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Methods for Monitoring Pump-and-Treat Performance

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METHODS FOR MONITORING PUMP-AND-TREAT PERFORMANCE

by

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FOREWORD

EPA is charged by Congress to protect the Nation's land, air and water systems. Under a mandate of national environmental laws focused on air and water quality, solid waste management and the control of toxic substances, pesticides, noise and radiation, the Agency strives to formulate and implement actions which lead to a compatible balance between human activities and the ability of natural systems to support and nurture life.

The Robert S. Kerr Environmental Research Laboratory is the Agency's center of expertise for investigation of the soil and subsurface environment. Personnel at the laboratory are responsible for management of research programs to: (a) determine the fate, transport and transformation rates of pollutants in the soil, the unsaturated and the saturated zones of the subsurface environment; (b) define the processes to be used in characterizing the soil and subsurface environment as a receptor of pollutants; (c) develop techniques for predicting the effect of pollutants on ground water, soil, and indigenous organisms; and (d) define and demonstrate the applicability and limitations of using natural processes, indigenous to the soil and subsurface environment, for the protection of this resource.

Since the 1980s, numerous pump-and-treat systems have been constructed to: (1) hydraulically contain contaminated ground water, and/or, (2) restore ground-water quality to meet a desired standard such as background quality or Maximum Contaminant Level (MCL) concentrations for drinking water. Although hydraulic containment is usually achievable, experience proves that aquifer restoration will be hindered at many sites due to Non-Aqueous Phase Liquid (NAPL) dissolution, contaminant desorption, inefficient hydraulic flushing of heterogeneous media, and other chemical and physical process limitations. Given the complexity and site-specific nature of ground-water remediation, pump-and-treat system objectives must be clearly identified and system operation carefully monitored to determine effectiveness. Typically, monitoring involves measuring hydraulic heads and contaminant concentrations to evaluate ground-water flow directions, recovery system capture zones, contaminant migration, and contaminant removal. This document was developed on behalf of the United States Environmental Protection Agency (EPA) to outline methods for evaluating the effectiveness and efficiency of pump-and- treat remediation systems.

Clinton W. Hall /s/
Director
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Research Laboratory

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EVALUATING GROUND-WATER PUMP-AND-TREAT SYSTEMS

Abstract

Since the 1980s, numerous pump-and-treat systems have been constructed to: (1) hydraulically contain contaminated ground water, and/or, (2) restore ground-water quality to meet a desired standard such as background quality or Maximum Contaminant Level (MCL) concentrations for drinking water. Although hydraulic containment is usually achievable, experience suggests that aquifer restoration can often be hindered at many sites due to the dissolution of Non-Aqueous Phase Liquids (NAPLs), contaminant desorption, inefficient hydraulic flushing of heterogeneous media, and other chemical and physical process limitations. Given the complexity and site-specific nature of ground-water remediation, pump-and-treat system objectives must be clearly identified and system operations carefully monitored to determine effectiveness. Typically, monitoring involves measuring hydraulic heads and contaminant concentrations to evaluate ground-water flow directions, recovery system capture zones, contaminant migration, and contaminant removal. This document was developed on behalf of the United States Environmental Protection Agency (EPA) to outline methods for evaluating the effectiveness and efficiency of pump-and-treat remediation systems.

1. INTRODUCTION

1.1 PUMP-AND-TREAT OBJECTIVES

Although this document focuses on the containment or remediation of contaminated ground water using pump and treat (P&T) systems, other technologies are discussed in a limited way, particularly as they are used in concert with P&T systems. It is important to note that in the selection and implementation of any remediation system, or consortia of systems which are designed to contain or remediate contaminated ground water, that the sources of contaminants must be removed from the site or sufficiently isolated to assure that they can no longer contribute contaminants to the ground water.

A common remedial strategy to deal with contaminated ground water is to extract the contaminated water and treat it at the surface prior to discharge or reinjection. This is referred to as conventional pump-and-treat (P&T) remediation. An overview of pump-and-treat ground-water remediation technology is provided by Mercer et al. (1990). Between 1982 and 1990, 72 percent (314) of all Superfund site Records of Decisions (RODs) addressing ground-water remediation specified P&T technology (Steimle, 1992).

P&T systems are designed to: (1) hydraulically contain and control the movement of contaminated ground water to prevent continued expansion of the contamination zone; (2) reduce dissolved contaminant concentrations to comply with clean-up standards and thereby "restore" the aquifer; or (3) a combination of these objectives.

Hydraulic containment of dissolved contaminants by pumping ground water from wells or drains has been demonstrated at numerous sites. The concept is illustrated in Figure 1-1. Fluid injection (using wells, drains, or surface application) and physical containment options (such as subsurface barrier walls and surface covers) can enhance hydraulic containment systems. Recovered und water is usually treated at the surface using methods selected to remove the contaminants of concern (Table 1-1). In many cases, hydraulic containment systems are designed to provide long-term containment of contaminated ground water at the lowest cost by optimizing well, drain, surface cover, and/or cut-off wall locations and by minimizing pumping rates.

P&T designed for aquifer restoration generally combines hydraulic containment with more active manipulation of ground water (i.e., higher pumping rates) to attain ground-water clean-up goals during a finite period. As described below, aquifer restoration is much more difficult to achieve than hydraulic containment.

Selection of P&T objectives depends on site conditions and remedial goals. Hydraulic containment is preferred where restoration is technically impracticable (e.g., not capable of being done or carried out) due to the presence of subsurface NAPL, buried waste, formation heterogeneity, or other factors (USEPA, 1993). Aquifer restoration may be an appropriate goal where these confounding factors are absent or minimal. At many sites, P&T systems can be used to contain contaminant sources areas and attempt restoration of downgradient dissolved contaminant plumes (Figure 1-2).

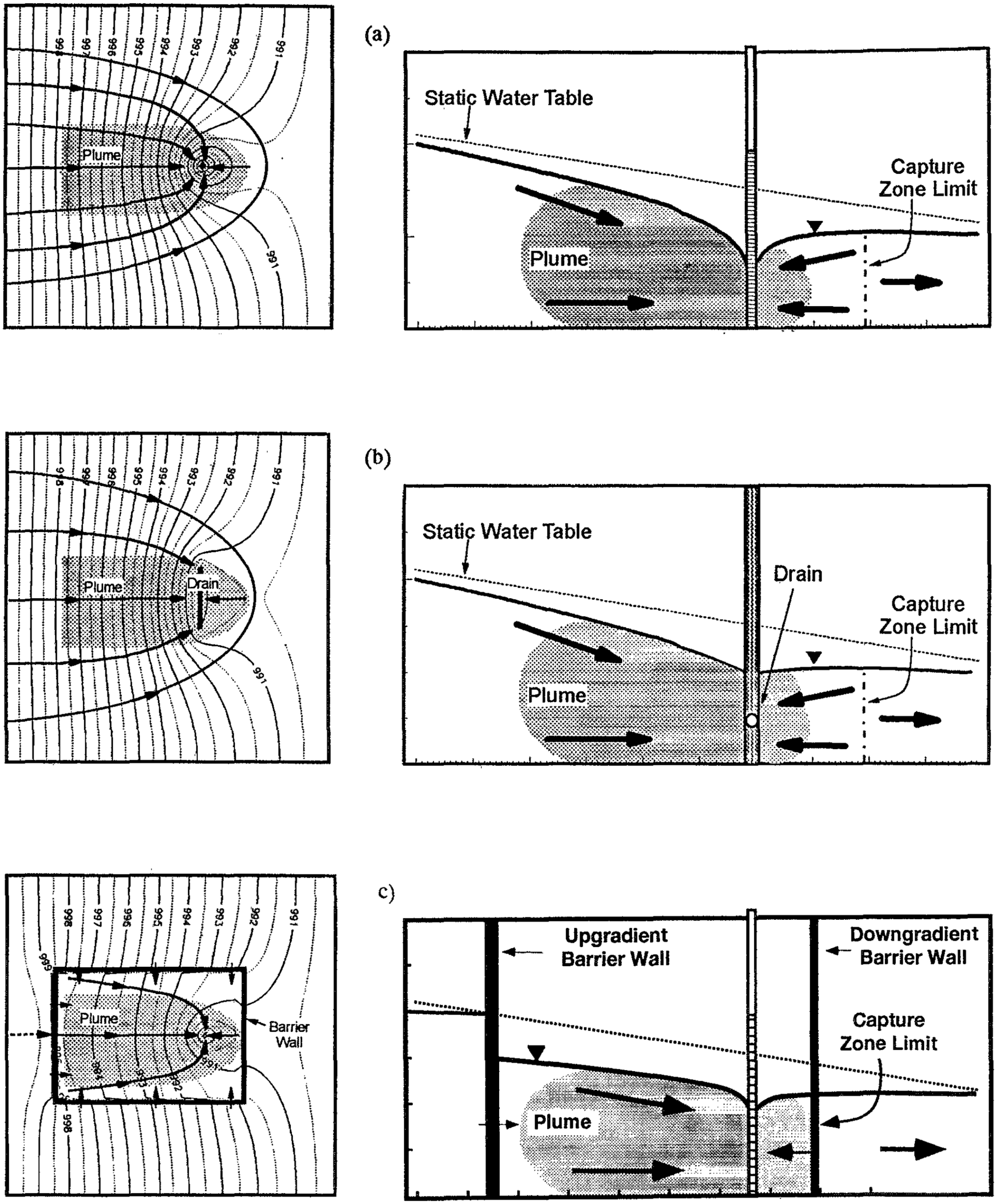


Figure 1-1. **Examples of hydraulic containment in plan view and cross section using P&T technology: (a) pump well, (b) drain, and (c) well within a barrier wall system.**

TABLE 1-1. SUMMARY OF SELECTED GROUND-WATER TREATMENT TECHNOLOGIES (FROM BOUWER ET AL., 1988).

Ground-Water Treatment Technology	*Representative Examples*	*Residual Streams*	*Status of Technology*
ORGANIC CONTAMINANTS:			
Air stripping	Packed towers, surface or diffused aeration removal of volatile compounds; soil venting	Air stream with VOCs	Commercial
Liquid-phase	GAC removal of broad spectrum of VOCs	GAC for regeneration or disposal	Commercial
Stream stripping	Packed tower with stream stripping, removal of low volatile organics	Recovered solvent	Some commercial
Membranes	Ultrafiltration for removal of selected organics	Concentrated brine side stream	Commercial
Oxidation	Ozone/UV, or ozone/H_2O_2, destruction of chlorinated organics	None	Some commercial in development stages
Activated sludge	Oxygen or air biological oxidation for removal/ destruction of degradable organics	Sludge	Commercial
Fixed-film biological reactors	Fixed-film fluidized bed, for oxidation of less degradable organics	Sludge	Commercial
Biophysical	Powdered carbon, with activated sludge, treatment of high strength wastewaters	Powdered carbon and bacterial	Commercial, PACT process
INORGANIC CONTAMINANTS:			
Alkaline precipitation	Heavy metals removal	Hazardous sludge	Commercial
Coagulation	Ferric sulfate or alum for heavy metals removal	Hazardous sludge	Commercial
Ion exchange	Heavy metals; nitrate	Regeneration stream	Commercial
Adsorption	Selenium removal on activated alumina	Regeneration stream	Commercial
Filtration	Removal of clays, other particulates	Backwash wastes	Commercial
Reduction	SO_2 reduction of CR (VI)	Chromium sludge	Commercial
Membranes	Reverse osmosis, ultrafiltration for removal or metals, other ions	Concentrated liquid waste	Commercial, new membranes under development
Oxidation	Fe(II) and Mn(II)	Sludge	Commercial

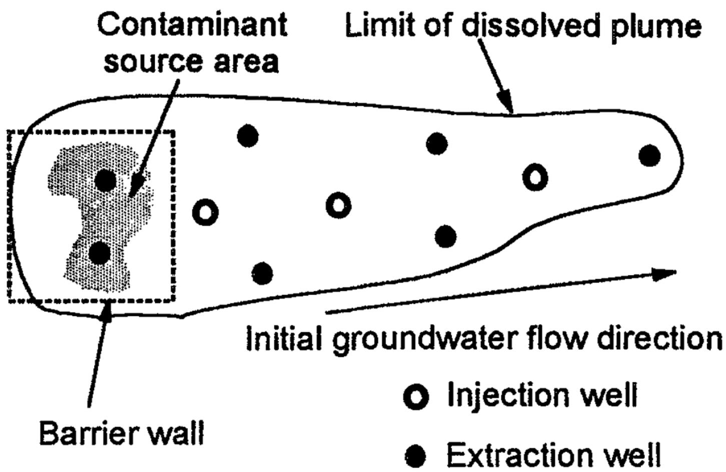


Figure 1-2. Plan view of the mixed containment-restoration strategy. P&T is used to contain ground-water contamination source areas (e.g., where NAPL or wastes may be present) and attempt aquifer restoration downgradient.

1.2 TAILING AND REBOUND CONSTRAINTS

Although P&T systems continue to be widely i4sed to reduce dissolved contaminants in ground water, experiences gained in recent years suggest that the efficiency of these systems can be compromised by a number of factors that are related to the contaminants of interest and characteristics of the site. As a result, it is often difficult to reduce dissolved contaminants to below drinking-water standards in reasonable time frames (e.g., less than 10 years) at many sites (Palmer and Fish, 1992; CH_2M Hill, 1992; Haley et al., 1991; Mercer et al., 1990; Mackay and Cherry, 1989; Keely, 1989; Harman et al., 1993; Doty and Travis, 1991). Monitoring contaminant concentrations in ground water with time at P&T sites reveals "tailing" and "rebound" phenomena. "Tailing" refers to the progressively slower rate of dissolved contaminant concentration decline observed with continued operation of a P&T system (Figure 1-3). At many sites, the asymptotic, apparent residual, contaminant concentration exceeds clean-up standards. Another problem is that dissolved contaminant concentrations may "rebound" if pumping is discontinued after temporarily attaining a clean-up standard (Figure 1-3).

Tailing and rebound may result from several physical and chemical processes that affect P&T remediation (Figure 1-4).

- *Non-Aqueous Phase Liquid (NAPL) dissolution* -- Subsurface NAPLs can be long-term sources of ground-water contamination due to their limited aqueous solubility that may greatly exceed drinking water standards (Cohen and Mercer, 1993). This long-term contamination potential is illustrated in Figure 1-4(d). If NAPLs are not removed (i.e., by excavation) or contained, tailing and rebound will occur during and after P&T operation, respectively, in and downgradient of the NAPL zone. The dissolution of a NAPL source may require the removal of thousands of equivalent pore volumes.

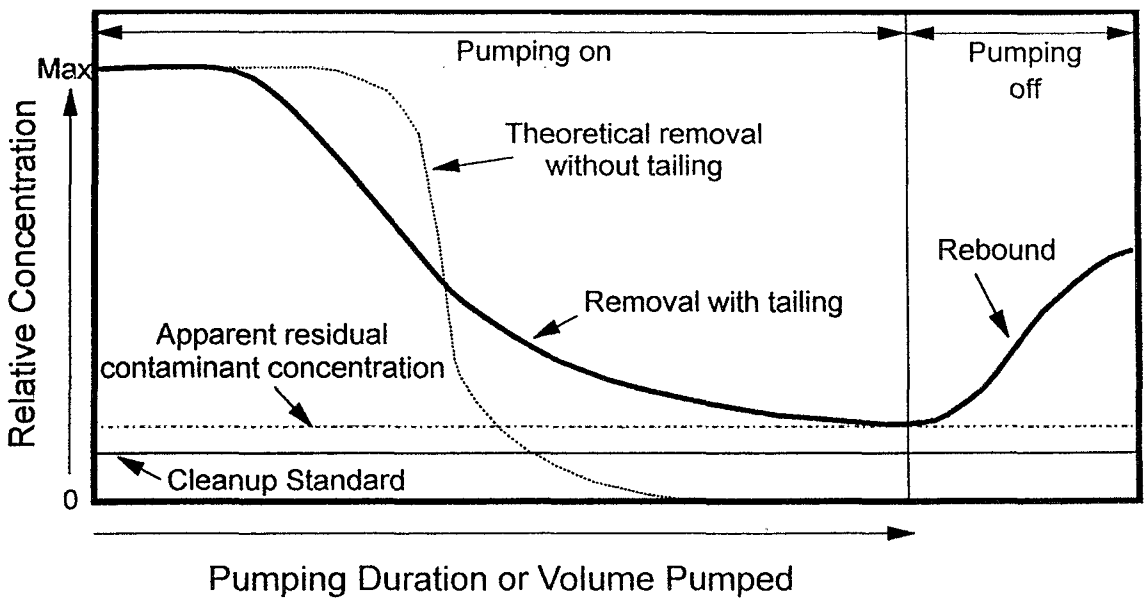


Figure 1-3. Concentration versus pumping duration or volume showing tailing and rebound effects (modified from Keely, 1989).

- *Contaminant desorption* -- As dissolved contaminant concentrations are reduced by P&T system operation, contaminants sorbed to subsurface media desorb from the matrix into ground water. This equilibrium partitioning process can be described by the Langmuir isotherm,

$$C_s = C_{smax} [K\, C_w) / (1 + K\, C_w)] \qquad (1\text{-}1)$$

or the Freundlich sorption isotherm,

$$C_s = K\, C_w{}^{n} \qquad (1\text{-}2)$$

where C_s and C_w are the contaminant concentrations associated with the solid and aqueous phases, respectively, K is the adsorption constant, C_{smax} is the maximum possible soil contaminant concentration, and n is a measure of nonlinearity (Figure 1-5). For the linear isotherms (n = 1) and for limited ranges of C_w, particularly at low concentration, where in the Freundlich constant can be identified as a distribution ratio, K_d, such that

$$K_d = C_s / C_w \qquad (1\text{-}3)$$

The K_d values for hydrophobic, nonpolar organic contaminants are frequently represented as the product of the organic carbon content of the media, f_{oc} (mass of carbon/mass of soil), and the organic carbon partition coefficient, K_{oc} (mass of contaminant per unit mass of carbon/equilibrium concentration in soil) such that

$$K_d = K_{oc}\ f_{oc} \qquad (1\text{-}4)$$

Values for f_{oc} and K_{oc} may be obtained from laboratory analyses of core material and literature sources (USEPA, 1990), respectively. By assuming a linear isotherm, these

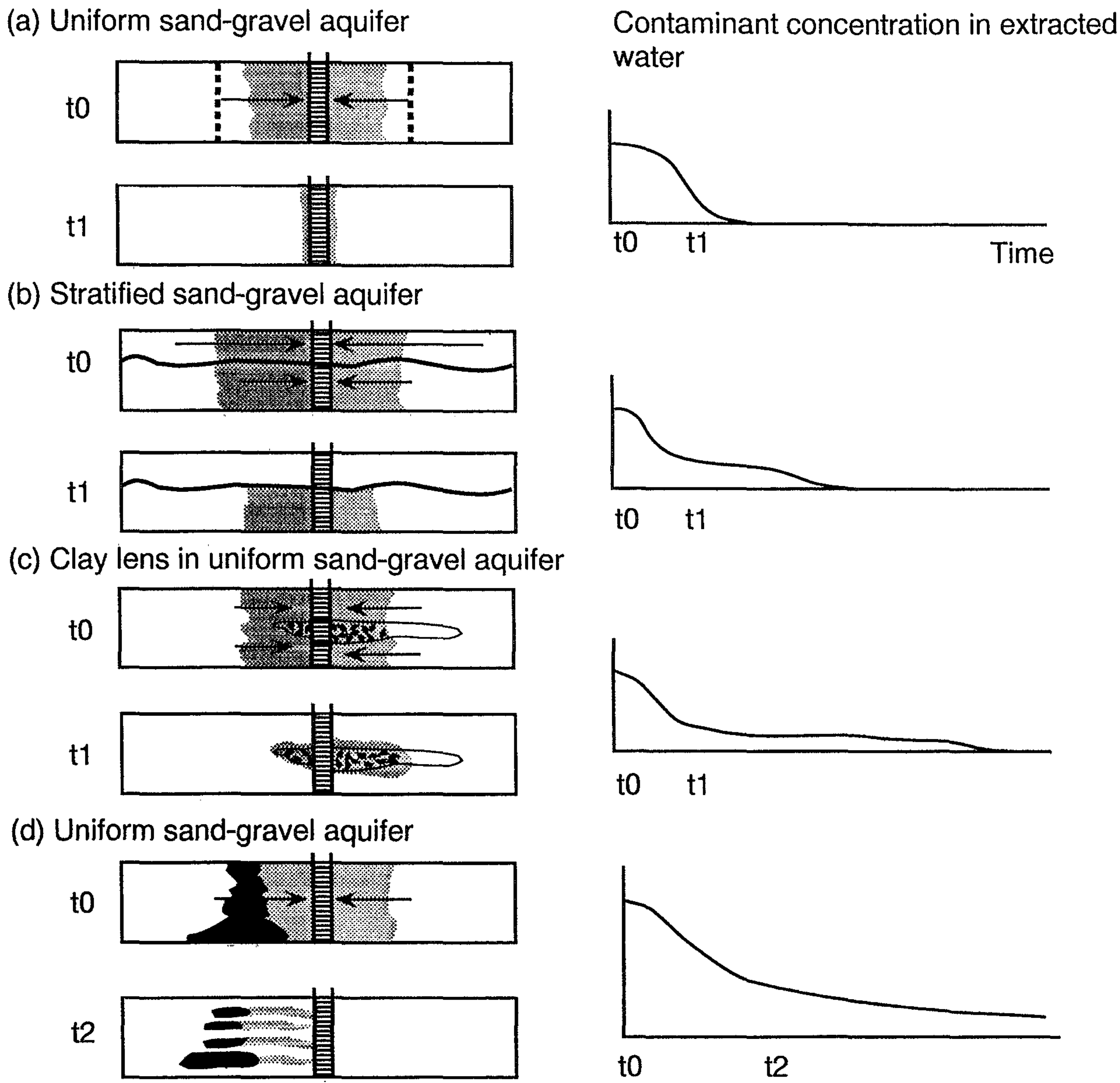


Figure 1-4. **Hypothetical examples of contaminant removal from ground water using P&T (modified from Mackay and Cherry, 1989). Black indicates NAPL presence; stippling indicates contaminant in dissolved and sorbed phases (with uniform initial distribution); and arrows indicate relative ground-water velocity. Ground water is pumped from the well at the same rate for each case. Note that the dotted lines in (a) represent the volume of ground water that would have to be pumped to flush slightly retarded contaminants from the uniform aquifer.**

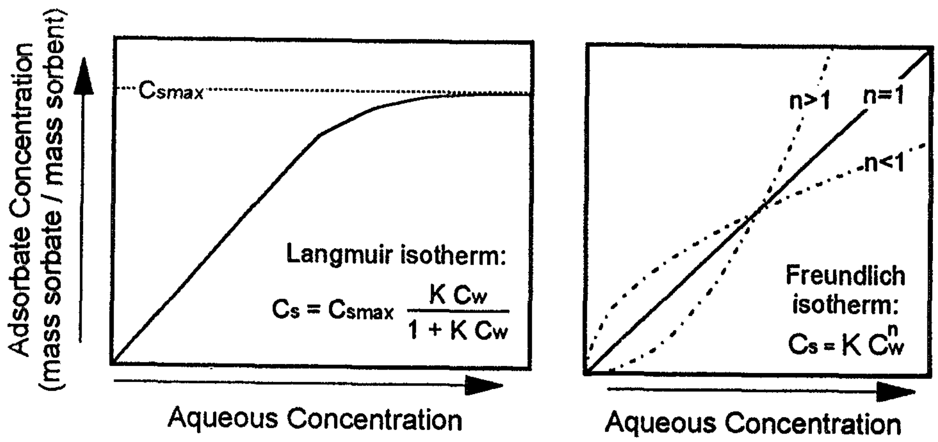


Figure 1-5. The Langmuir and Freundlich adsorption isotherms (modified from Palmer and Fish, 1992).

relationships can be used to estimate: (1) the retardation factor, R_f, or velocity of dissolved contaminant movement, v_c, relative to ground-water flow, v_{gw},

$$R_f = v_c/v_{gw} = 1/[1 + (K_d\rho_b/n)] \qquad (1\text{-}5)$$

(2) the retardation coefficient, R, which is the reciprocal of R_f,

$$R = 1 + (K_d\rho_b/n) \qquad (1\text{-}6)$$

and (3) the equilibrium distribution of contaminant mass between the solid and aqueous phases

$$f_w = C_wV_w / [(C_wV_w)+(C_sM_s)] = V_w / (V_w + K_dM_s) \qquad (1\text{-}7)$$

where ρ_b is the dry bulk density, n is the porosity, V_w is the volume of water in the total subject volume, M_s is the mass of solids in the total subject volume, and f_w is the fraction of mass residing in the aqueous phase.

Sorption and retardation are site-specific. Field retardation values vary between different contaminants at a given site and between different sites for a given contaminant (Mackay and Cherry, 1989). As illustrated in Figure 1-4, desorption and retardation increase the volume of ground water which must be pumped to attain dissolved contaminant concentration reductions. Tailing and rebound effects will be exacerbated where desorption is slow relative to ground-water flow and kinetic limitations prevent sustenance of equilibrium contaminant concentrations in ground water (Palmer and Fish, 1992; Haley et al., 1991; Brogan, 1991; Bahr, 1989). This concept is illustrated in Figure 1-6. Kinetic limitations to mass transfer are likely to be relatively significant in the high g round-water velocity zone in the vicinity of

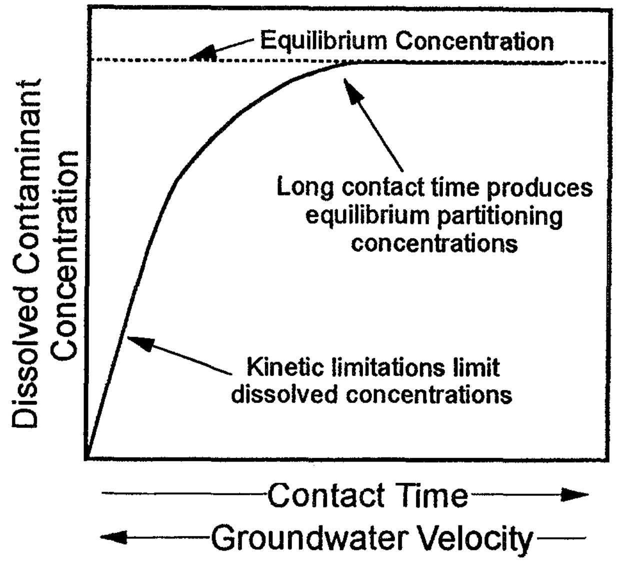


Figure 1-6. Relationship between ground-water velocity induced by pumping and the concentration of dissolved contaminants that (a) desorb from the porous media, (b) dissolve from precipitates, or (c) dissolve from NAPL (modified from Keely, 1989). Kinetic limitations to dissolution exacerbate tailing.

injection and extraction wells. Under such conditions, insufficient control time is available between the adsorbed contaminants and ground water to allow the development of maximum concentrations.

- *Precipitate dissolution* -- Large quantities of inorganic contaminants, such as chromate in $BaCrO_4$, may be bound with crystalline or amorphous precipitates on porous media (Palmer and Fish, 1992). Dissolution of contaminant precipitates may cause tailing (Figure 1-7) and rebound. These effects may increase due to mass transfer limitations where the dissolution rate is slow relative to ground-water flow.

- *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 (Figures 1-4 and 1-8). Ground water at the edge of a capture zone travels a greater distance under a lower hydraulic gradient than ground water closer to the center of the capture zone. Additionally, contaminant-to-well travel times vary as a function of the initial contaminant distribution and differences in hydraulic conductivity. If pumping is stopped, rebound will occur wherever the resulting flow path modification causes the magnitude of contaminant dilution to be reduced.

- *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). Where contamination persists for long periods, this diffusion may cease when contaminant concentrations equilibrate between the different strata. During a P&T operation, dissolved contaminant concentrations in the relatively permeable zones may be quickly reduced by advective flushing relative to the less permeable zones as illustrated in Figure 1-1 (c). This causes a reversal in the initial concentration gradient and the slow diffusion of contaminants from the low to high permeability media. This slow process can cause long-term tailing, and rebound after the termination of pumping.

Tailing and rebound patterns associated with these different physical and chemical processes are similar. Multiple processes (i.e., dissolution, diffusion and desorption) will typically be active at a P&T site. Diagnosis of the cause of tailing and rebound, therefore, requires careful consideration of site conditions and usually cannot be made by examination of concentration versus time data alone.

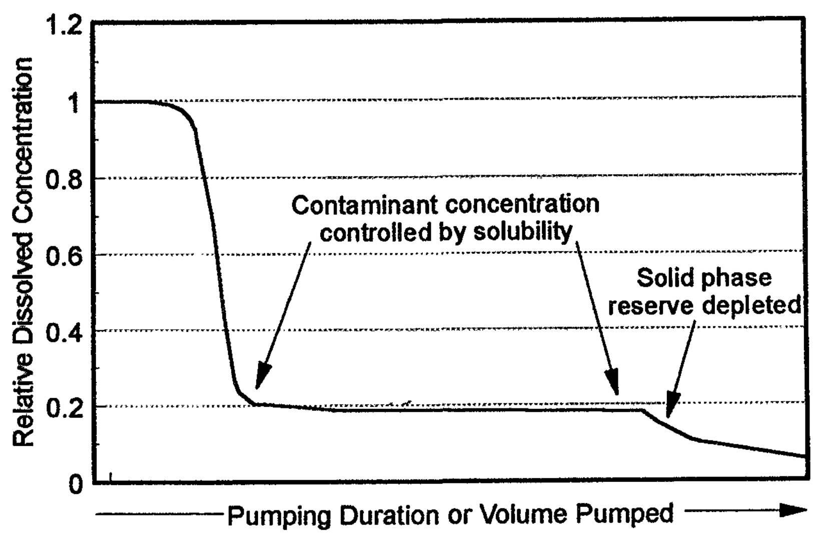


Figure 1-7. Dissolved contaminant concentration in ground water pumped from a recovery well versus time in a formation that contains a solid phase contaminant precipitate (from Palmer and Fish, 1992).

1.3 HOW IS SUCCESS MEASURED?

A successful P&T system is a design and implementation that has been determined capable of accomplishing the remedial action . objectives of containment and/or restoration in a desired time period. For containment, success is usually defined as the achievement of hydrodynamic control at the outer limits (horizontal and vertical) of the contaminant plume such that hydraulic gradients are inward to the pumping system. Measuring the effectiveness of a restoration program is generally more difficult due to: (1) limitations of methods used to estimate contaminant mass distribution prior to and during remediation, and (2) the inherent difficulty of aquifer restoration as discussed in the previous section.

Tracking the performance of a containment or restoration P&T system is achieved by setting performance criteria, monitoring to assess these criteria, and assessing operational efficiency. Performance measures such as induced hydraulic gradients and contaminant concentration reductions are monitored to verify that the system is operating as designed and achieving remediation goals. If the performance criteria have not been adequately formulated, perhaps due to a flawed site conceptual model,

(a)

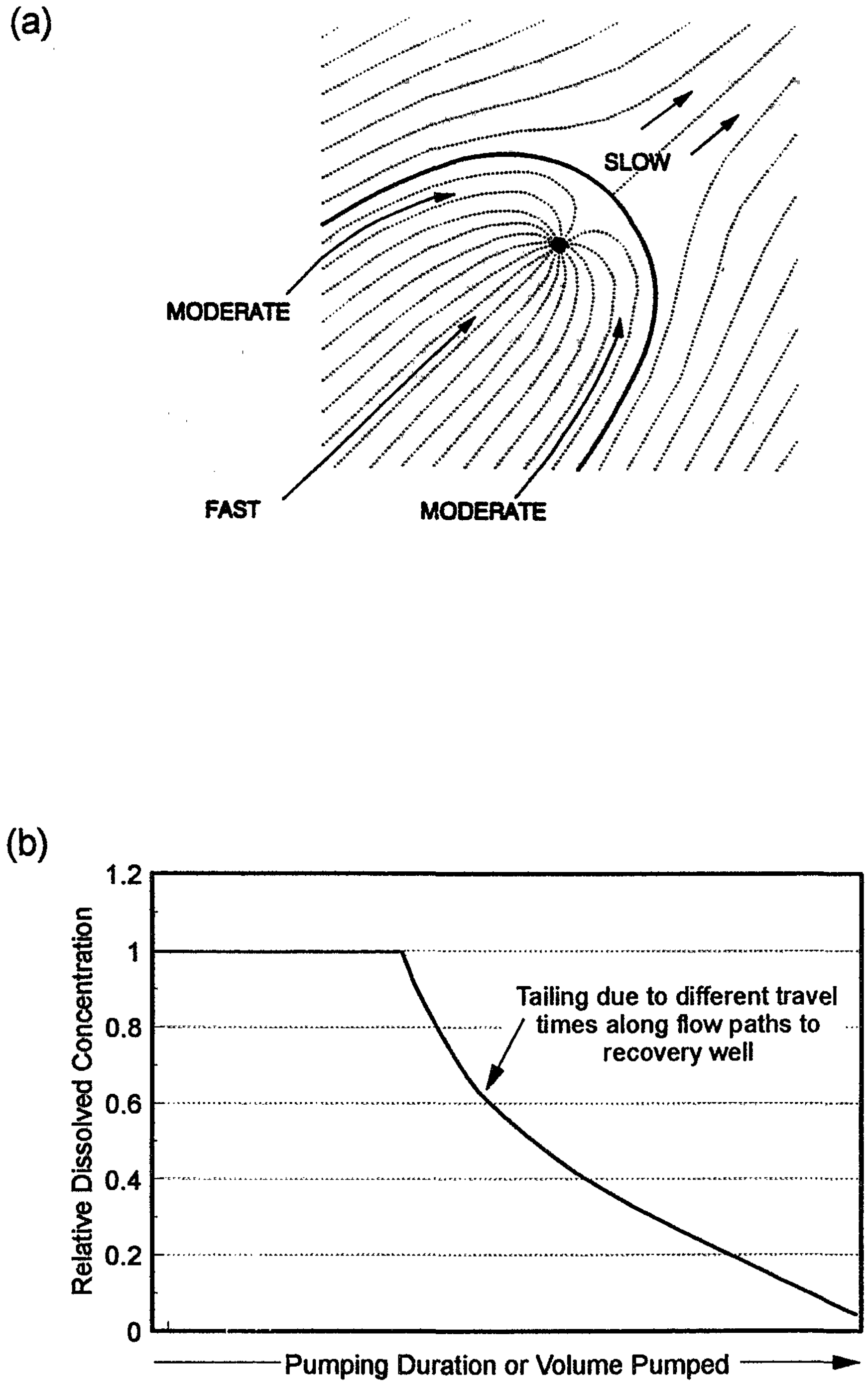


Figure 1-8. **Advective velocity, flowpath, and travel time variations (a) to a recovery well (from Keely, 1989) and (b) induce tailing (from Palmer and Fish, 1992).**

then meeting specified criteria may provide a misleading sense of system effectiveness. Operational efficiency is also a measure of success for a P&T system. It refers to the cost-effectiveness of a system, and can be measured by monitoring costs and assessing related environmental benefits. For example, a highly efficient and cost-effective hydraulic containment system may extract ground water at the minimum rate required to demonstrate attainment of hydraulic gradient objectives. Ideally, a phased remedial approach, whereby system improvements evolve from performance monitoring, will maximize both the performance effectiveness and efficiency of a P&T system.

1.4 PURPOSE AND FORMAT OF REPORT

The purpose of this report is to provide guidance for monitoring the effectiveness and efficiency of P&T systems. Related complementary guidance is given by USEPA (1992a). Emphasis herein is placed on the "pump" portion of P&T technology. Chemical enhancements to P&T remediation, such as injection of cosolvents or surfactants, are discussed by Palmer and Fish (1992). For details on ground-water treatment techniques and strategies, see AWWA (1990), Nyer (1992), and USEPA (1987), among others. It is assumed that the reader is familiar with basic concepts of hydrogeology and P&T technology.

The report is divided into six main sections: (1) Introduction, (2) Monitoring Hydraulic Containment, (3) Monitoring Ground-Water Restoration, (4) Evaluating Restoration Success/Closure, (5) A Case Study, and (6) References. Examples and illustrations are provided to convey concepts. This section provides an overview of P&T use, objectives, and limitations. Sections 2 and 3 describe performance criteria, monitoring objectives, data analysis, system enhancements, and protocols for evaluating the effectiveness of the P&T systems designed for containment and restoration, respectively. Methods for determining the timing of system closure are addressed in Section 4. In Section 5, monitoring data from the Chem-Dyne site in Hamilton, Ohio are presented as an example of a P&T system effectiveness evaluation.

2. MONITORING HYDRAULIC CONTAINMENT

2.1 OBJECTIVES AND PROCESS

Monitoring programs are designed to measure the effectiveness and efficiency of P&T system performance in achieving hydraulic containment objectives. For successful hydraulic containment, contaminants moving with ground water in the containment zone must follow pathlines that are captured by the P&T system (Figure 1-1). In addition to P&T systems designed to remove dissolved contaminants and contaminants that may be adsorbed to mobile colloids, remedial designs should be developed to preclude the migration of NAPLs, if present, beyond the containment perimeter.

In general, containment monitoring involves: (1) measuring hydraulic heads to determine if the P&T system affects hydraulic gradients in such a way as to prevent ground-water flow and dissolved contaminant migration across the containment zone boundary; and (2) ground-water quality monitoring to determine if temporal and spatial variations in contaminant distribution are consistent with hydraulic containment (i.e., no contaminant movement or increase of contaminant mass across the containment zone boundary). Containment monitoring activities, therefore, typically include some combination of hydraulic head measurement, ground-water sampling and analysis, tracer monitoring, and pumping rate measurement.

Containment monitoring plans are developed and revised during a phased remedial program. As outlined in Figure 2-1, the first step in establishing performance criteria, after characterizing pre-remedy ground-water flow patterns and contaminant distributions, is to determine the desired containment area (two-dimensional) and volume (three-dimensional). These should be clearly specified in site remedial action and monitoring plans.

At any particular site, there may be multiple separate containment areas, or a contaminant source containment area within a larger dissolved plume containment area (e.g., Figure 1-2), or a containment area that does not circumscribe the entire ground-water contamination zone. As shown in Figure 1-1, barrier walls are often used along the containment perimeter, while drains and recovery wells are located within the containment area. After defining the containment area, a capture zone analysis (Section 2.6) is conducted to design a P&T system and a performance monitoring plan is developed based on the predicted flow system (Figure 2-1). The monitoring plan may be revised as improvements to the site conceptual model and the P&T system evolve, and, if the containment area/volume is modified based on changes in contaminant distribution with P&T operation.

2.2 PERFORMANCE MONITORING MEASUREMENTS AND INTERPRETATION

Various hydraulic containment performance criteria are described in this section. Monitoring of these criteria is done to determine if the containment system is functioning as designed and to provide guidance for P&T system optimization. Performance is monitored by measuring hydraulic heads and determining gradients, ground-water flow directions, pumping rates, ground-water chemistry, and, possibly, tracer movement.

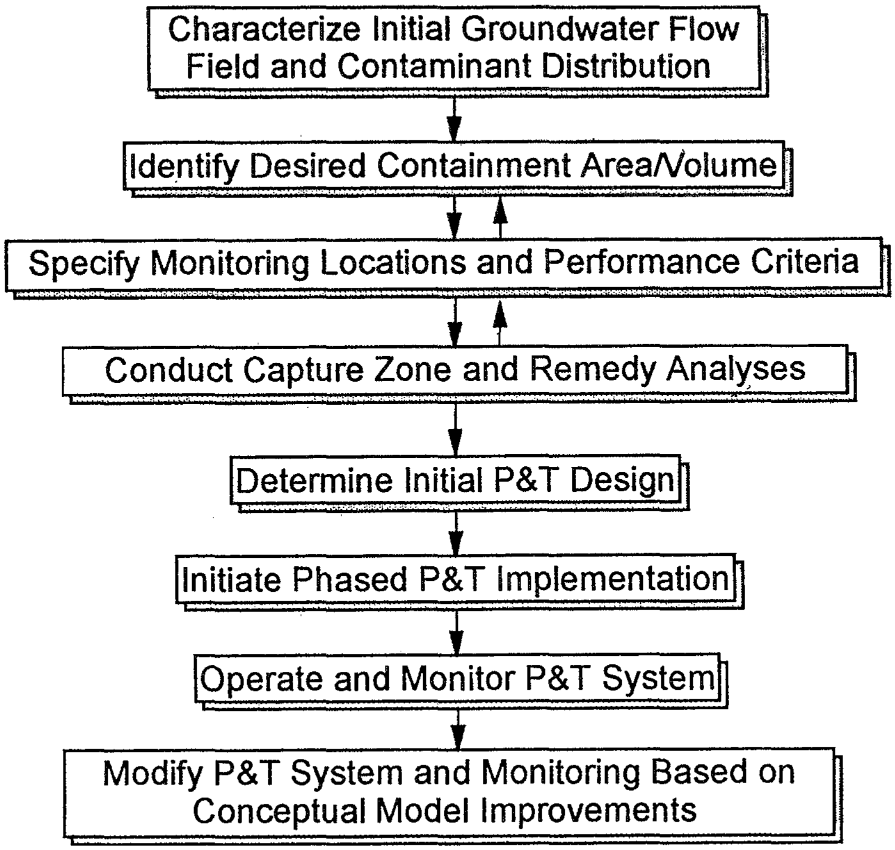


Figure 2-1. **Components of a phased design and implementation of a P&T monitoring program.**

2.2.1 Inward Hydraulic Gradients and Capture Zone Analysis

2.2.1.1 Performance Concept

Inward hydraulic gradients across the boundary of, and/or within, the desired containment may be specified as part of the performance standard. An inward gradient indicates that the ground-water flow is inward, thus allowing the capture of dissolved contaminants by the P&T system.

Hydraulic head and gradient data are interpreted within the context of capture zone analysis (Section 2.6). The capture zone concept is illustrated in Figure 2-2. Note that the capture zone of a well is not coincident with its zone of influence (ZOI) except in those incidences where the hydraulic gradient is negligible prior to pumping. Therefore, there can be locations in the vicinity of a pumping well where a drawdown within that well does not indicate that the ground water will be contained by the capture zone. It should also be noted that successful containment does not require the establishment of inward hydraulic gradients all around the containment zone when it is larger than the contaminated zone. In either case, the subsurface volume showing inward hydraulic gradients will not correspond to the actual capture volume (Larson et al., 1987).

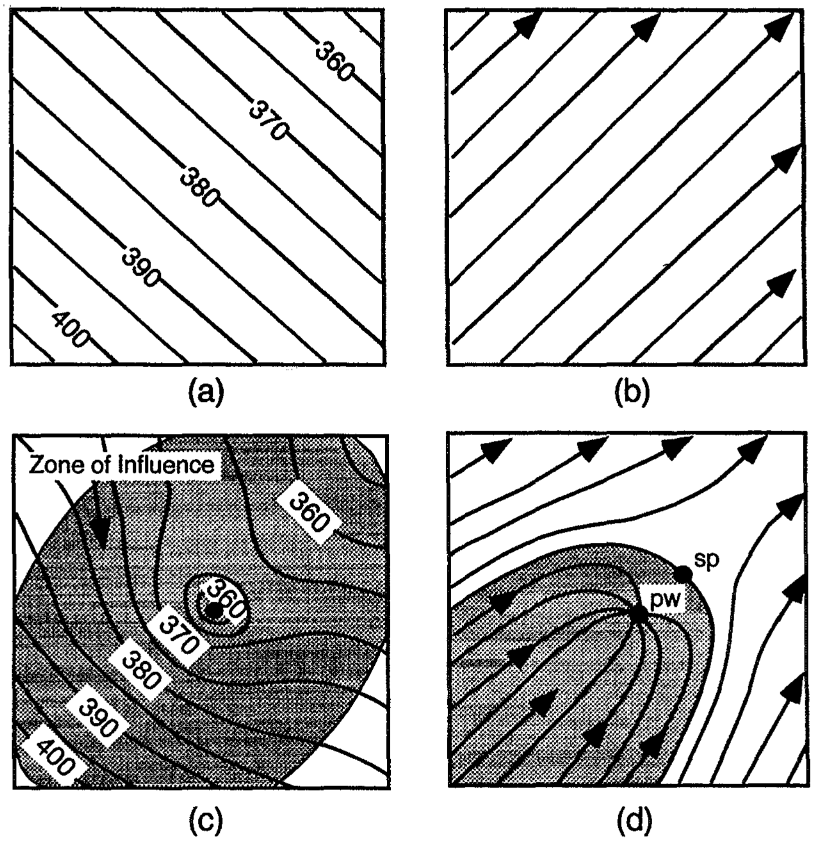


Figure 2-2. **In isotropic media, ground-water flow lines (b) are orthogonal to hydraulic head contours (a) (modified from Gorelick et al., 1993). Pumping causes drawdowns and a new steady-state potentiometric surface (c). Following the modified hydraulic gradients, ground water within the shaded capture zone flows to the pump well (d). The stagnation point is designated sp.**

2.2.1.2 Methods

Depth-to-water measurements can generally be made to +/- 0.01 or 0.02 ft. The accuracy of depth-to-water measurement methods is discussed by Thornhill (1989), USGS (1977), and Dalton et al. (1991). Well reference point elevations should be surveyed to +/- 0.01 ft and checked periodically due to the potential for settlement of surface materials, compaction of pumped strata, or physical damage to the well. This is particularly important when measuring small head differences because the flow direction may be misinterpreted due to slight elevation errors.

2.2.1.3 Measurement Locations

In relatively simple hydrogeologic settings inward hydraulic gradients can be estimated by comparing hydraulic heads in paired piezometers near the containment perimeter, primarily in the pre-pumping downgradient direction (Figure 2-3). For more complex flow systems, this may not always be true and gradients can only be determined by using three or more wells. Capture zone analysis incorporating aquifer tests and potentiometric surface data should be used to help select inward gradient control monitoring locations.

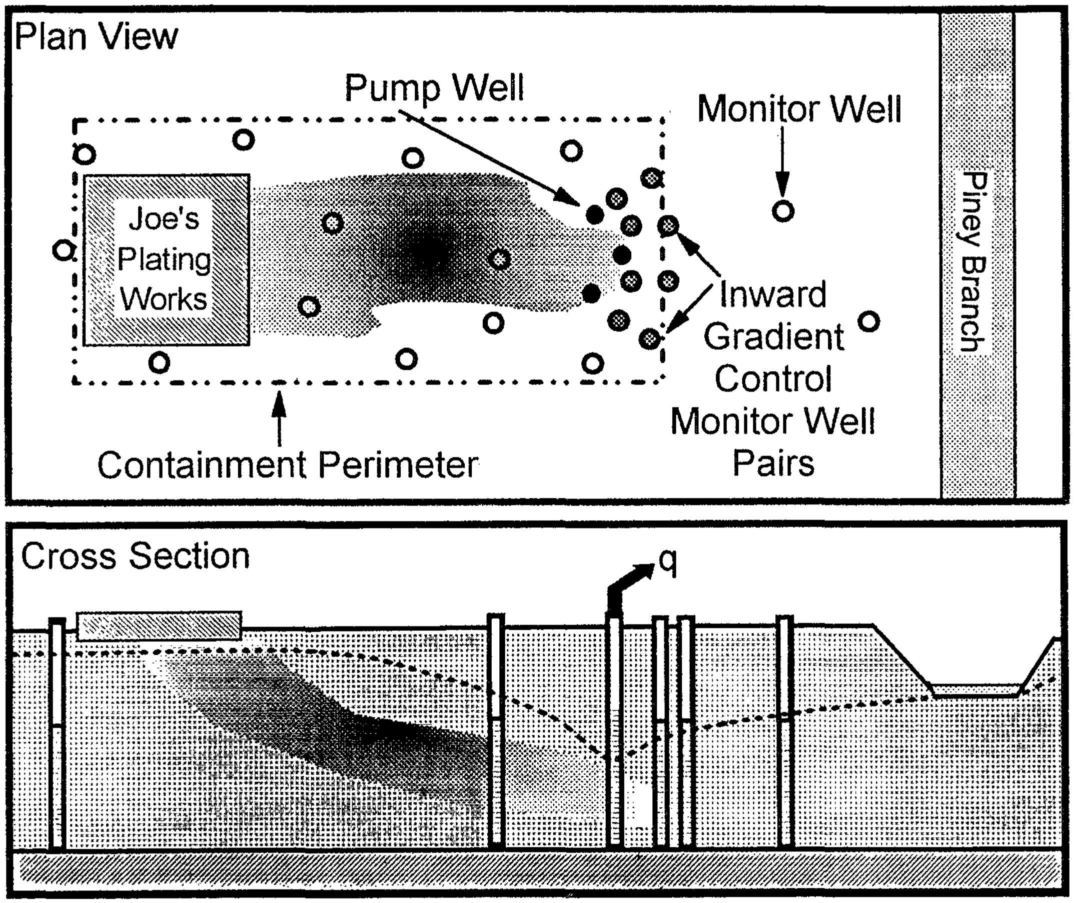


Figure 2-3. **Inward gradients are often monitored by comparing hydraulic heads in paired piezometers near the containment perimeter and primarily in the pre-pumping downgradient direction.**

Inward gradients can also be evaluated by interpreting potentiometric surface maps developed using all available and comparable hydraulic head data (measured in wells within and outside of the containment area). Since ground-water flow is perpendicular to the equipotential lines in the direction of decreasing potential, containment is inferred if flow lines at the containment boundary converge at extraction wells. However, it is critical that potentiometric surface maps be developed using hydraulic heads measured in comparable stratigraphic intervals to avoid misinterpreting horizontal flow directions, especially where significant vertical gradients are present. For this reason, care should be exercised with regard to incorporating measurements from wells with unknown or inconsistent completions. Potentiometric surface maps developed from wells completed in different geologic units may result in misleading interpretations and containment.

In addition to focusing on the downgradient side of the plume, containment boundary monitoring should also target the more permeable portions of the subsurface. Ground-water flow and contaminant migration occur preferentially in these zones. Ideally, the spatial distribution of preferential pathways will be identified during the remedial investigation. However, additional site characterization may be warranted to allow adequate performance monitoring.

Hydraulic gradients across the containment volume should be measured in three dimensions. This may be difficult to accomplish in areas lacking a sufficient number of observation wells to define the convoluted potentiometric surface that may develop due to complex site conditions (i.e., multiple pumping or injection wells, heterogeneity, anisotropy, transient effects, etc.). In addition to horizontal flow divides near pumping wells, flow divides also exist in the vertical dimension (Figure 2-4) because the hydraulic influence of each well extends only a limited depth (Larson et al., 1987; Keely, 1989). As shown in Figure 2-4, capture zone volume may be misinterpreted by neglecting vertical hydraulic gradients. Monitoring vertical hydraulic gradients is discussed further in Section 2.2.2.

In general, the number of observation wells needed to evaluate hydraulic containment increases with site complexity and with decreasing gradients along the containment perimeter. This latter factor is of particular concern with P&T systems that seek to minimize ground-water treatment and/or disposal costs by decreasing pumping to impose the smallest gradients needed for capture. In some cases, it may be practical (and necessary) to use a modeling analysis to interpret hydraulic head measurements and evaluate containment performance (Larson et al., 1987). In other cases, it will be cost-effective to overpump to achieve more demonstrable containment.

It is often easier to demonstrate that inward hydraulic gradients exist toward such systems as recovery drains than toward recovery wells (Figure 1-1). In some cases, this is a significant advantage of P&T systems that incorporate drains and walls.

2.2.1.4 Measurement Frequency

Inward gradients and hydraulic containment may be affected by hydraulic head fluctuations caused by the startup and cycling of P&T operations, offsite well pumping, tidal and stream stage variations, and seasonal factors. If the P&T site is located in an active hydrogeologic setting, hydraulic heads may rise and fall on the order of feet several times a day. To adequately monitor inward gradients and hydraulic containment, consider the following strategies.

(1) Monitor intensively during system startup and equilibration to help 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 is used to examine the significance of hydraulic head fluctuation and justify any subsequent decrease in monitoring frequency. An example of the use of frequent measurements to assess transient effects of daily pumping cycles on hydraulic gradients is shown in Figure 2-5.

(2) Make relatively frequent hydraulic head measurements when the P&T system 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 may arise from extraordinary recharge, flooding, drought, new offsite well pumping, improved land drainage, etc.

(3) Acquire temporally consistent hydraulic head data when measuring inward hydraulic gradients or a potentiometric surface so that differences in ground-water elevations within the well network represent spatial rather than temporal variations.

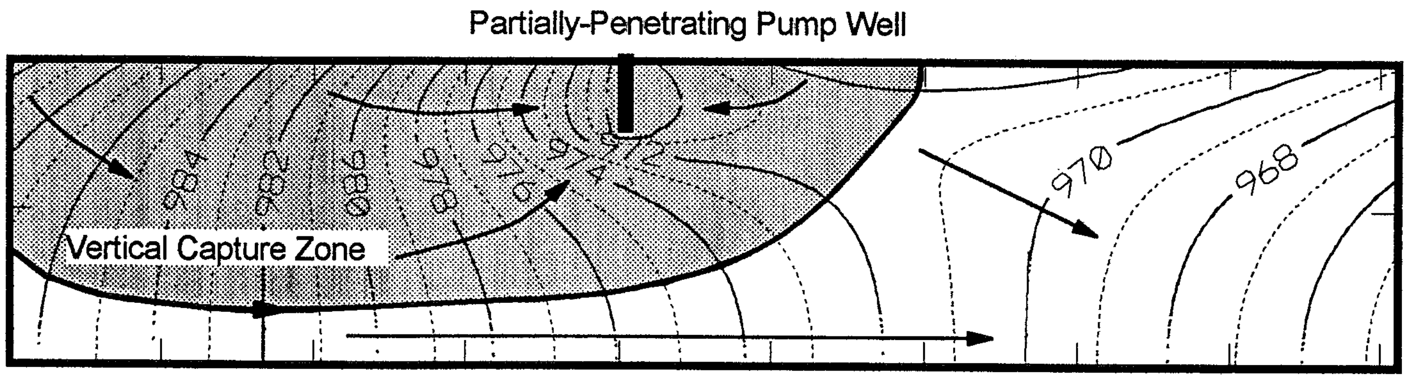


Figure 2-4. **Cross-section showing equipotential contours and the vertical capture zone associated with ground-water withdrawal from a partially-penetrating well in isotropic media. Ground-water flow at depth beneath the well is not captured by pumping despite the presence of apparent upward gradients. In stratified, anisotropic media (e.g., Kx>Kz), the vertical hydraulic control exerted by a partially-penetrating well will be further diminished.**

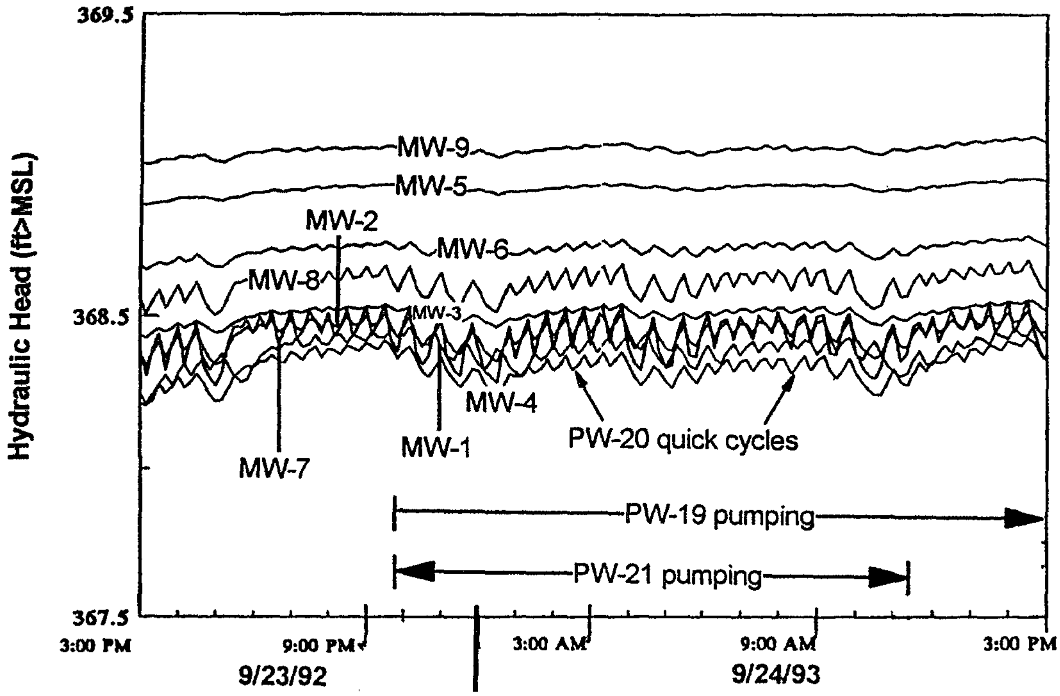


Figure 2-5. **Near continuous hydraulic head measurements were made in several observation wells in the vicinity of a recovery well line to examine the transient water table response to pump cycles and recharge events (modified from ESE, 1992). The data reveal that ground-water flow directions are fairly constant during pump cycles. In conjunction with weekly data, it was determined that the frequency of hydraulic head surveys should be reduced to monthly.**

If inward gradients are not maintained during P&T operation, an analysis should be made to determine if containment is threatened or lost. 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 2-6). Transient capture zone analysis, perhaps using a numerical model and particle tracking, may be required to assess containment effectiveness. Even where the time-averaged flow direction is toward the P&T system, containment can be compromised if contaminants escape from the larger capture zone during transient events or if there is a net component of migration away from the pumping wells over time.

2.2.1.5 Some Additional Considerations

Use of Pump Well Data -- Hydraulic heads and extraction rates associated with recovery wells should be factored into capture zone analysis. It is generally inappropriate, however, to interpret inward gradients by comparing the hydraulic head measured in a piezometer to that in a pump well (Figure 2-7). Rather, hydraulic gradients and flow patterns should be interpreted primarily based on head

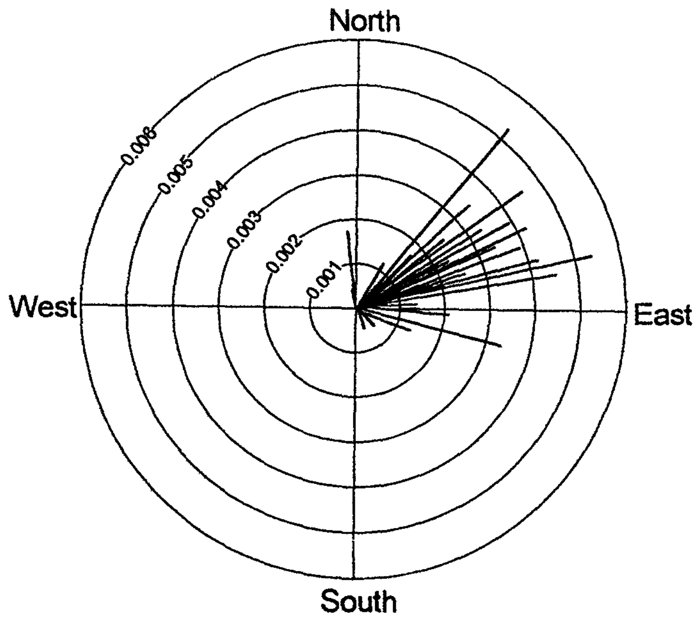


Figure 2-6. Example display of ground-water flow directions and hydraulic gradients determined between three observation wells.

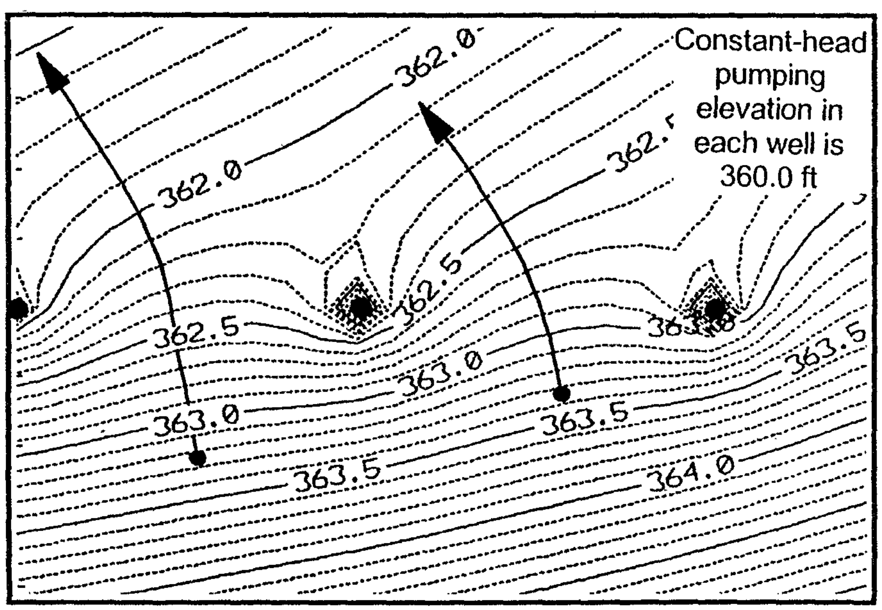


Figure 2-7. Ground water flows between and beyond the recovery wells even though hydraulic heads throughout the mapped aquifer are higher than the pumping level. Rely primarily on observation well data to determine flow directions.

measurements in observation wells or piezometers. Useful estimates of hydraulic heads in the vicinity of a pump well with a known pumping rate and level can be derived using well hydraulics equations (i.e., the Theis or Theim equations, Bear, 1979) or a ground-water flow model; but uncertainties associated with formation properties and well loss may confound the analysis.

Horizontal Anisotropy -- Where strata are inclined or dipping, particularly foliated media such as schist with high-angle dip, significant horizontal anisotropy may be present. The directions of maximum and minimum permeability are usually aligned parallel and perpendicular, respectively, to foliation or bedding plane fractures. In anisotropic media, the flow of ground water (and contaminants moving with ground water) is usually not perpendicular to the hydraulic gradient. This is demonstrated at a petroleum tank farm site in Virginia where the flow of leaked LNAPL and ground water is offset significantly from the hydraulic gradient toward the direction of maximum permeability (Figure 2-8). Interpretation of hydraulic head data and capture zone analysis must account for anisotropy to evaluate containment effectiveness. Various well hydraulics equations incorporate anisotropy (Papadopulos, 1965; Kruseman and deRidder, 1990) and many numerical models can treat anisotropic conditions.

Transient Loss of Capture during Early Pumping -- Given the steep initial hydraulic gradient induced by pumping, hydraulic containment provided by P&T operation may decrease with time due to the flattening of the drawdown cone(s) as illustrated by the computer simulations shown in Figure 2-9. Early demonstration of inward hydraulic gradients, therefore, does not ensure continued containment. Long-term monitoring must be relied upon to assess long-term P&T system performance.

Drawdown Limitations -- Under some conditions, inward hydraulic gradients cannot be maintained unless barrier walls are installed and/or water is injected (or infiltrated) downgradient of or within the contaminated zone. Limited aquifer saturated thickness, a relatively high initial hydraulic gradient, a sloping aquifer base, and low permeability are factors that can prevent hydraulic containment using wells or drains (Saroff et al., 1992). Where these conditions exist and hydraulic containment is planned, particular care should be taken during pilot tests to assess this limitation.

Injection/Extraction Cells -- Two prime objectives of aquifer restoration are to contain and/or remove contaminant plumes. Hydraulic controls provide an opportunity to concurrently accomplish both of these objectives. Recharging upgradient of the contaminant plume and flushing it toward downgradient collection points creates a ground-water recirculation cell that isolates the plume from the surrounding ground water. By properly adjusting recharge and extraction rates, these cells can minimize the volume of water requiring treatment, thereby reducing the flushing time. If permitted, water injection can greatly enhance hydraulic control of contaminated ground water. Options associated with selecting injection locations and rates provide great containment flexibility (e.g., Wilson, 1985).

Highly Permeable and Heterogeneous Media -- In highly permeable media, high pumping rates are usually required to attain hydraulic containment and performance monitoring can be complicated by flat hydraulic gradients. Barrier walls and containment area surface covers installed to reduce the rate of pumping needed for containment also facilitate demonstration of inward gradients (Figure 1-1). Complex heterogeneous media are difficult to characterize. Ideally, monitor wells are installed in the more

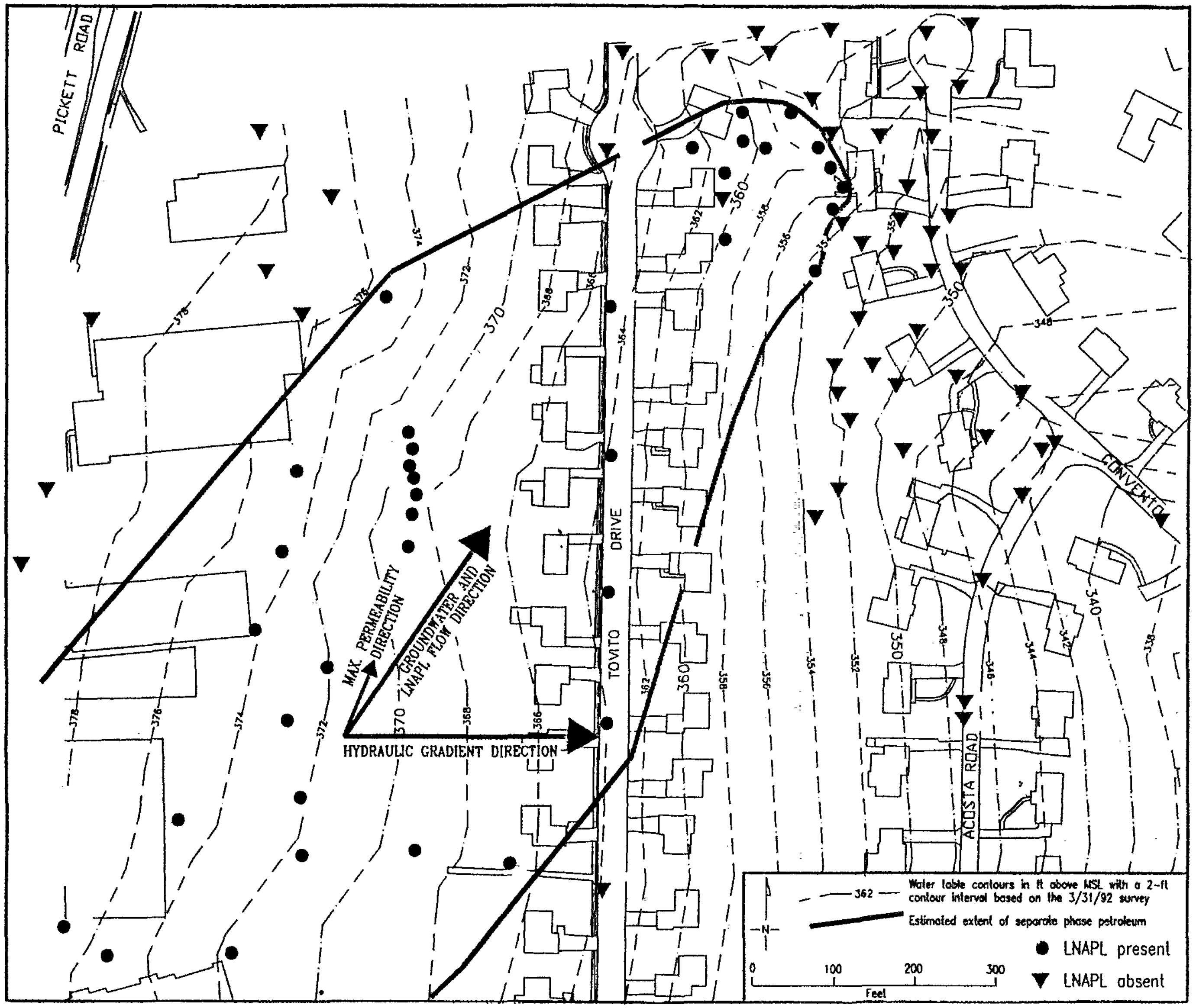


Figure 2-8. **Ground-water and LNAPL flow in anisotropic saprolite soil from a petroleum-product tank farm in Fairfax, Virginia is offset from the hydraulic gradient toward the strike of saprolite foliation.**

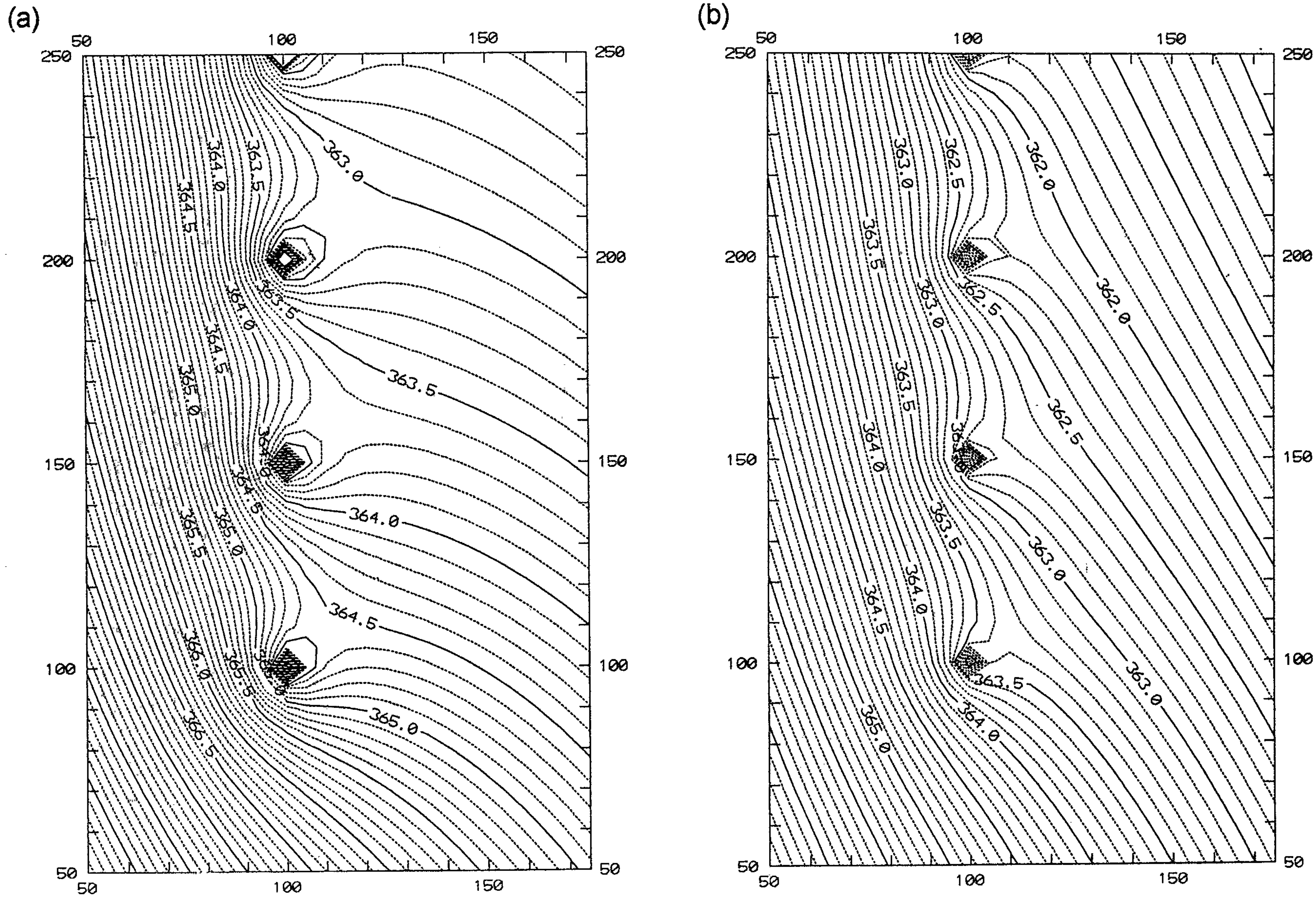


Figure 2-9. **As this computer simulation illustrates, the initial steep drawdown induced by pumping flattens out with time, hydraulic containment may be diminished significantly as exemplified by the hydraulic head contours associated with a line of recovery wells after (a) 5 days of pumping and (b) after 30 days of pumping.**

permeable strata to provide optimal chemical detection and gradient control monitoring capability. Hydraulic containment, inward gradient monitoring, and site characterization are also facilitated in heterogeneous media by installing barrier drains and walls, particularly if done in a manner that allows subsurface examination during construction.

NAPL Containment -- Inward hydraulic gradients will contain LNAPL migration. DNAPL, however, may migrate under the influence of gravity in directions that are counter to the hydraulic gradient. Unless of sufficient magnitude to overcome the gravitational force, therefore, inward hydraulic gradients cannot be relied upon to contain DNAPL movement. Cohen and Mercer (1993) describe several approaches for estimating hydraulic gradients required to arrest DNAPL migration.

Ambiguous Gradient Data -- At many P&T sites, interpretation of hydraulic gradients will provide an ambiguous measure of containment effectiveness. To raise confidence in the monitoring program, consider: (1) increasing the frequency and locations of hydraulic head measurements; (2) conducting more robust data analysis, perhaps using models; (3) relying more on chemistry monitoring; or (4) modifying the P&T system (e.g., by increasing the pumping rate) to provide more demonstrable containment.

2.2.2 Vertical Hydraulic Gradients

Inward gradients may also be specified as upward gradients at the base of the contaminant plume or containment volume. This is important because a P&T system may fail to prevent downward contaminant migration (e.g., where remediation wells are too shallow or have insufficient flow rates). For dissolved contaminants, in many cases, the magnitude of the upward gradient need only be measurable. For DNAPLs, the inward gradient must be large enough to overcome the potential for DNAPL to move via gravity and capillary pressure forces (Cohen and Mercer, 1993). At sites where upward hydraulic gradients sufficient to arrest DNAPL migration cannot be developed, consideration must be given to other containment strategies. For example, if DNAPL can be reduced to residual saturation by pumping, capillary forces may be sufficient to overcome gravitational forces and prevent downward migration.

Upward gradients across the bottom of the containment volume can be monitored by comparing (1) hydraulic head differences measured in adjacent nested wells that are screened at different depths and/ or (2) potentiometric surfaces developed for different elevations, stratigraphic units, or flow zones. Generally, a nested cluster of wells consists of three monitoring wells/piezometers completed at different depths. However, the required number of wells depends on site-specific monitoring objectives, contaminant distribution, P&T system design, and the degree of site complexity.

In a layered multiaquifer system, where the entire thickness of a contaminated upper aquifer is within the containment volume, upward gradient control wells can be completed above and below the underlying aquitard to determine the direction of flow across the aquitard (Figure 2-10). If, however, the containment volume bottom is within a flow zone of significant thickness, nested wells will generally be required at different elevations (above and below the containment volume bottom) within the flow zone. For this case, upward gradients may not ensure containment (Figure 2-4), and it may be necessary

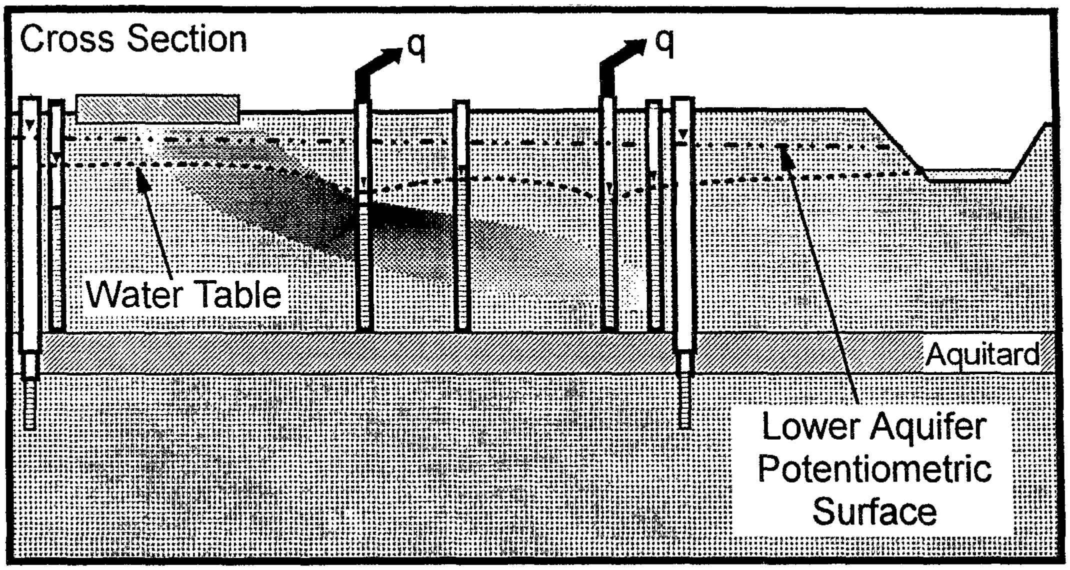


Figure 2-10. Vertical hydraulic gradients across an aquitard between aquifers are typically measured using observation well nests.

to rely on a careful three-dimensional analysis of flow and chemical monitoring to evaluate containment effectiveness.

A more thorough analysis of upward hydraulic gradients can be made by comparing potentiometric surface maps for different elevations (or stratigraphic units) to develop a contour map of vertical hydraulic gradients. A vertical gradient contour map can be used to delineate areas of upward and downward flow components.

Special precautions should be taken when drilling monitor wells into and/or below a contaminated zone to minimize the potential for cross-contamination. Where DNAPL is present, it may be advisable to monitor potentially uncontaminated, deep units by installing wells beyond the DNAPL zone limit even though this will diminish the upward gradient monitoring capability.

2.2.3 Hydraulic Head Differences

True hydraulic gradients may be difficult to determine; therefore, the objective may revert to determining a measurable quantity, such as hydraulic head. Hydraulic head differences may be specified as performance criteria at pumping or observation wells as either differences in head between different locations at the same time or as time-dependent drawdown in particular wells. In any event, hydraulic head performance criteria must be developed within the context of capture zone analysis based on an understanding of the relationship between hydraulic heads at specific locations and local hydraulic gradients. Otherwise, they may be poor indicators of system performance.

2.2.4 Flow Meters

A few techniques and tools have been developed recently to measure horizontal ground-water flow directions directly in a single well. Such techniques include using a special flowmeter in a well to measure horizontal flow direction (Kerfoot, 1984; Melville et al., 1985; Guthrie, 1986) and a colloidal borescope that measures the movement of naturally occurring colloids in ground water (Kearl and Case, 1992). If these tools are found to be reliable at a site, then flow directions (and hence inward hydraulic gradients) can be determined directly in wells placed along the containment boundary and elsewhere.

Technologies for measuring vertical flows within wells under ambient and pumping conditions hence also have been developed (Molz and Young, 1993). These tools allow better characterization of the relative permeability distributions and hence preferential flow paths.

2.2.5 Pumping Rates

For hydraulic containment, the placement and extraction or injection rates of wells are determined so that ground water in the containment area/volume follow pathlines to the P&T system. The initial design may be based on the results of ground-water modeling (Section 2.6) and may designate pumping rates, pump well drawdowns, or high-low pumping level ranges for the P&T system. However, it is not appropriate to specify model-determined pumping rates or levels as long-term performance criteria, because these may be too high or too low if the model is inaccurate. The feasibility of pumping rates and levels determined using a model must be verified during onsite aquifer testing, upon initiation of the P&T system, and by long-term monitoring.

Pumping rates and levels are monitored to: (1) demonstrate that the system is operational (or alert managers to make necessary repairs if pumps are found to be inoperable); (2) determine if pumping rates and levels are within specified tolerances; and, (3) provide data necessary for system optimization. Pumping rates must be maintained to control hydraulic gradients. As discussed in Section 2.2, if the rates are "optimized" to reduce P&T costs, it may become very difficult to demonstrate containment by measuring hydraulic gradients. When analyzing P&T system behavior, particularly where there are multiple pumping wells, it is important to monitor (and document) pumping rates, times, and levels on a well-specific basis (rather than simply monitoring totalized flows from multiple wells).

Well discharge rates can be determined by several methods, including the use of a pipe orifice weir, weirs and flumes, and flowmeters (Driscoll, 1986). During P&T system operation, however, pumping rates are usually monitored in a closed system using flowmeters which provide pumping rate and totalized discharge data. Several different types of flowmeters (e.g., rotameters, ultrasonic Doppler flowmeters, turbine/paddlewheel flowmeters, magnetic flowmeters, etc.) and automated data logging and alarm systems are available.

2.2.6 Ground-Water Chemistry

2.2.6.1 Performance Concept

Ground-water quality monitoring is performed at nearly all P&T operations to determine if temporal or spatial variations in contaminant distribution are consistent with effective hydraulic containment. If not, the monitoring identifies areas and temporal conditions of inadequate containment which should then be improved by a P&T system upgrade.

At sites where contamination is enclosed by the containment volume perimeter, a detection monitoring program can be implemented at or beyond this perimeter to evaluate P&T performance. Chemical analysis should target the most mobile site contaminants. Detection of contaminants above background concentrations (if any) indicates a lack of containment, unless the contaminant presence can be attributed to an alternate source.

Ground-water quality monitoring to assess containment may provide ambiguous results if some site contaminants are located beyond the containment volume perimeter prior to P&T system startup. Given this scenario, containment failure is suggested if: (1) the estimated total contaminant mass in ground water beyond the containment perimeter increases with time (see Section 3 and Appendix A); (2) contaminant concentrations change with time (e.g., increase) in perimeter or downgradient monitor wells in a manner that is inconsistent with effective containment; and/or (3) relatively retarded contaminants, that were previously restricted to the containment area, are detected in perimeter monitor wells. If the spatial distribution of contaminants or the ground-water flow field is ill-conceived, then each of these criteria is subject to misinterpretation. Where ground-water chemistry data limitations are significant, greater reliance is placed on hydraulic gradient monitoring.

Tracers can be injected within the plume and monitored outside the containment volume to discriminate between lack of containment, pre-existing contamination beyond the containment limit, and potential offsite contaminant sources. Detecting a unique tracer beyond the containment area indicates a lack of containment. The use of tracers is discussed in Section 2.2.8.

2.2.6.2 Ground-Water Quality Monitoring Locations

Monitor well locations and completion depths are selected to provide a high probability of detecting containment system leaks in a timely manner. Site characterization data and capture zone analysis are used to identify potential areas and pathways of contaminant migration across the containment volume perimeter during P&T operation and inoperation (due to mechanical failure or routine system maintenance). These potential migration routes may include the more permeable media, areas and depths subject to relatively weak ground-water flow control, and manmade or natural drainage features (e.g., sewers, streams, etc.). Using this hydrogeologic approach, site-specific conditions are evaluated to choose optimum ground-water sampling locations. Various geostatistical methods (e.g., Haug et al., 1990) and plume generation models (e.g., Wilson et al., 1992; Meyer and Brill, 1988) can also be used to help assess well spacing and depths. Loaiciga et al. (1992) present a review of the application of hydrogeologic and geostatistical approaches to ground-water quality network design. In general, as with mapping hydraulic gradients, the number of ground-water quality monitor wells needed to assess containment effectiveness increases with plume size and site complexity.

Ideally, P&T system failure will be detected before contaminants migrate far beyond the containment perimeter toward potential receptors. Consequently, monitor wells with a relatively close spacing are usually located along or near the potential downgradient containment boundary. Inward gradient control wells (discussed in Section 2.2.1) are frequently used for ground-water sampling. Public or private water supply wells located downgradient of the contamination may also be used to monitor containment effectiveness and to determine the quality of ground water being consumed by local residents.

Modifications to monitoring locations and criteria may be needed to complement changes in P&T operation, ground-water flow directions, contaminant distributions, and/or the specified containment volume.

2.2.6.3 Ground-Water Quality Monitoring Frequency

Ground-water quality surveys are usually conducted less frequently than hydraulic head surveys because: (1) contaminant movement is a slower process than that controlling transient hydraulic head propagation; and (2) ground-water quality surveys are much more expensive to conduct than groundwater elevation surveys. Determining ground-water sampling frequency requires consideration of site-specific conditions. It should not be assumed that all wells must be sampled at the same time, for the same parameters, or during every sampling episode.

In general, it is good practice to sample at a higher frequency and perform more detailed chemical analyses in the early phase of the monitoring program, and then to use the information gained to optimize sampling efficiency and reduce the spatial density and temporal frequency of sampling in the later phases. For example, consider the following strategies.

(1) Monitor ground-water quality in perimeter and near-perimeter leak detection wells more frequently than in wells that are more distant from the contaminant plume limit.

(2) Specify sampling frequency based on potential containment failure migration rates that consider the hydraulic conductivity (k) and effective porosity (n) of the different media, and maximum plausible outward hydraulic gradients (i). If appropriate, account for the retardation factor, R_f (Section 1.2, Equation 1-4). Use modeling results or simple calculations of contaminant average linear velocity (v_c, where $v_c = R_f ki/n$) to estimate potential contaminant transport velocities. Consider sampling more permeable strata in which migration may occur relatively quickly more frequently than less permeable media.

(3) After performing detailed chemical analyses during the remedial investigation or the early phase of a monitoring program, increase monitoring cost-effectiveness by focusing chemical analyses on site contaminants of concern and indicator constituents. Conduct more detailed chemical analyses on a less frequent basis or when justified based on the results of the more limited analyses.

At sites with inorganic contamination or where organic site contaminants are present initially beyond the containment perimeter, it may be necessary to use statistical methods to: (1) distinguish contaminant detections from background concentrations; and (2) assess the influence of various temporal and spatial factors (e.g., recharge rate and heterogeneity, respectively) on contaminant concentration variability. Sampling locations and frequency, therefore, may be dictated by the requirements of statistical analyses. Guidance on applying statistics to differentiate contamination from background and to identify concentration trends with statistical significance is provided by USEPA (1986, 1988a, 1989, 1992b, 1992c) and Gilbert (1987). At some sites, identifying background contaminant concentrations and trends may not be cost-effective given monitoring program objectives.

2.2.7 Perimeter Monitoring Using Noninvasive Methods

At sites where contaminants have not migrated beyond the containment perimeter, it may be cost-effective to enhance P&T monitoring by conducting surface geophysical or soil gas surveys along transects between monitor wells (Figure 2-11). Using this approach, an initial baseline survey is made along well-defined transects. Repeat surveys are then conducted periodically to detect changes from the baseline condition that evidence contaminant migration.

Electrical geophysical methods (EM-conductivity and resistivity) can be used to detect the migration of conductive contaminants in ground water. An application of this strategy using quarterly EM-conductivity surveys along transects between wells to augment a landfill leachate detection monitoring network is described by Rumbaugh et al. (1987). Similarly, under appropriate conditions, volatile organic contaminant movement in the upper saturated zone can be inferred by analysis of soil gas samples (Devitt et al., 1987; Cohen and Mercer, 1993).

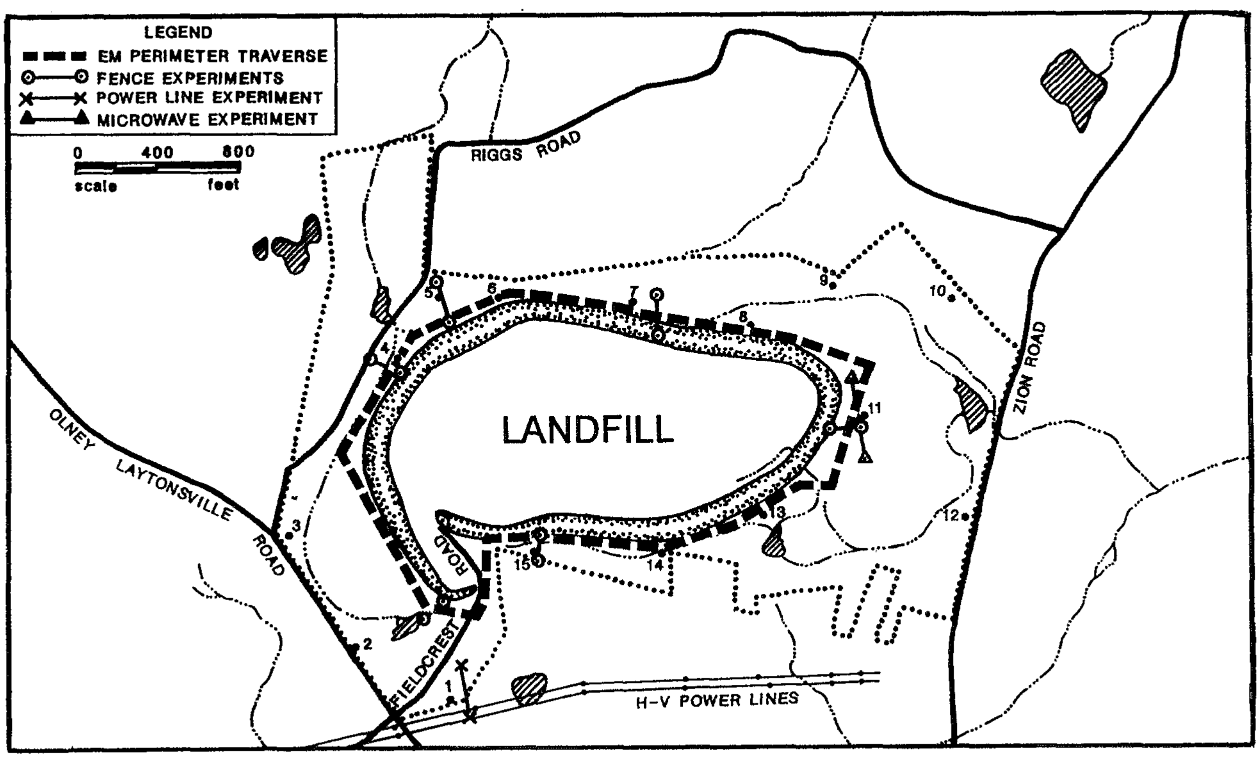


Figure 2-11. Surface geophysical EM-Conductivity) surveys were conducted periodically along transects between monitor wells encircling a sanitary landfill in Maryland to augment the leak detection monitoring network (from Rumbaugh et al., 1987).

Although often less costly, data acquired using noninvasive methods is also less definitive than direct ground-water sampling data. As a result, inferences derived from these techniques must be confirmed by ground-water sampling and analysis.

2.2.8 Tracers

Tracers are used in ground-water studies to determine flow path, velocity, solute residence time, and formation properties such as hydraulic conductivity, dispersivity, and effective porosity (Davis et al., 1985). At sites where contaminants are present beyond the containment zone, ground-water tracers can be used to enhance performance monitoring. A tracer can be released periodically into ground water inside the containment zone where hydraulic control is considered least effective. Subsequent tracer detection in ground water beyond the containment perimeter (e.g., during regular monitoring surveys) would indicate containment failure and possibly the general location of the failure. Tracers can also be used to help delineate the P&T capture zone by releasing tracer in areas of uncertain capture and monitoring for tracer presence in pumped ground water.

A detailed discussion of tracer selection and use for ground-water investigations is provided by Davis et al. (1985). Important ground-water tracers include particulates (spores, bacteria, and viruses), ions (chloride and bromide), dyes (Rhodamine WT and Fluorescein), radioactive tracers, fluorocarbons, and organic anions. Tracers are selected based on their properties (e.g., toxicity and mobility) and the availability of reliable analytical techniques. Determination of the amount of tracer to inject is based on its background concentration, the analytical detection limit, and the expected degree of tracer dilution at sampling locations. Tracer concentration should not be increased so much that density effects become a problem for the particular application.

2.3 MONITORING LOCATION SUMMARY

Hydraulic head and ground-water chemistry monitoring locations are discussed in Section 2.2 for each performance measure. In summary, monitoring is conducted within, at the perimeter, and downgradient of the containment zone to interpret ground-water flow, contaminant transport, and P&T system performance. Containment area monitoring is used particularly to assess extraction/injection impacts and hydraulic control at the containment volume bottom. Perimeter monitoring facilitates contaminant leak detection and evaluation of inward gradients. Downgradient monitoring provides additional containment failure detection capability and helps assess potential contaminant migration to water-supply wells and/or surface water.

2.4 OPERATIONS AND MAINTENANCE (O&M) MANUAL

Many P&T systems may be dysfunctional due to a lack of adequate monitoring and maintenance. O&M manuals should be prepared for each P&T system. Elements of an O&M plan should: (1) provide an introductory description of the P&T system; (2) identify and describe system components (e.g., pumps, controllers, piping, wiring, treatment system parts, alarms, etc.); (3) include detailed drawings of system layout, equipment schematic diagrams, and parts listings; (4) enumerate system installation, startup, and operation procedures; (5) provide a troubleshooting guide and problem call-down or contact list; and (6) detail system monitoring, maintenance, and record-keeping requirements and schedules. Much of this information is available from equipment vendors.

2.5 P&T MONITORING PLAN

As noted in Section 2.1, a written monitoring plan should also be developed for P&T system operation. The plan should describe: (1) monitoring objectives; (2) the types of measurements to be made (e.g., pumping rates, hydraulic heads, ground-water chemistry, precipitation); (3) measurement locations; (4) measurement methods, equipment, and procedures; (5) measurement schedules; and (6) record-keeping and reporting requirements. It is important that the monitoring plan be revised as data is collected and improvements are realized with respect to the site conceptual model and knowledge of the distribution of contaminants is enhanced.

2.6 CAPTURE ZONE ANALYSIS AND OPTIMIZATION MODELING

In recent years, many mathematical models have been developed or applied to compute capture zones, ground-water pathlines, and associated travel times to extraction wells or drains (Javandel et al., 1984; Javandel and Tsang, 1986; Shafer, 1987a,b; Newsom and Wilson, 1988; Blandford and Huyakorn, 1989; Pollock, 1989; Strack, 1989; Bonn and Rounds, 1990; Bair et al., 1991; Rumbaugh, 1991; Bair and Roadcap, 1992; Fitts, 1993; Gorelick et al., 1993. These models provide insight to flow patterns generated by alternative P&T schemes and the selection of monitoring locations and frequency. Additionally, linear programming methods are being used to optimize P&T design (Ahlfeld and Sawyer, 1990; Hagemeyer et al., 1993; Gorelick et al., 1993) by specifying an objective function subject to various constraints (e.g., minimize pumping rates but maintain inward hydraulic gradients). Given their application to the design, evaluation, and monitoring of P&T systems, a brief overview of a few capture zone analysis and optimization techniques follows. It must be kept in mind, however, that the accuracy of modeling predictions is dependent on the availability and validity of the required input data.

Several semianalytical models employ complex potential theory to calculate stream functions, potential functions, specific discharge distribution, and/or velocity distribution by superposing the effects of multiple extraction/injection wells using the Thiem equation on an ambient uniform ground-water flow field in a two-dimensional, homogeneous, isotropic, confined, steady-state system (e.g., RESSQ, Javandel et al., 1984; DREAM, Bonn and Rounds, 1990; and, RESSQC, Blandford and Huyakorn, 1989). Based on this approach, the simple graphical method shown in Figure 2-12 can be used to locate the stagnation point and dividing streamlines, and then sketch the capture zone of a single well in a uniform flow field. The extent to which these results represent actual conditions depends on the extent to which the assumptions vary from actual site conditions.

This analysis is extended by Javandel and Tsang (1986) to determine the minimum uniform pumping rates and well spacings needed to maintain capture between two or three pumping wells along a line perpendicular to the regional direction of ground-water flow. Their capture zone design criteria and type curves given in Figure 2-13 can be used for capture zone analysis, but more efficient P&T systems can be designed with nonuniform pump well orientations, spacings, and extraction rates. Streamlines and capture zones associated with irregular well spacings and variable pumping rates can be simulated by the complex potential flow models, RESSQ, RESSQC, and DREAM. Reverse particle tracking is implemented in RESSQC to derive steady-state capture zones by releasing particles from the stagnation point(s) of the system and tracking their advective pathlines in the reversed velocity field. Similarly, time-related captures zones (Figure 2-14) are obtained by tracing the reverse pathlines formed by particles released all around each pumping well (Blandford and Huyakorn, 1989; Shafer, 1987a).

Application of semianalytical models to field problems requires careful evaluation of their limiting assumptions (e.g., isotropic and homogeneous hydraulic conductivity, fully-penetrating wells, no recharge, no vertical flow component, and constant transmissivity). Several analytic models relax these restrictive assumptions by superposition of various functions to treat recharge, layering, inhomogeneity, three-dimensional flow, etc. (Fitts, 1989; Strack, 1989; Rumbaugh, 1991). Where field conditions do not conform sufficiently to model assumptions, the simulation results will be invalid (e.g., Springer and Bair, 1992).

Numerical models are generally used to simulate ground-water flow in complex hydrogeologic systems (e.g., MODFLOW, McDonald and Harbaugh, 1988; and SWIFF/486, Ward et al., 1993). For example, the benefits of using partially-penetrating recovery wells to minimize pumping rates and unnecessary vertical spreading of contaminants can be examined using a three-dimensional flow model.

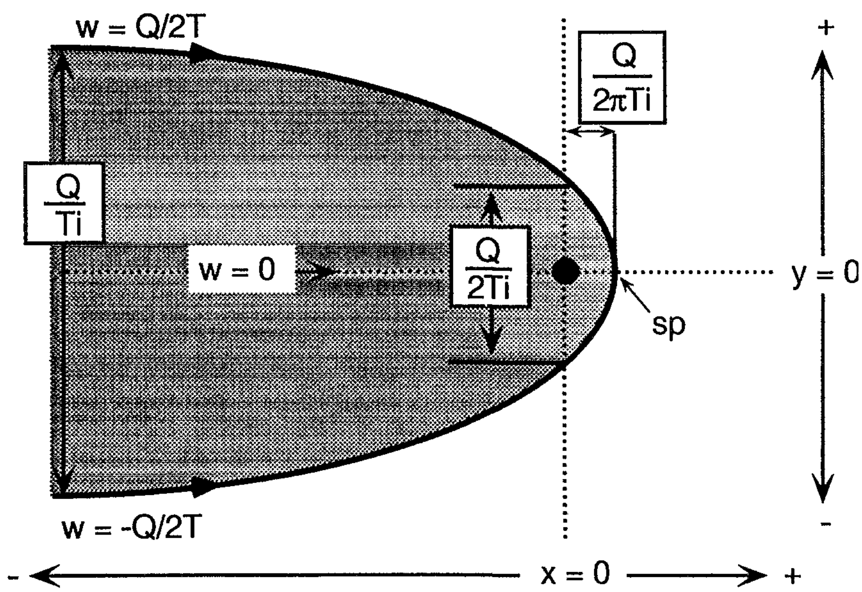
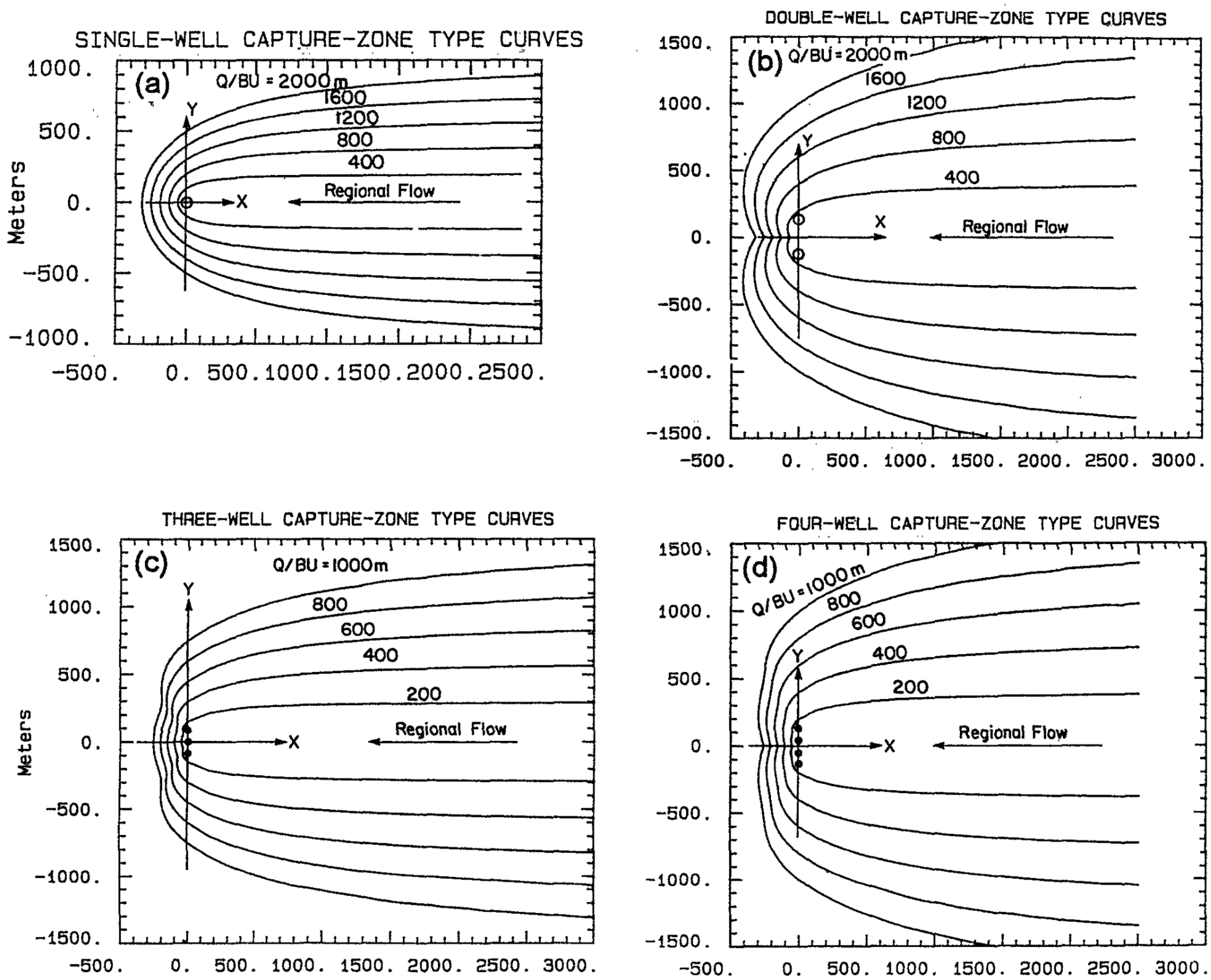


Figure 2-12. Equations for the dividing streamlines (w=Q/2T) that separate the capture zone of a single well from the rest of an isotropic, confined aquifer with a uniform regional hydraulic gradient (modified from Gorelick et al., 1993). Note that T=transmissivity (L^2/T), Q=pump rate (L^3/T), and i=initial uniform hydraulic gradient).



Number of Wells	Recommended Distance between Each Pumping Well	Distance between Dividing Streamlines at Well Line	Distance between Dividing Streamlines Far Upstream from Well Line	Distance to Stagnation Point at the Center of the Capture Zone
1	--	Q/(2Ti)	Q/Ti	Q/(2πTi)
2	Q/(πTi)	Q/Ti	2Q/Ti	Q/(2πTi)
3	1.26Q/(πTi)	3Q/(2Ti)	3QTi	3Q/(4πTi)

Figure 2-13. Type curves showing the capture zones of 1 (a), 2 (b), 3 (c), and 4 (d) pump wells spaced evenly along the y-axis for several values of Q/BU (where Q = pumping rate (L^3/T), B = aquifer thickness (L), and U = Darcy velocity for regional flow (L/T) (from Javandel and Tsang, 1986). To assess the number of wells, pumping rates, and well spacings needed to capture a plume using evenly spaced recovery wells along a line: (1) Construct a plume map at the same scale as the type curves; (2) Superimpose the 1-well type curve over the plume with the x-axis parallel to the regional flow direction and overlying the center of the plume such that the plume is enclosed by one Q/BU curve; (3) Calculate the required single well pumping rate as Q=B*U*TCV where TCV is the bounding Type Curve Value of Q/BU; and, (4) If a single well cannot produce the calculated pump rate, repeat the steps using the 2, 3, and 4 well type curves until a feasible single well pump rate is calculated. Use the above equations to determine optimum well spacings. See Javendel and Tsang (1986) for details.

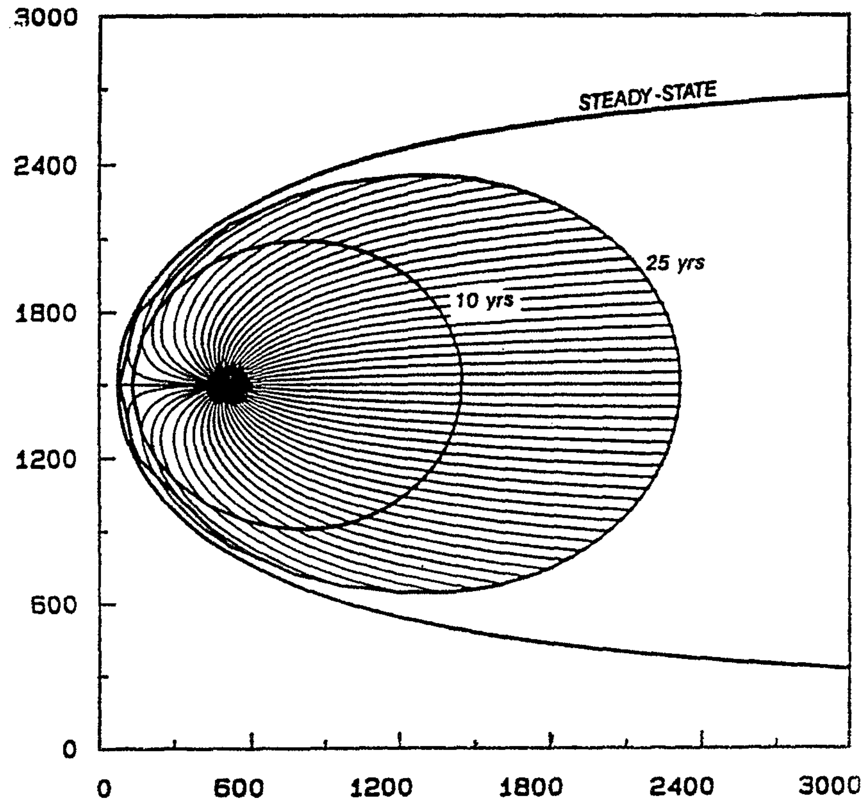


Figure 2-14. Example of steady-state, and 10-year and 25-year time-related capture zones delineated using reverse particle tracking (from Blandford and Huyakorn, 1989).

Numerical flow model output is processed using reverse or forward particle-tracking software such as MODPATH (Pollock, 1989), GWPATH (Shafer, 1987b), STLINE (Ward et al., 1993), FLOWPATH (Franz and Guiguer, 1990), PATH3D (Zheng, 1989), and the GPTRAC module of WHPA (Blandford and Huyakorn, 1989) to assess pathlines and capture zones associated with P&T systems at sites that cannot be accurately modeled using simpler techniques. Solute transport models are primarily run to address aquifer restoration issues such as changes in contaminant mass distribution with time due to P&T operation (e.g., Ward et al., 1987).

Ground-water flow models can be coupled with linear programming optimization schemes to determine the most effective well placements and pumping rates for hydraulic containment much more quickly than a trial-and-error approach. The optimal solution maximizes or minimizes a user-defined objective function subject to all user-defined constraints. In a P&T system, a typical objective function may be to minimize the pumping rate to reduce cost, while constraints may include specified inward gradients at key locations, and limits on drawdowns, pumping rates, and the number of pump wells. Gorelick et al. (1993) present a review of the use of optimization techniques in combination with groundwater models for P&T system design. Available codes include AQMAN (Lefkoff and Gorelick, 1987) an optimization code that employs the Trescott et al., (1976) two-dimensional ground-water flow model, and MODMAN (GeoTrans, 1992), which adds optimization capability to the three-dimensional USGS MODFLOW model (McDonald and Harbaugh, 1988) and others (USEPA, 1993a). A case study of the application of an optimization code to assist P&T design is given by Hagemeyer et al. (1993).

Coupled ground-water flow-optimization models can also be used to evaluate monitoring well network design (Meyer and Brill, 1988; Meyer, 1992). Objectives might be to (1) minimize the total number of monitor wells, (2) maximize the probability of detecting contaminant migration, and (3) minimize the area of expected contamination at the time of leak detection. The first two objectives are addressed using the Maximal Covering Location Problem method illustrated in Figure 2-15 to find well locations and depths that maximize the probability of future plume detection (Meyer, 1992). Another approach, the Extended P-Median Problem, addresses all three objectives by tracking plume size as it grows with time (Meyer, 1992).

Although P&T and monitoring design can be aided by the use of ground-water models, actual field monitoring must be carried out in order to provide information necessary to evaluate model predictions. As described in this Chapter, hydraulic containment effectiveness is determined by monitoring hydraulic heads and ground-water chemistry.

2.7 OPERATIONAL EFFICIENCY

Operational efficiency refers to the cost-effectiveness of actions taken to attain remedial objectives. These actions include P&T system design, operation, monitoring, and modification. Efficient P&T performance requires that there be a clear statement of remedial objectives.

For perpetual hydraulic containment, an appropriate objective might be to minimize the total cost required to maintain hydraulic containment and satisfy associated regulatory requirements. Given this objective, installing low permeability barriers to reduce pumping rates might be cost-effective. At sites with an economic incentive to remove contaminant mass (i.e., where the containment area size may be diminished or P&T discontinued if clean-up goals are met), a more complex cost-effectiveness trade-off exists between minimizing hydraulic containment costs and maximizing contaminant mass removal rates.

Comparative cost-benefit analysis requires evaluation of the benefits, costs, and risks of each design alternative based on P&T component and site specific factors. A framework for risk-based decision analysis applicable to P&T system design (Figure 2-16) is provided by Massmann and Freeze (1987), Freeze et al. (1990), and Massmann et al. (1991). Using this method, an objective function , $_j$, is defined for each remedial alternative, j = 1...N, as the net present value of the anticipated stream of benefits, costs, and risks taken over a remedial time period and discounted at the market interest rate. The goal is to maximize the objective function (Freeze et al., 1990):

$$\Phi_j = \sum_{t=0}^{T} \frac{[B_j(t) - C_j(t) - R_j(t)]}{(1+i)^t} \qquad (2\text{-}1)$$

where Φ_j = the objective function for alternative j [$]; $B_j(t)$ = benefits of alternative j in year t [$]; $C_j(t)$ = costs of alternative j in year t [$]; $R_j(t)$ = risks of alternative j in year t [$]; T = time horizon [years]; and i = discount rate [decimal fraction]. The probabilistic risk cost, R(t), is defined as (Freeze et al., 1990):

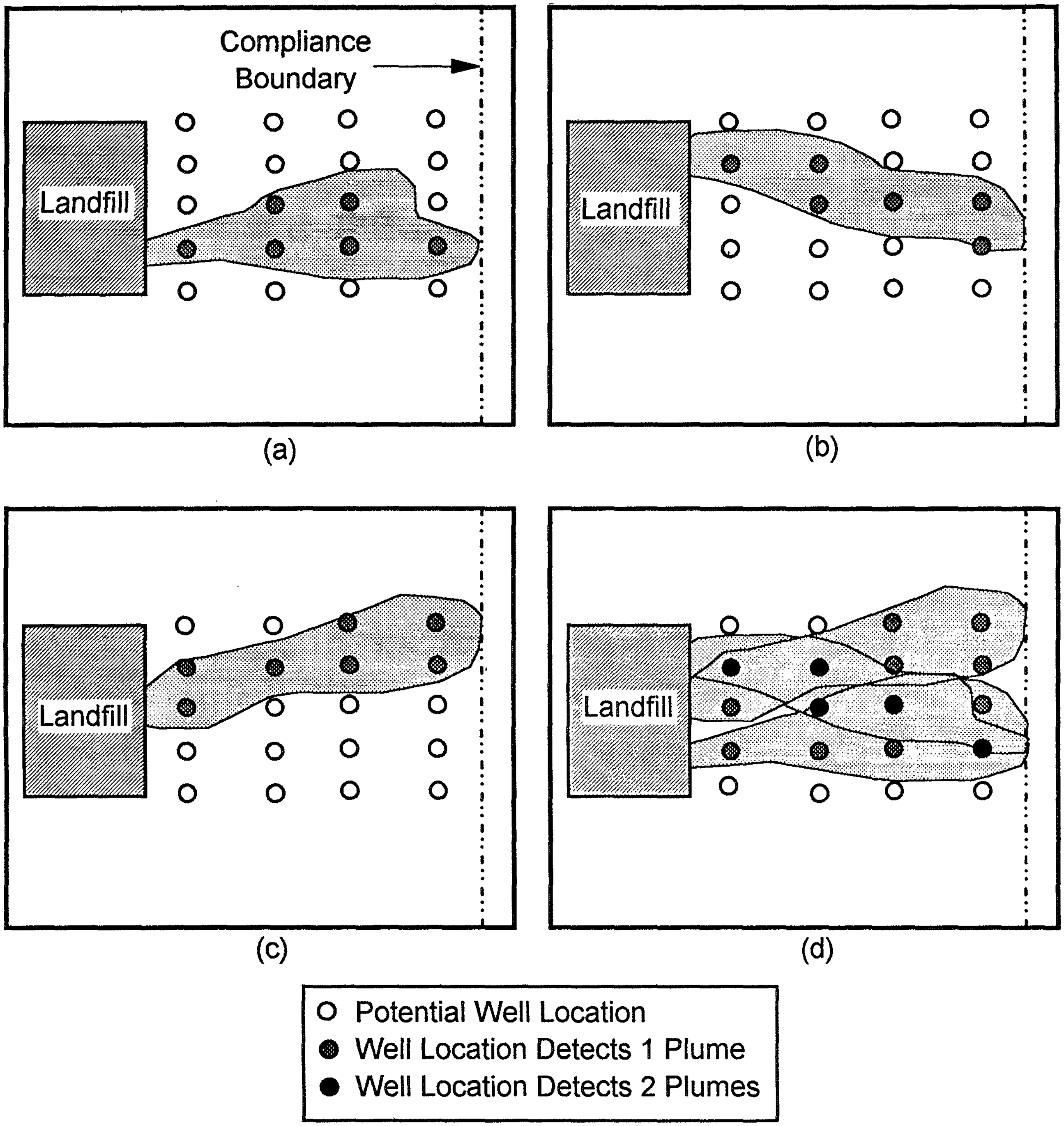


Figure 2-15. **An example of the Maximal Covering Location Problem applied to monitor well network design (from Meyer, 1992). The capability of different monitor well locations to detect random plumes generated using a Monte Carlo simulator in (a), (b), and (c) are combined to indicate optimum well locations in (d).**

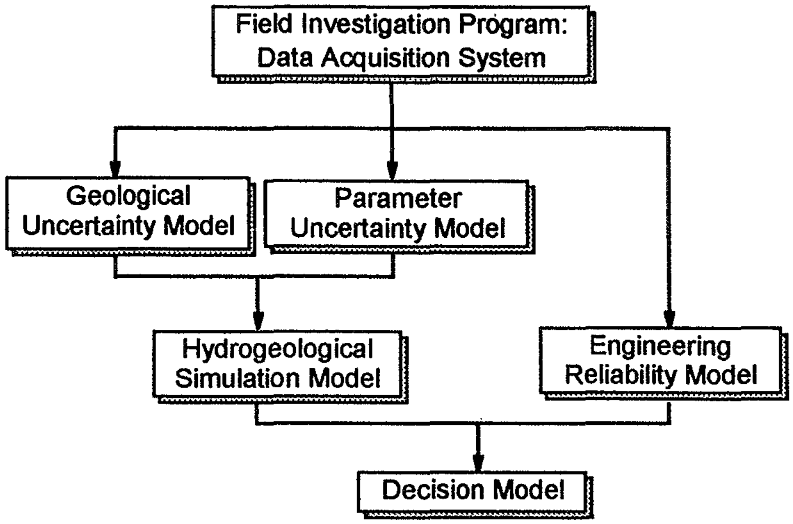


Figure 2-16. A framework for risk-based decision making regarding P&T system design and monitoring (modified from Freeze et al., 1990.)

$$R(t) = Pr(t)\ Cr(t)\ \gamma(Cr) \qquad (2\text{-}3)$$

where Pr(t) = the probability of failure in year t [decimal fraction] $C_f(t)$ = costs associated with failure in year t [$]; and γ(Cr) = the normalized utility function [decimal fraction, ? $ 1] which can be used to account for possible risk-averse tendencies of decision makers. The benefits of an alternative, B(t), can similarly be formulated as probabilistic benefits. Trade-offs between cost and risk and the concept of optimal risk are illustrated in Figure 2-17. Note that acceptable risk, from a societal or regulatory perspective, may be less than an owner-operator's optimal risk.

Example applications of this risk-based decision analysis approach to P&T system design are given by Massmann et al. (1991) and Evans et al. (1993). Variables pertaining to P&T monitoring design, such as well spacing and sampling frequency, can also be evaluated using this methodology, as can proposed modifications to system design that might be derived from monitoring data. Monitoring contributes to the objective function by reducing the probability of failure, or equivalently, increasing the probability of detection (Meyer and Brill, 1988).

Remedial efficiency can be also be enhanced by applying total quality management practices to P&T operation. Hoffman (1993) recommends nine steps to increase the efficiency of a P&T system designed for hydraulic containment and contaminant mass removal: (1) perform a thorough site characterization; (2) establish a decision support system that allows rapid interpretation and integration of new data; (3) locate and remove or contain shallow sources of ground-water contamination; (4) design the

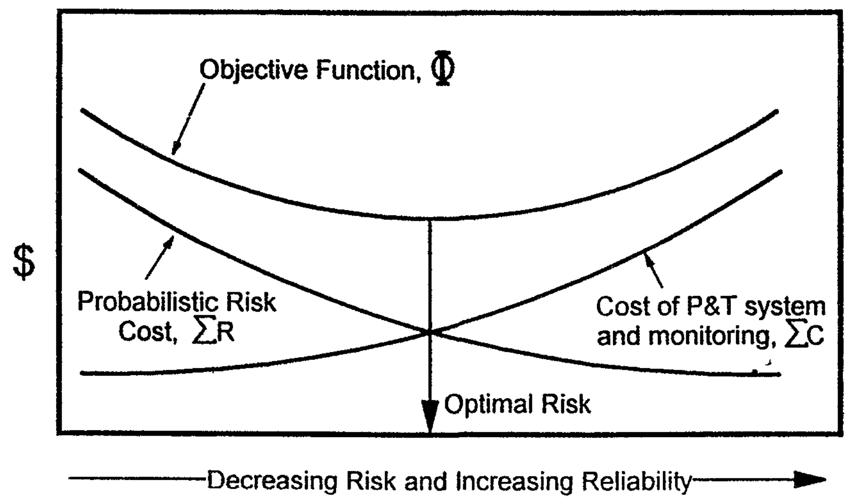


Figure 2-17. The concept of optimal risk (from Freeze et al., 1990).

P&T system to contain and remove contaminant mass; (5) phase in the remedial program to take advantage of ongoing conceptual model improvements; (6) maintain extensive monitoring of the P&T system; (7) design the well field such that extraction and injection rates and locations can be varied to minimize ground-water stagnation; (8) use reinjection of treated ground water and other techniques to enhance contaminant mass removal; and (9) set contaminant concentration goals (e.g., at the containment area perimeter) that will allow appropriate water standards to be met at the downgradient point of use. Although the applicability of various monitoring and remedial measures depends on site-specific conditions, active P&T system management will usually be cost-effective and lead to enhanced operational efficiency.