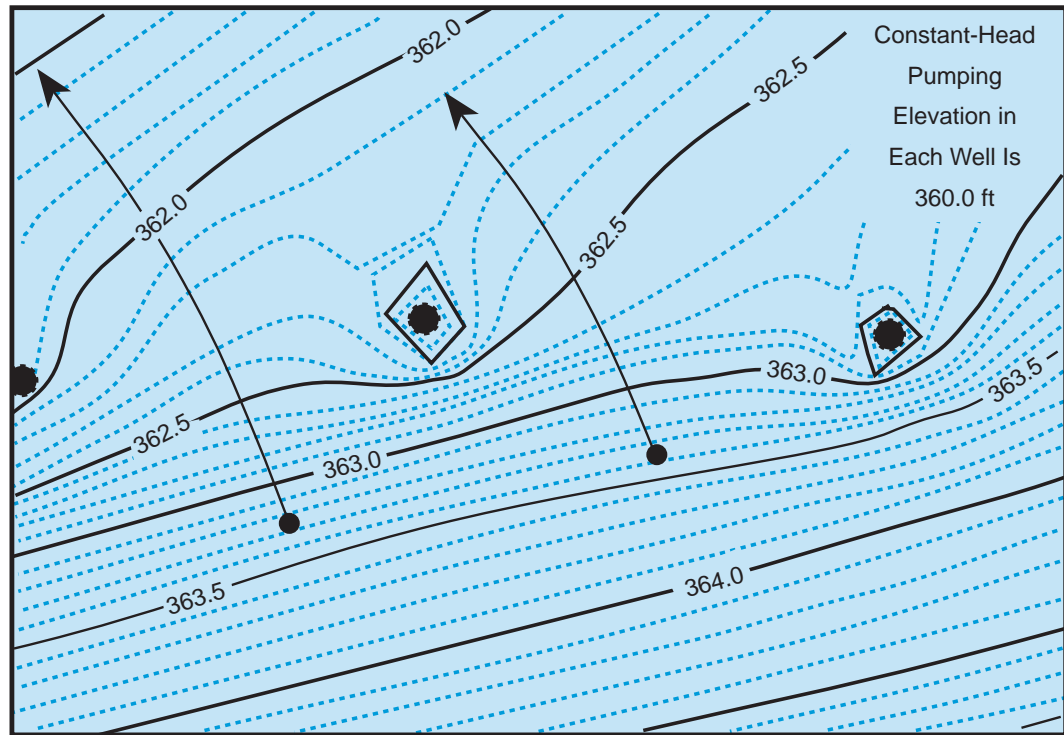
- Sampling more frequently and performing more detailed chemical analyses in the early phase of the monitoring program, and using the information gained to optimize sampling efficiency and reduce the spatial density and temporal frequency of sampling in the later phases.
- Monitoring ground-water quality in perimeter and near-perimeter leak detection wells more frequently than in wells that are at a greater distance from the contaminant plume limit.
- Specifying sampling frequency based on potential containment failure migration rates that factor in hydraulic conductivity and effective porosity of the different media as

well as the maximum plausible outward hydraulic gradients. Consider more frequent sampling of more permeable strata in which migration might occur relatively quickly as compared to the sampling frequency for less permeable media.

- Focusing chemical analyses on site contaminants of concern and indicator constituents after performing detailed chemical analyses during the remedial investigation or the early phase of a monitoring program. Conduct more detailed chemical analyses less frequently or when justified based on the results of the more limited analyses.

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6.4.3. Aquifer Restoration Monitoring

Aquifer restoration monitoring consists of three main elements:

- Ground-water sampling from *all* extraction wells and selected observation wells within the contaminant plume to interpret cleanup progress. Parameters analyzed should include (1) the chemicals of concern, (2) chemicals that could affect the treatment system, such as iron, which can precipitate and clog treatment units if ground water is aerated, and (3) chemicals that may indicate the occurrence of other processes of interest, such as dissolved oxygen, carbon dioxide, and biodegradation products. These sampling data are important for making adjustments for efficient well operation (Section 6.2).

- Periodic sampling and chemical analysis of aquifer materials from representative locations in the contamination zone to measure removal of nondissolved contaminants.
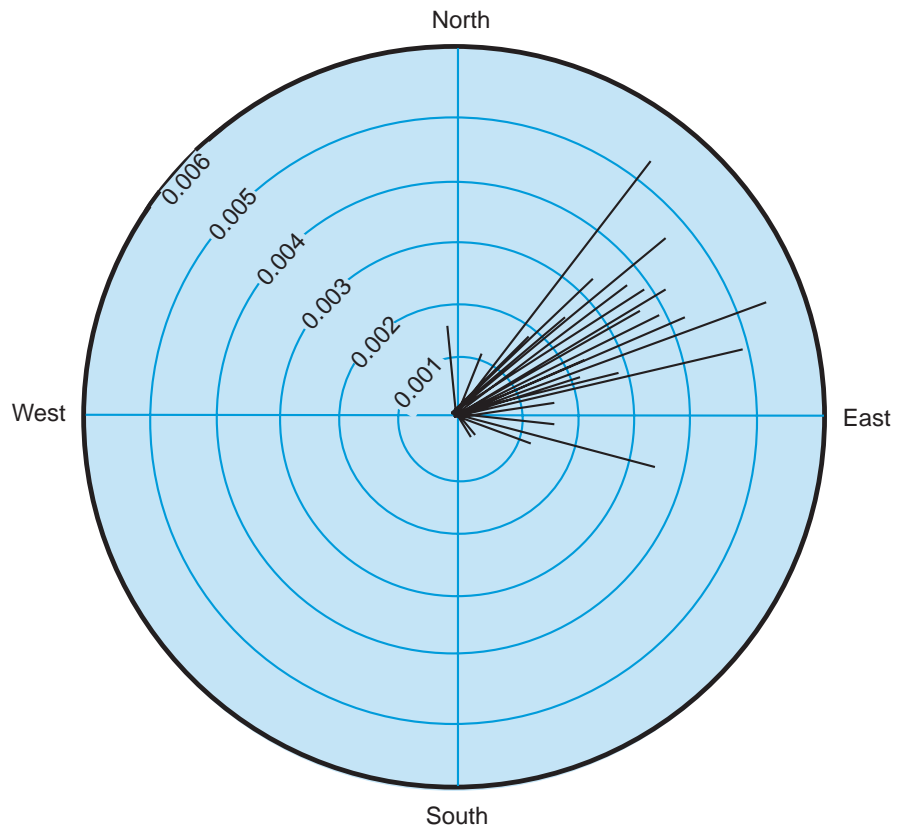

Figure 29.
Example display of ground-water flow directions and hydraulic gradients determined between three observation wells (Cohen et al., 1994).

• Regular sampling and analysis of treatment system influent and effluent to assess (1) treatment system performance, (2) change in influent chemistry that may influence treatment effectiveness, and (3) dissolved contaminant concentration trends. Figure 30 shows influent and effluent VOC concentrations for the first 6 years of operation at the Chem-Dyne Superfund site treatment plant. Influent concentrations data showed a large drop in the first year, and then a more gradual decline over the next 5 years due to tailing effects (Section 4).

The simplest indicator of progress in removing ground-water contaminants is a plot of the cumulative mass removed from the aquifer as measured by influent concentrations to the treatment system. Figure 31 shows the cumulative mass of VOC removal at the Chem-Dyne site. Approximately 27,000 pounds of VOCs have been removed since the system became operational. As is apparent from both Figures 30 and 31, however, the rate of removal slowed significantly in the sixth year. Consequently, removal of the remaining one-third of the in-place mass will take much longer than 6 years.
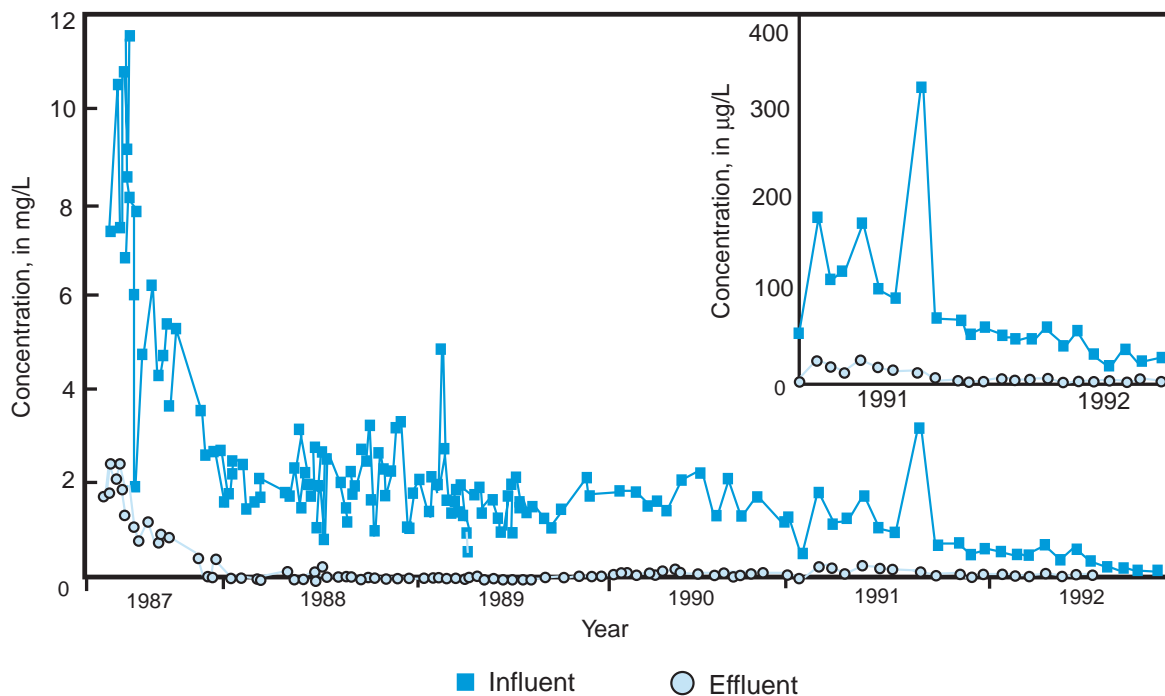

Figure 30. Influent and effluent VOC concentrations (mg/L) at the Chem-Dyne treatment plant from 1987 to 1992 (Cohen et al., 1994, after Papadopulos & Associates, 1993).

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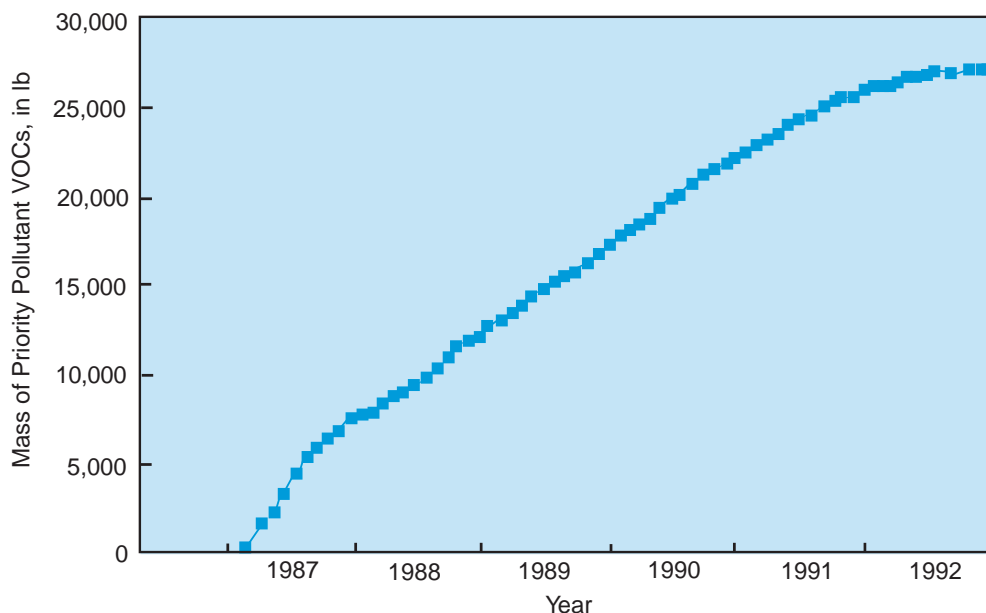
Figure 31. Cumulative mass of VOCs removed from the aquifer at the Chem-Dyne site from 1987 to 1992 (Cohen et al., 1994, after Papadopulos & Associates, 1993).

6.5. Evaluating Restoration Success and Closure

Ground-water restoration, as operationally defined, is achieved when a predefined cleanup standard is attained and sustained. Figure 32 outlines procedures for determining the success and/or timeliness of closure of a pump-and-treat system. U.S. EPA (1992) defines six stages of remediation using water quality data from a single well (Figure 33):

• *Stage 1*. Site evaluation to determine the need for and conditions of a remedial action; define cleanup standard.

• *Stage 2*. Operation of the remediation system, during which contaminant concentrations decline.

• *Stage 3*. Conclusion of treatment after contaminant concentrations have remained below the cleanup standard for a sufficient period of time based on expert knowledge of the ground-water system and data collected during pump-and-treat operations.

• *Stage 4*. Post-termination monitoring of water levels and contaminant concentrations to determine when the ground-water flow system is reestablished.
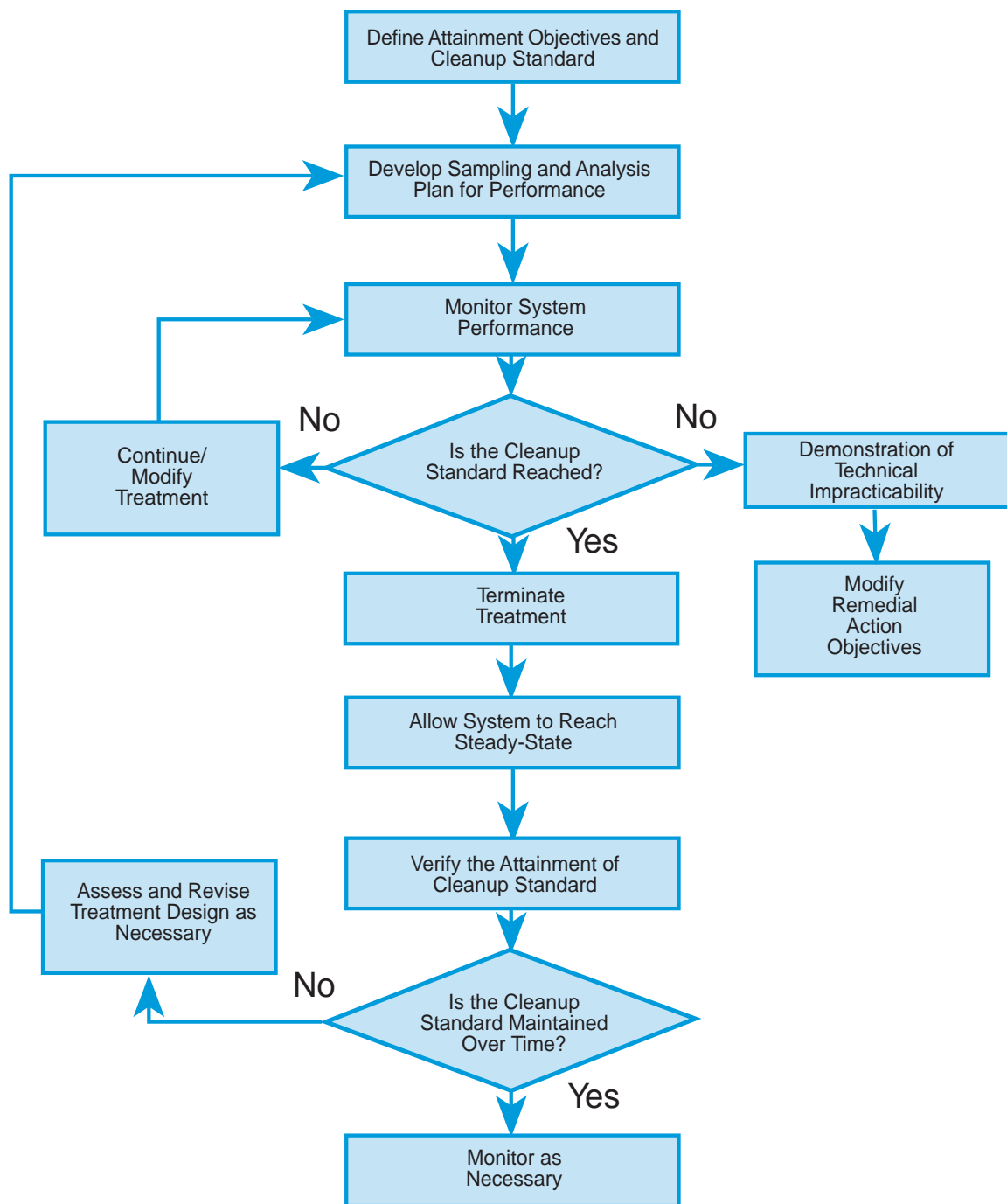
Figure 32. Determining the success and/or timeliness of closure of a pump-and-treat system (Cohen et al., 1994).

The flowchart contains the following elements:

Define Attainment Objectives and Cleanup Standard

↓

Develop Sampling and Analysis Plan for Performance

↓

Monitor System Performance

↓

Is the Cleanup Standard Reached?

No → Continue/Modify Treatment (returns to Monitor System Performance)

No → Demonstration of Technical Impracticability → Modify Remedial Action Objectives

Yes ↓

Terminate Treatment

↓

Allow System to Reach Steady-State

↓

Verify the Attainment of Cleanup Standard

↓

Is the Cleanup Standard Maintained Over Time?

No → Assess and Revise Treatment Design as Necessary (returns to Develop Sampling and Analysis Plan for Performance)

Yes ↓

Monitor as Necessary

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Figure 33. Stages of remediation in relation to example contaminant concentrations in a well at a pump-and-treat site (U.S. EPA, 1992).

- *Stage 5*. Sampling to assess attainment of the cleanup standard. If the treatment standard is not met, the treatment design may need to be assessed and revised (Figure 32).
- *Stage 6*. Declaration that the aquifer is clean or still contaminated based on data collected during Stage 5.

Cohen et al. (1994) and U.S. EPA (1992) address in more detail the types of statistical techniques that are required to analyze short-term and long-term trends in contaminant concentrations.

7.   Variations and Alternatives to Conventional Pump-and-Treat Methods

Numerous variations and enhancements of pump-and-treat systems are possible. Major types include

- Using trenches or drains in combination with or to replace vertical pumping wells (Section 7.1). Where site conditions are favorable (i.e., shallow contamination), trenches are a commonly used method for intercepting contaminated ground water.

- Using horizontal wells or trenches to replace or complement vertical wells (Section 7.1). Recent developments in directional drilling technology make the use of horizontal or inclined wells an attractive alternative approach.

- Inducing fractures in the subsurface to improve the yield of wells (Section 7.1). Although widely used by the petroleum industry, the use of induced fractures is considered an emerging technology in ground-water remediation with applications limited to contaminated ground water in low-permeability materials.

- Implementing vadose zone source control and remediation, often as a necessary adjunct to ground-water cleanup (Section 7.2).

- Making chemical enhancements, which can have the potential to accelerate aquifer remediation (Section 7.3).

- Making biological enhancements, which can present opportunities for eliminating or

reducing the requirements for surface treatment of contaminated ground water (Section 7.4).

Notably few alternatives to pump-and-treat systems are without requirements for continuous energy input for pumping fluids (Section 7.4).

7.1.   Alternative Methods for Fluid Delivery and Recovery

Conventional pump-and-treat systems usually involve extraction wells—and possibly injection wells—placed vertically in an aquifer. Alternative methods of delivery and recovery of contaminated ground water might enhance the performance of a pump-and-treat system, especially while interim measures are undertaken, by improving the effectiveness of containment. These methods also might augment the performance of a variety of remedial actions selected as possible long-term remedies. Major alternatives include

- *Interceptor Trenches*. After vertical wells, trenches are the most widely used method for controlling subsurface fluids and recovering contaminants. They function similarly to horizontal wells, but also can have a significant vertical component, which cuts across and can allow access to the permeable layers in interbedded sediments. For shallower applications, trenches can be installed at relatively low cost using conventional equipment. Recent innovations combine trench excavation and well screen installation into a

single step for depths up to 20 feet (U.S. EPA, 1994). Where depth is not a constraint, interceptor trenches are generally superior to vertical wells. In such situations, they are especially effective in low-permeability materials and heterogeneous aquifers.

- *Horizontal and Inclined Wells*. Relatively recent advances in directional drilling technology, which use specialized bits to curve bores in a controlled arc, have revolutionized the field of well design. Directional drilling methods can create wellbores with almost any trajectory. Wells that curve to a horizontal orientation are especially suited to environmental applications (Figure 34).

- *Induced Fractures*. EPA research has shown that petroleum engineering technology used to induce fractures for increased productivity of oil wells also can improve the performance of environmental wells. Induced fractures are used mainly where low-permeability aquifer materials create problems for the recovery of contaminants.

Table 4 rates the potential applications of alternative methods for delivery or recovery of subsurface fluids in relation to (1) access, (2) depth, (3) recovered phases, (4) geology, and (5) availability. Figure 35 illustrates two ways in which horizontal wells or trenches can be used to intercept a contaminant plume. In many applications, deciding between use of a trench or a horizontal well hinges on economic rather than technical issues, with trenches generally being more cost effective at depths less than 20 feet and horizontal wells being generally more cost effective at depths greater than 20 feet. Cost savings can be substantial compared to vertical well systems. For example, initial remediation plans at a site in North Carolina called for 100 vertical wells to recover a hydrocarbon plume at an estimated cost of $1 million. Instead, a continuous excavation and completion system was installed for less than $350,000 (U.S. EPA, 1994). EPA's Manual *Alterative Methods for Fluid Delivery and Recovery* (U.S. EPA, 1994) provides more detailed information on design considerations and applications of these methods.

7.2.   Vadose Zone Source Control

Removal of contaminants from the vadose (unsaturated) zone is an essential part of any remedial action plan to clean up contaminated ground water. Major methods include

- *Capping* to reduce infiltration of precipitation.

- *Excavation* to remove contaminated soil for ex situ treatment, which is most commonly used where contaminants have not penetrated deeply into the subsurface.

- *Soil vapor extraction* (SVE), which is used to extract volatile organic contaminants by flushing with air, and *bioventing*, a SVE system in which the addition of nutrients further enhances the biodegradation of organic contaminants. Both techniques, considered innovative technologies a few years ago, are widely used.

- *In situ thermal* technologies to enhance the mobility of volatile and semivolatile organic contaminants; for example, steam-enhanced extraction and radio frequency heating are promising innovative technologies.

7.3.   Physical and Chemical Enhancements

Physical and chemical enhancements to pump-and-treat systems primarily function by enhancing the mobility of contaminants, thus increasing their recovery in ground water that has been pumped to the surface for treatment. Some chemical enhancements transform contaminants in place in the subsurface to reduce toxicity.
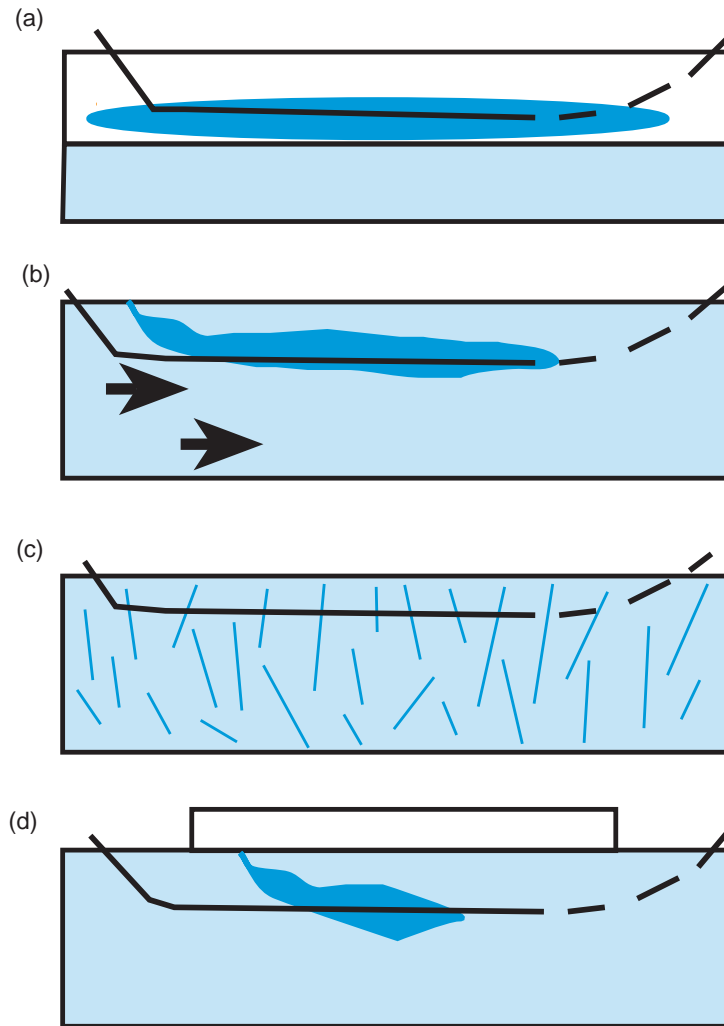
Figure 34. Some applications of horizontal wells: (a) intersecting flat-lying layers, (b) intercepting plume elongated by regional gradient, (c) intersecting vertical fractures, and (d) access beneath structures (U.S. EPA, 1994).

Table 4. Issues Affecting Application of Alternative Methods for Delivery or Recovery (U.S. EPA, 1994)

| Issue	Horizontal Well		Induced Fracture		Trench	
Access						
Fragile structures over target	●	Minimal surface disturbance	■	Evaluate effects of surface displacement	■	Excavation expected to be infeasible
Poor access over target	●	Standoff required	◆	Possible with horizontal well	■	Excavation expected to be infeasible
Depth						
<6m	●	1 m minimum depth	●	1-2 m minimum depth	●	Installation with common equipment
6-20 m	●	Cost of guidance system increases at >6 m	●		✿	Excavation costs increase with depth
>20 m	●	No depth limit within environmental applications	●	No depth limit within environmental applications	◆	Specialized excavation methods required
Recovered Phase						
Aqueous	●		●		●	
LNAPL	◆	Requires accurate drilling; best if water table fluctuations are minor	✿	Best with access to individual fractures	●	Widely used to ensure capture; accommodates water table fluctuations
DNAPL	✿	Requires accurate drilling and site characterization	◆	Caution; steeply dipping fractures may cause downward movement	●	Assuming mobile phase present and accurately located
Vapor	●	Consider omitting gravel pack to save costs	●	Best with access to individual fractures	✿	Requires tight seal on top of trench
Geology						
Normally consolidated clay	✿	Smearing of bore wall may reduce performance	◆	Induced fractures may be vertical and limited in size	●	Large discharge expected relative to alternatives
Swelling clay	✿	Smearing of bore wall may reduce performance	●	Relatively large, gently dipping fractures expected	●	Large discharge expected relative to alternatives
Silty clay till	✿	Smearing of bore wall may reduce performance	●	Relatively large, gently dipping fractures expected	●	Large discharge expected relative to alternatives
Stratified sediment or rock	◆	Anisotropy may limit vertical influence of well	✿	Stratification may limit upward propagation and increase fracture size	●	Good way to access many thin beds or horizontal partings

(Continued)

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Table 4. (Continued)

Issue	Horizontal Well		Induced Fracture		Trench	
Vertically fractured sediment or rock	●	Orient well normal to fractures when possible	❀	Good where induced fractures cross-cut natural fractures (overconsolidated sediment and rock)	❀	Orient trench perpendicular to natural fractures when possible
Coarse gravel	◆	Possible problems with hole stability; penetrating cobbles	■	Permeability enhancement may be unnecessary	●	Stability a concern during excavation
Thick sand	❀	May be difficult to access top and bottom of formation; hole stability problems	■	Permeability enhancement may be unnecessary	●	Stability a concern during excavation
Rock	◆	Feasible, but drilling costs more in rock than in sediment	●	Widely used in oil, gas, and water wells drilled in rock	■	Excavation difficult but blasting possible to make trench-like feature
Availability	10 to 20 companies with capabilities; nationwide coverage but may require equipment mobilization		Several companies offer service; nationwide coverage with equipment mobilization		Shallow trench (<6 m) installation widely available from local contractors; deep trench will require mobilization	
Current Experience (Approximate)	150 to 250 wells at 50 to 100 sites		200 to 400 fractures at 20 to 40 sites		1,000+ trenches at many hundreds of sites	

Key
● Good application
❀ Moderately good
◆ Fair, with possible technical difficulties
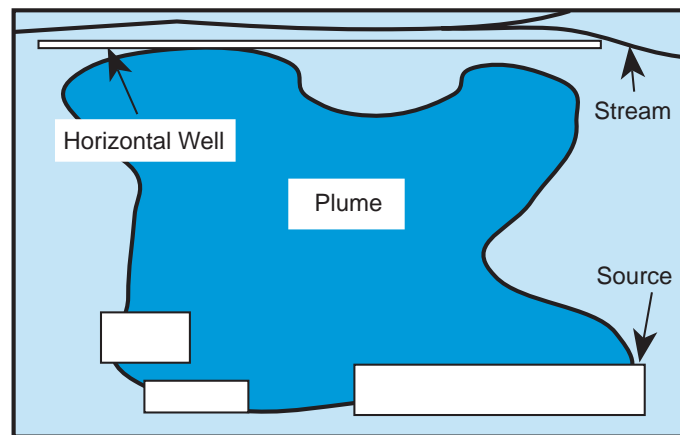■ Poor; not recommended using available methods

(a)
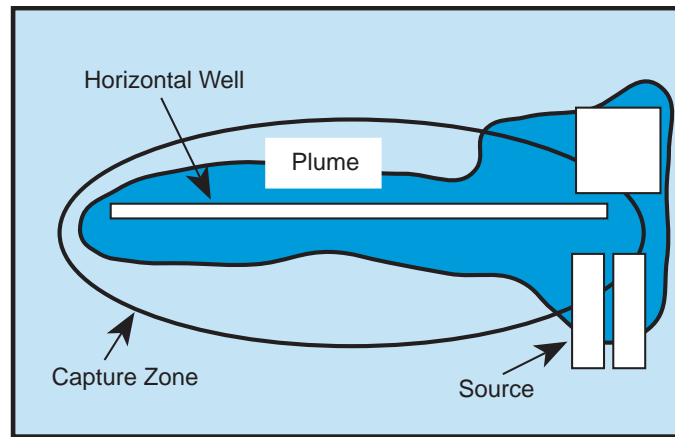
(b)

Figure 35. Two approaches using trenches or horizontal wells to intercept contaminant plumes (U.S. EPA, 1994).

7.3.1. Physical Enhancements

Air sparging, also known as *in situ aeration*, is an approach that is similar to soil vapor extraction except that air is injected into the saturated zone rather than the vadose zone (Figure 36). Air sparging systems can effectively remove a substantial amount of volatile aromatic and chlorinated hydrocarbons in a variety of geologic settings, but significant questions remain about the ability of this technology to achieve health-based standards throughout the saturated zone (NRC, 1994). *Thermal* enhancements, such as steam and hot-water flooding, increase the mobility of volatile and semivolatile contaminants. Use of *induced fractures* (Section 7.1) is another form of physical enhancement to pump-and-treat systems.

7.3.2. Chemical Enhancements

Chemically enhanced pump-and-treats systems require use of injection wells to deliver reactive agents to the contaminant plume and extraction wells to remove reactive agents and contaminants (Figure 37). The major types of chemical enhancements are

- *Soil flushing*, which enhances recovery of contaminants with low water solubility, free-product and residual NAPLs, and sorbed contaminants. Two major types of chemical agents can be used: (1) *cosolvents*, which, when mixed with water, increase the solubility of some organic compounds, and (2) *surfactants*, which may cause contaminants to desorb and may increase NAPL mobility by lowering the interfacial tension between the NAPL and water, increasing the solubility. Soil flushing is one of the most promising innovative technologies for dealing with separate phase DNAPLs in the subsurface (NRC, 1994).

- *In situ chemical treatment*, which involves reactive agents that oxidize or reduce contaminants, converting them to nontoxic forms or immobilizing them to minimize contaminant migration. This innovative technology is still in the early stages of development.

The EPA report *Chemical Enhancements to Pump-and-Treat Remediation* (Palmer and Fish, 1992) provides additional information on technical issues related to this topic.

7.4. Biological Enhancements

Biological enhancements to pump-and-treat systems stimulate subsurface microorganisms, primarily bacteria, to degrade contaminants to harmless mineral end products, such as carbon dioxide and water. In situ bioremediation of certain types of hydrocarbons (primarily petroleum products and derivatives), encouraged by addition of oxygen and nutrients to the ground water, is an established technology. Other readily biodegradable substances, such as phenol, cresols, acetone, and cellulosic wastes, are also amenable to aerobic in situ bioremediation. Key elements in such a system are delivery of oxygen and nutrients by use of an injection well (Figure 38a) or an infiltration gallery (Figure 38b). A limitation of in situ bioremediation is that minimum contaminant concentrations required to maintain microbial populations may exceed health-based cleanup standards, particularly where heavier hydrocarbons are involved.

In situ bioremediation of chlorinated solvents is less well demonstrated because metabolic processes for their degradation are more complex than those for hydrocarbon degradation (NRC, 1994). Nonetheless, methanotrophs are able to degrade some chlorinated solvents under aerobic conditions if methane is supplied as an energy source. Also, the ability of anaerobic bacteria to degrade a variety of chlorinated solvents is well

(a)

Vent to
Atmosphere

Air Compressor

Vacuum

Vapor Extraction
Wells

Vapor
Treatment

Surface Soil/Cap

Unsaturated Zone

Saturated Zone

Contaminated Zone

Streamtubes of Air

Direction of Ground-
Water Flow

(b)

Injection Point for Flushing Gas

Extraction of Contaminated Gas

Surface Soil/Cap

Unsaturated Zone
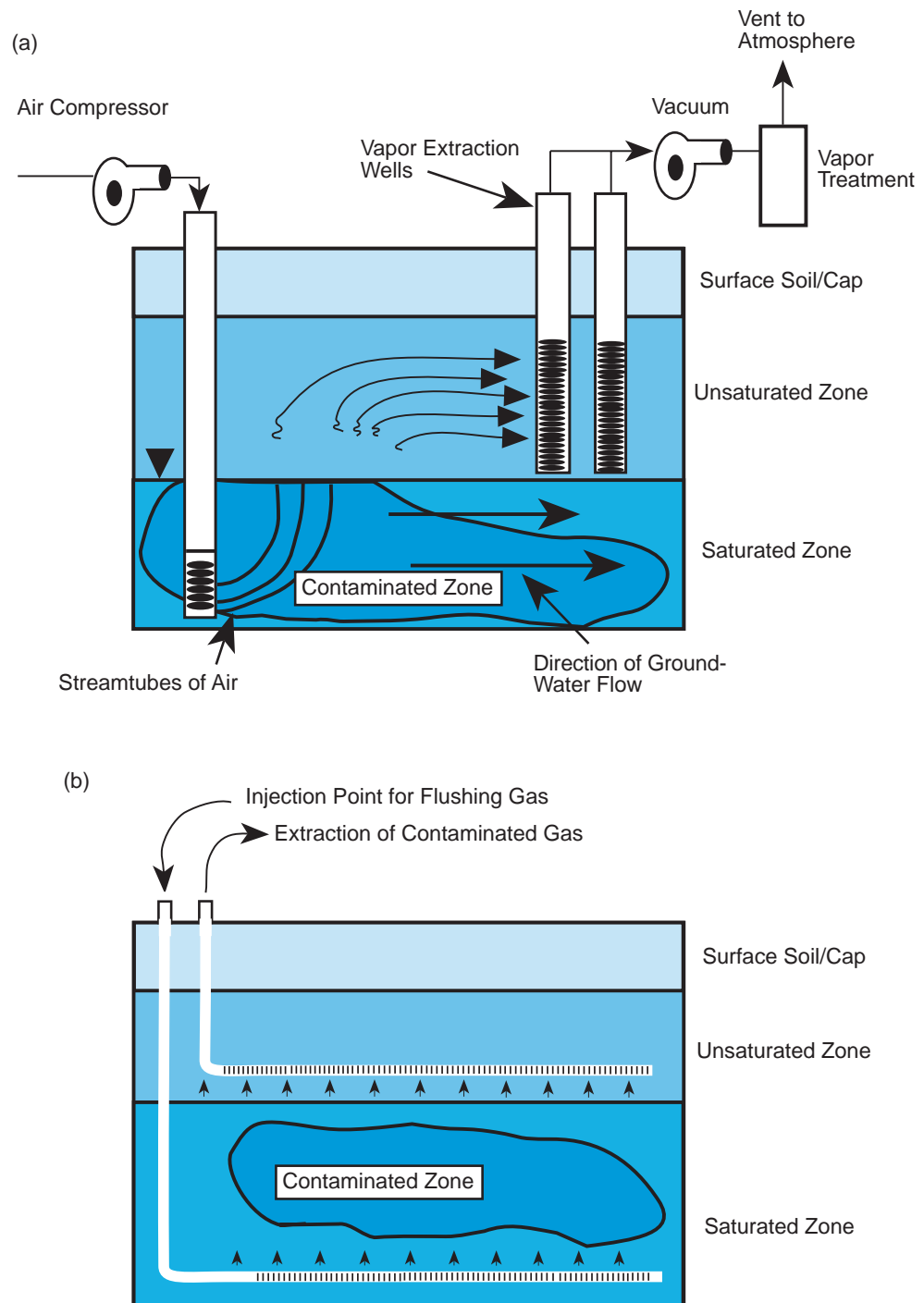
Contaminated Zone

Saturated Zone

Figure 36.
Process diagram
for air sparging
with (a) vertical
wells, and (b)
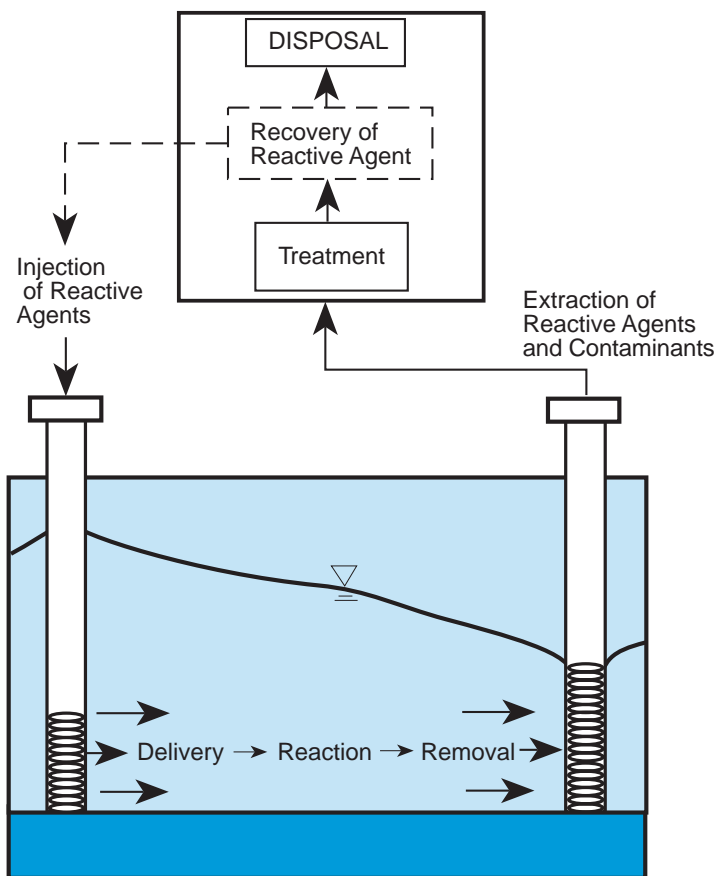horizontal wells
(after NRC,
1994).

Figure 37. Schematic of chemical enhancement of a pump-and-treat system. Key areas of concern are shown in boxes. In some cases, the reactive agent will be recovered and reused (Palmer and Fish, 1992).

documented. Two major obstacles to the use of anaerobic processes for in situ bioremediation are that (1) hazardous intermediate degradation products can accumulate, and (2) undesirable water quality changes, such as dissolution of iron and manganese, can occur.

EPA reference sources identified at the end of this guide (Section 9) that are particularly relevant to *in situ* bioremediation include Norris et al. (1993), Sims et al. (1992), and U.S. EPA (1993, 1994).

7.5. Alternatives to the Pump-and-Treat Approach

Nearly all approaches to ground-water cleanup involve some degree of ground-water pumping. Even when containment is the primary objective, low-flow pump-and-treat systems are usually required to prevent the escape of contaminated water from the confined area. Two remediation approaches that eliminate pumping as a component of the system are (1) intrinsic bioremediation, and (2) in situ reactive barriers. Although both of these methods show promise, they are still
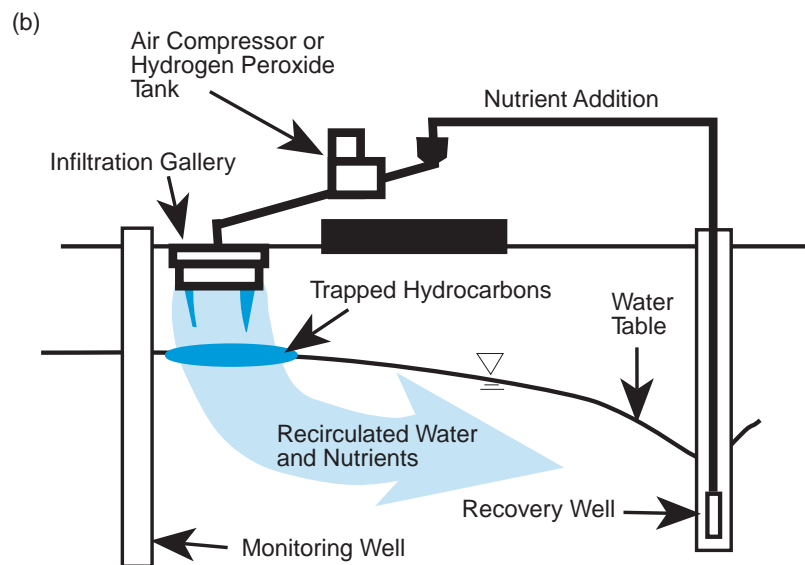
(a)

To Sewer or Recirculate

Nutrient Addition Tank

Air Compressor

Water Supply

Course Sand

Production Well

Injection Well

Water Table

Spilled Materials

Sparger

Clay

(b)

Air Compressor or Hydrogen Peroxide Tank

Nutrient Addition

Infiltration Gallery

Trapped Hydrocarbons

Water Table

Recirculated Water and Nutrients
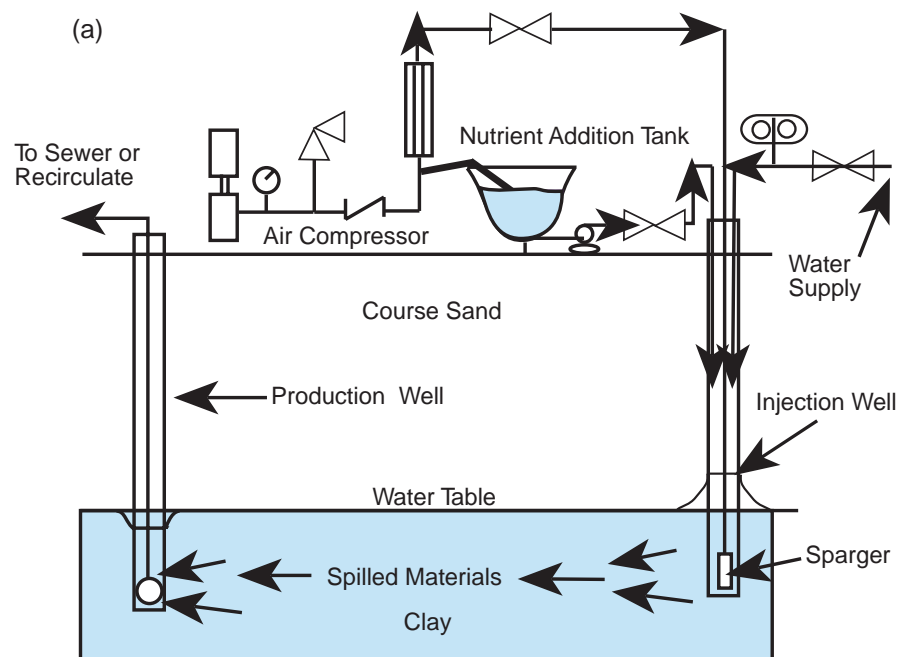
Recovery Well

Monitoring Well

Figure 38.
Two types of aerobic *in situ* bioremediation systems: (a) injection well with sparger, (b) infiltration gallery (Sims et al., 1992, after Thomas and Ward, 1989).

in development and their effectiveness remains to be demonstrated.

7.5.1. *Intrinsic Bioremediation*

Intrinsic bioremediation relies on indigenous microbes to biodegrade organic contaminants, without human intervention in the form of supplying electron acceptors, nutrients, and other materials. The processes that occur are the same as those in engineered bioremediation systems, but they occur more slowly. A decision to refrain from active site manipulation does not eliminate the need to conduct ground-water sampling within the contaminant plume to document that biodegradation is occurring. Moreover, sampling would still need to be performed outside the contaminated area to identify any offsite migration of contaminants that might require initiation of more active remedial measures (Figure 39b). There is a greater risk of failure with intrinsic bioremediation compared to engineered bioremediation because no active measures are used to control the contaminant plume. The possible perception that intrinsic bioremediation is the equivalent to doing nothing is also a barrier to its acceptance (NRC, 1994).

7.5.2. **In Situ *Reactive Barriers***

The concept of using permeable *in situ* reactive barriers to treat a contaminant plume as it moves through an aquifer under natural hydraulic gradients (Figure 39c and 39d) was first suggested by McMurty and Elton (1985), but it has only recently begun to receive significant attention from the research community (Starr and Cherry, 1994). The funnel-and-gate concept, which combines impermeable barriers to contain and channel the flow of the contaminant plume toward the reactive barrier has received the most attention because numerous possible configurations can be developed to address different types of contaminant plumes and geologic settings (Figure 40). Depending on the contaminants present in the plume, the reactive zone uses a combination of physical, chemical, and biological processes.

The great promise of in situ reactive barriers is that they will require little or no energy input once installed, yet provide more active control and treatment of the contaminant plume than intrinsic bioremediation. The main engineering challenges involve provision of suitable amounts of reactive materials in a permeable medium and proper placement to avoid short-circuiting the contact between the gate and the cutoff wall.
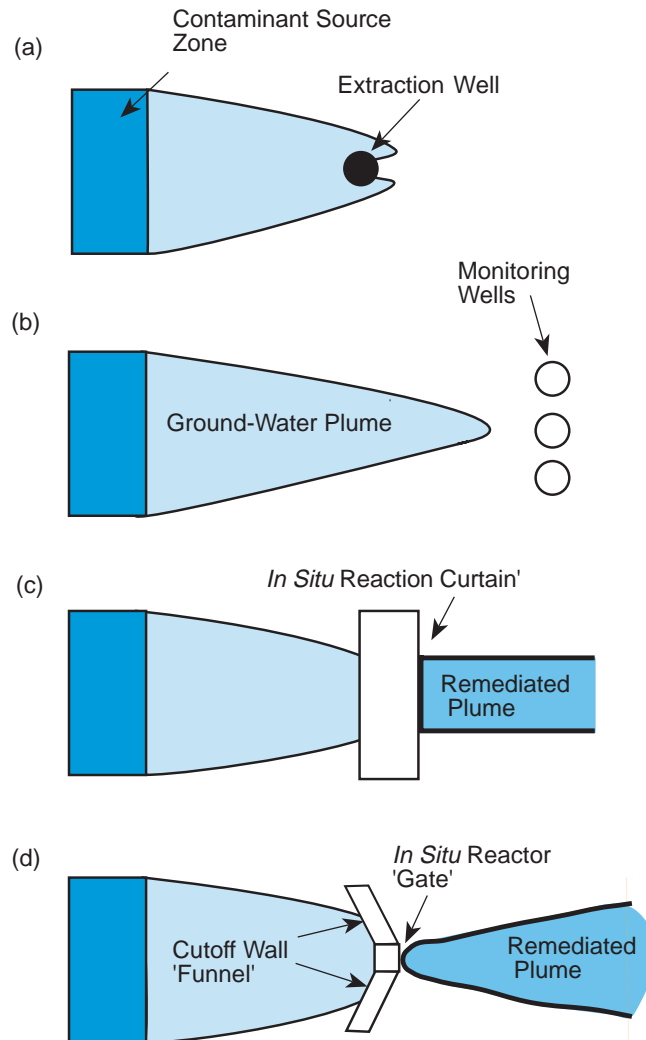
Figure 39. Alternative ground-water plume management options: (a) pump-and-treat system, (b) intrinsic bioremediation, (c) *in situ* reaction curtain, (d) funnel-and-gate system (adapted from Starr and Cherry, 1994).
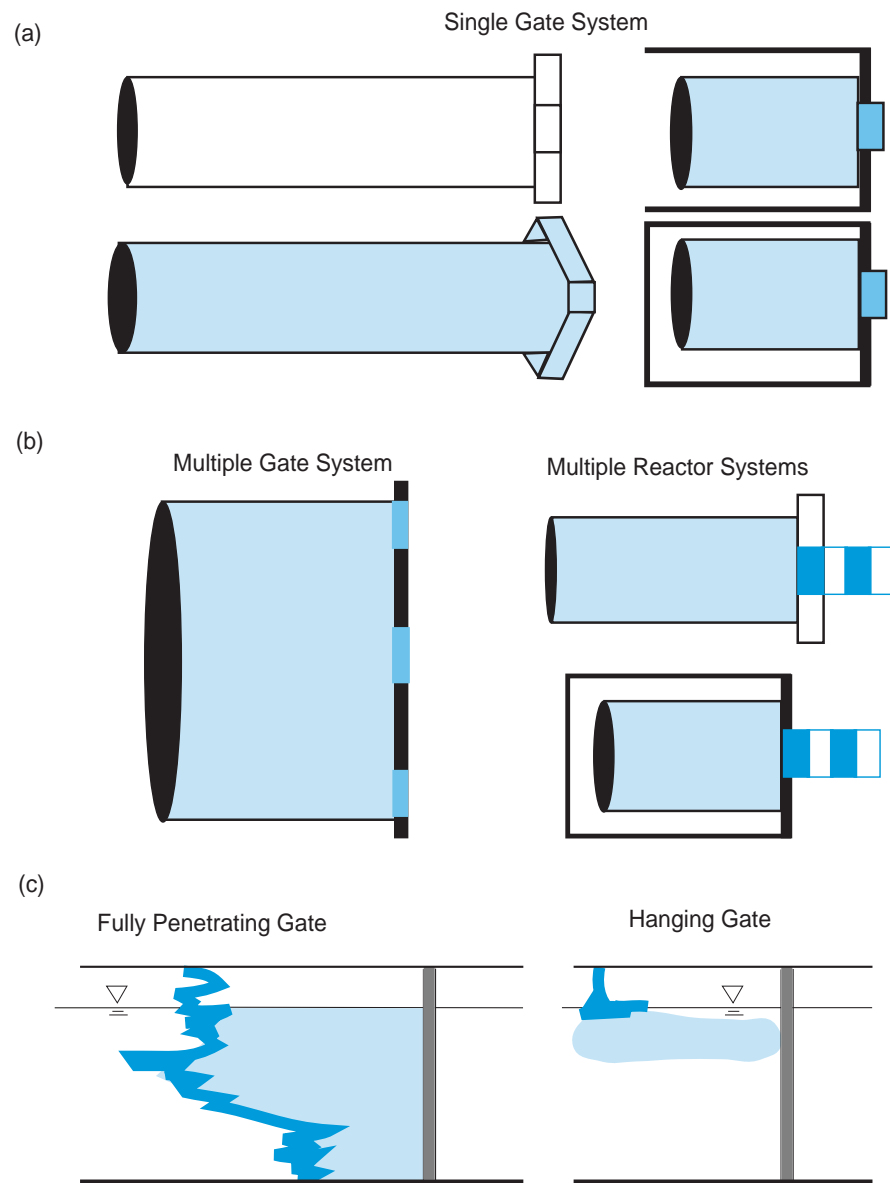
(a) Single Gate System

(b) Multiple Gate System   Multiple Reactor Systems

(c) Fully Penetrating Gate   Hanging Gate

Figure 40. Funnel-and-gate configurations (Starr and Cherry, 1994).

8. References

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9. EPA Publications Providing Further Information

The EPA publications listed below provide more detailed information on the subjects discussed in this document. Publications and additional copies of this brochure can be obtained at no charge (while supplies are available) from the following sources:

EPA/625-series documents: Office of Research and Development (ORD) Publications, P.O. Box 19968, Cincinnati, OH 45219-0968; phone 513 569-7562, fax 513 569-7562.

Other EPA documents: National Center for Environmental Publications and Information (NCEPI), 11029 Kenwood Road, Cincinnati, OH 45242; fax 513 891-6685.

Other documents, for which an NTIS acquisition number is shown can be obtained from the National Technical Information Service (NTIS), Springfield, VA 22161; 800 336-4700, fax 703/321-8547.

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