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EPA Ground Water Issue

Performance Evaluations of Pump-and-Treat Remediations

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One of the most commonly used ground-water remediation technologies is to pump contaminated waterto the surfacefor treatment, Evacuating the effectiveness of pump-and-treat remediations at Superfund sites is an issue identified by the Regional Superfund Ground Water Forum as a concern of Superfunddecision-makers. The Forum is a group of ground-water scientists, representing EPA's Regional Superfund Offices, organized to exchange up-to-date information related to ground-water remediation at Superfund sites.

Recent research has led to a better understanding of the complex chemical and physical processes controlling the movement of contaminants through the subsurface, and the abilitytopump such contaminantsto the surface. Understanding these processes permits the development and use of better site characterization technology and the design and implementation of more effective and efficient site remediation programs.

This document is an interim product of a research project that is developing a protocol for evacuating the effectiveness of ground-water remediations. It has been reviewed by members of EPA's Robert S. Kerr Environmental Research Laboratory.

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Summary

Pump-and-treat remediations are complicated by a variety of factors. Variations in ground-water flow velocities and directions are imposed on natural systems by remediation wellfields, and these variations complicate attempts to evaluate the progress of pump-and-treat remediations. This is in part because of the tortuosity of the flowlines that are generated and the concurrent re-distribution of contaminant pathways that occurs. An important consequence of altering contaminant pathways by remediation wellfields is that historical trends of contaminant concentrations at local monitoring wells may not be useful for future predictions about the contaminant plume.

An adequate understanding of the true extent of a contamination problem at a site may not be obtained unless the site's geologic, hydrologic, chemical, and biological complexities are appropriately defined. By extension, optimization of the effectiveness and efficiency of a pump-and-treat remediation may be enhanced by the utilization of sophisticated site characterization approaches to provide more complete, site-specific data for use in remediation design and management efforts.

Introduction

Pump-and-treat remediations of ground-water contamination are planned or have been initiated at many sites across the country. Regulatory responsibilities require that adequate oversight of these remediations be made possible by structuring appropriate monitoring criteria for monitoring and extraction wells. These efforts are nominally directed at answering the question: What can be done to show whether a remediation is generating thedesired control of the contamination? Recently, other questions have come to the forefront, brought on by the realization that many pump-and-treat remediations may not function as well as has been expected: What can be done to determine whether the remediation will meet its timelines? and What can be done to determine whether the remediation will stay within budget?

Superfund Technology Support Centers for Ground Water

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Conventional wisdom has it that these questions can be answered by the use of sophisticated data analysis tools, such as computerized mathematical models of ground-water flow and contaminant transport. Computer models can indeed be used to make predictions about future performance, but such predictions are highly dependent on the quality and completeness of the field and laboratory data utilized. This is also true of models used for performance evaluations of pump-and-treat remediations. In most instances an accurate performance evaluation can be made simply by comparing data obtained from monitoring wells during remediation to thedatagenerated priortothe onset of remediation. Historical trends of contaminant levels at local monitoring wells are often not useful for comparisons with data obtained during the operation of pump-and-treat remediations. This is a consequence of complex flow patterns produced locally by the extraction and injection wells, where previouslythere was a comparatively simple flow pattern.

Complex ground-waterflow patterns present great technical challenges in terms of characterization and manipulation (management) of the associated contaminant transport pathways. In Figure I, for example, waters moving along the flowline that proceeds directly into a pumping well from upgradient are moving the most rapidly, whereas those waters at the limits of the capture zone move much more slowly. One result is that certain parts of the aquifer are flushed quite well and other parts poorly. Another result of the pumpage is that previously uncontaminated portions of the aquifer at the outer boundary of the contaminant plume may become contaminated by the operation of an extraction well that is located too close to the plume boundary, because the flowline pattern extends downgradient of the well.

The latter is not a trivial situation that can be avoided without repercussions by simply locating the extraction well far enough inside the plume boundary so that its flowline pattern does not extend beyond the edge of the plume. Such actions would result In very poor cleansing of the aquifer between the extraction well and the plume boundary, because of the stagnation of flow that occurs downgradient of the well. Detailed field investigations are required during remediation to determine the locations of the various flowlines generated byapump-and-treat operation. Consequently, there maybe a need for more data to be generated during the site remediation (especially inside the contamination plume boundaries) than were generated during the site investigation, and for interpretations of those data to require highly sophisticated tools. For most settings, it is likelythat interpretations of the data that are collected during a pump-and-treat remediation will require the use of mathematical and statistical models to organize and analyze those data.

Contaminant Behavior and Plume Dynamics

Ground water flows from recharge zones to discharge zones in response to the hydraulic gradient (the drop in hydraulic pressure) along that path. The hydraulic gradient may be obtained from water-level elevation contours for ground water that has constant fluid density, but it must be obtained from water pressure contours when the fluid density varies. This is because hydraulic pressure is created by the combined effects of elevation, fluid density, and gravity. Additions to the dissolved solids content of a fluid increase its density. For example, synthetic seawater can be prepared by adding mineral salts to fresh water. Landfill leachate is often so laden with dissolved contaminants that its density approaches that of seawater.

As ground water flows through the subsurface It may dissolve some of the materials it contacts and may also transport viruses and small bacteria. This gives rise to natural water quality -- a combined chemical, biological, and physical state that may, or may not, be suitable for man's uses. Brines and brackish waters are examples of natural ground waters that are unsuitable for man's use. It is this same power of water to solubilize minerals and decayed plant and animal residues that causes contamination when ground water Is brought into contact with manmade solids and liquids (Figure 2). Once contaminated, ground water also provides a medium for

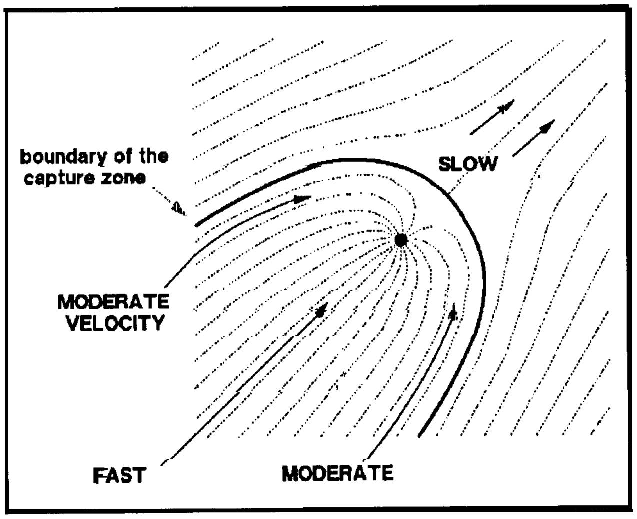

Figure 1. Flowline pattern generatad by an extraction well. Ground-water within the bold line will be captured by the well. Prior to pumping, the flowlines were straight diagonals.

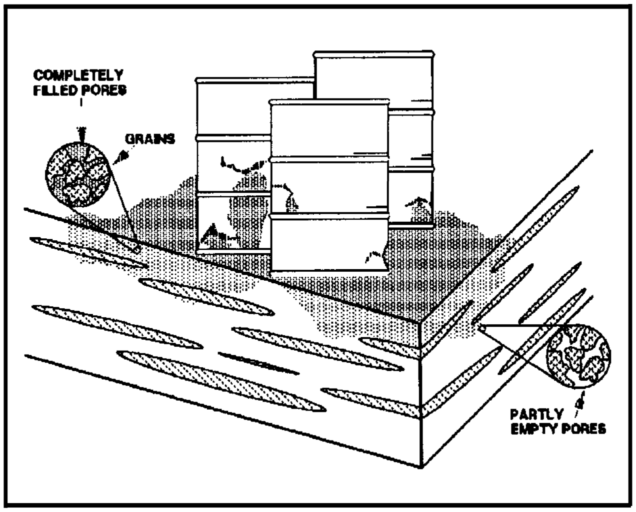

Figure 2. Above-ground spill of chemicals from storage drums. Spilled fluids initially fill the upper most soil pores. As much as half of the fluids remain in each pore after drainage.

potentially destructive interactions between contaminants and subsurface formations, such as the dissolution of limestone arid dolomite strata by acidic wastewaters. Contaminated ground water is a major focus of many hazardous waste site cleanups, At these sites, a large number of EPA's Records of Decision (ROD's) call for pump-and-treat remediations.

The mechanism by which a source introduces contaminants to ground water has a profound effect on the duration and areal extent of the resulting contamination. Above-ground spills (Figure 2) are commonly attenuated over short distances by the moisture retention capacity of surface soils. By contrast, there is much less opportunityfor attenuation when the contaminant is introduced below the surface, such as occurs through leaking underground storage tanks, injection wells, and septic tanks.

The hydraulic impacts of some sources of ground-water contamination, especially injection wells and surface impoundments, may impart a strongly three-dimensional character to local flow directions. The water-table mounding that takes place beneath surface impoundments (Figure 3), for instance, is often sufficient to reverse ground-water flow directions locally and commonly results in much deeper penetration of contaminants into the aquifer than would otherwise occur. Interactions with streams and other surface water bodies may also impart three-dimensional flow characteristics to contaminated ground water (e.g., a losing stream creates local mounding that forces ground-waterflow downward). In addition, contaminated ground water may move from one aquifer to another through a leaky aquitard, such as a tight silt layer that is sandwiched between two sand or gravel aquifers.

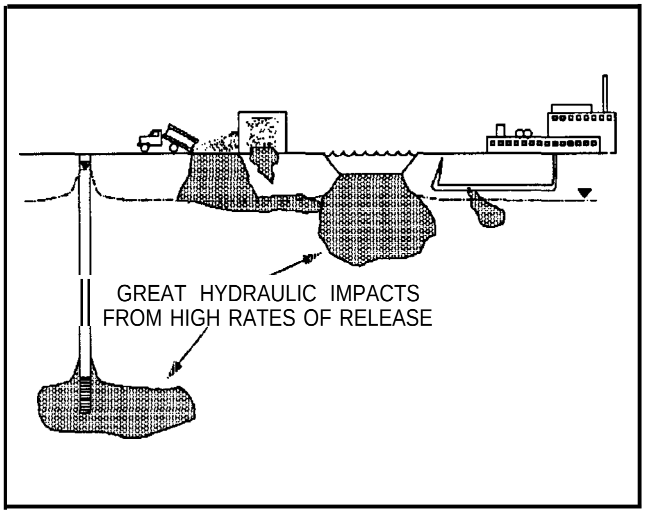

Figure 3. Hydraulic impacts of contarninant sources. Injection wells and surface impoundments may release fluids at a high rate, resulting in local mounding of the water table.

As ground water moves, contaminants are transported by advection and dispersion (Figure 4). Advection, or velocity, estimates can be obtained from Darcy's Law, which states that the amount of water flowing through porous sediments in a given period of time is found by multiplying together values of the hydraulic conductivity of the sediments, the cross-sectional area through which flow occurs, and the hydraulic gradient along the flowpath through the sediments. The hydraulic conductivities of subsurface sediments vary considerably over small distances. It is primarily this spatial variability in hydraulic conductivity that results in a corresponding distribution of flow velocities and contaminant transport rates.

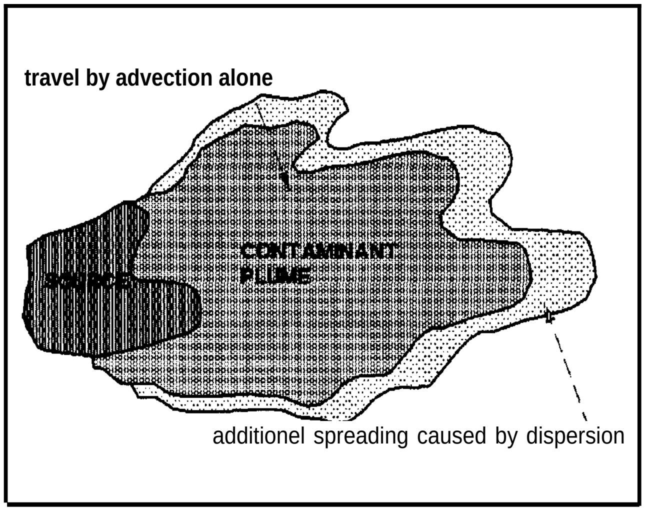

Figure 4. Bird's-eye view of contarninant plume spreading. Advection causes the majority of plume spreading in most cases Dispersion adds only marginally to the spreading.

The plume spreading effects of spatially variable velocities can be confused with hydrodynamic dispersion (Figure 5), If the details of the velocity distribution are not adequately known. Hydrodynamic dispersion results from the combination of mechanical and chemical phenomena at the microscopic level.

The mechanical component of dispersion derives from velocity

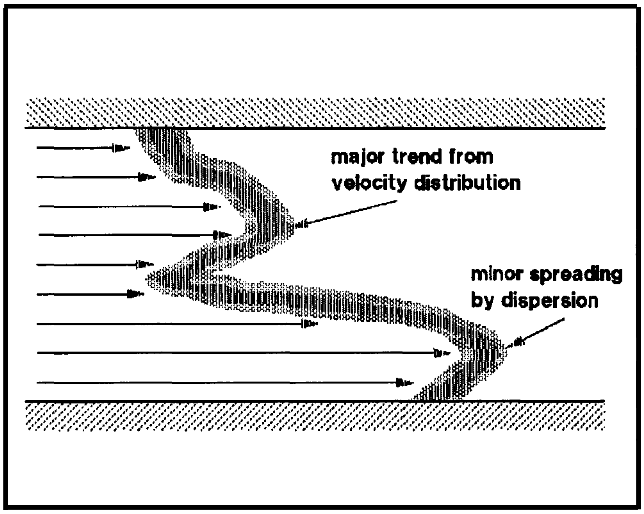

Figure 5. Cross-sectional view of contaminant spreading. Permeability differences between strata cause comparable differences in advection and, hence, plume spreading.

variations among water molecules traveling through the pores of subsurface sediments (e.g., the water molecules that wet the surfaces of the grains that bound each pore move little or not at all, whereas water molecules passing through the center of each pore move most rapidly) and from the branching of flow into the accessible pores around each grain. By contrast, the chemical component of dispersion is the result of molecular diffusion. At modest ground-water flow velocities, the chemical (or diffusive) component of dispersion is negligible and the mechanical component creates a small amount of spreading about the velocity distribution. At very slow ground-waterflow velocities, such as occur in clays and silts, the mechanical component of dispersion is negligible and contaminant spreading occurs primarily by molecular diffusion.

In some geologic settings, most of the ground-water flow occurs through fractures in low permeability rock formations. The flow in the fractures often responds quickly to rainfall events and other fluid inputs, whereas the flow through the bulk matrix of the rock is extremely slow -- so slow that contaminant movement by molecular diffusion may be much quicker by comparison. On the other end of the ground-water flow velocity spectrum is the flow in karst aquifers, since it may occur mostly through large channels and caverns. In these situations, ground-water flow is often turbulent, and the advection and dispersion of dissolved contaminants are not adequately describable by Darcy’s Law and other porous media concepts. Dye tracers have been used to study contaminant transport in fractured rock and karst aquifers, but such studies have yet to yield relationships that can be transferred from the study site to other sites.

Regardless of the character of ground-water flow, contaminants may not be transported at the same rate as the water itself. Variations in the rate of contaminant movement occur as a result of sorption, ion-exchange, chemical precipitation, and biotransformation. The movement of a specific contaminant may be halted completely by precipitation or biotransformation, because these processes alter the chemical structure of the contaminant. Unfortunately, the resulting chemical structure may be more toxic and more mobile than the parent compound, such as in the anaerobic degradation of tetrachloroethene (PCE), which yields, successively, trichloroethene (TCE), dichloroethene (DCE), and monochloromethene (vinyl chloride).

Sorption and ion-exchange (Figure 6), conversely, are completelyreversibie processes that release the contaminant unchanged after temporarily holding it on or in the aquifer solids. This effect is commonly termed retardation and is quantified by projecting or measuring the mobility of the contaminant relative to the average flow velocity of the ground water. Projections of retardation effects on the mobility of contaminants are baaed on equations that incorporate physical (e.g., bulk density) and chemical (e.g., partition coefficients) attributes of the real system. Direct measurement of the effective mobility of contaminants can be made by observations of plume composition and spreading overtime. Alternatively, samples of soils or sediments from the contamination site may be used in laboratory studies to determine the effective partitioning of contaminants between mobile (water) and immobile (solids) phases.

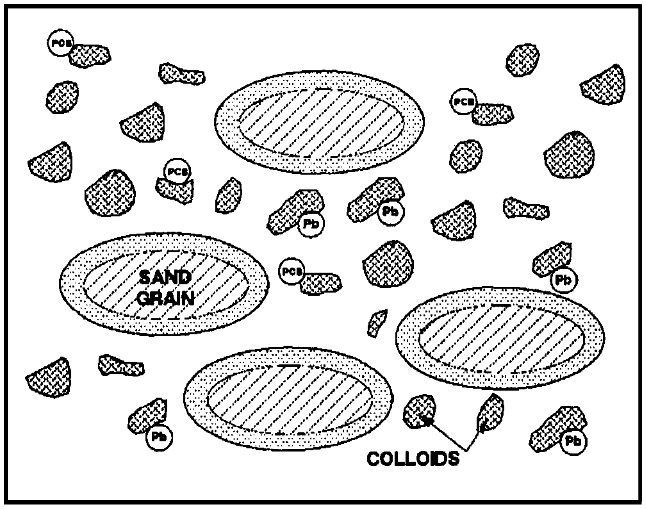

Figure 6. Contaminant transport facilitated by particles. Sorption of organics (e.g., PCB’S) or metals (e.g., Pb) onto particles may be effective in increasing their transport.

Retardation effects can be short-circuited by facilitated transport, a term that refers to the combined effects of two or more discrete physical, chemical, or biological phenomena that act in concert to materially increase the transport of contaminants, Examples of facilitated transport include particle transport, cosolvation, and phase shifting.

Particle transport (Figure 7) involves the movement of colloidal particles to which contaminants have adhered by sorption, ion-exchange, or other means. Contaminants that otherwise exhibit moderate to extreme retardation may travel far greater distances than projected from their nominal retardation values. Pumping often removes many colloidal particles from the subsurface. This fact can complicate remediations, and is also relevant to public water supply concerns.

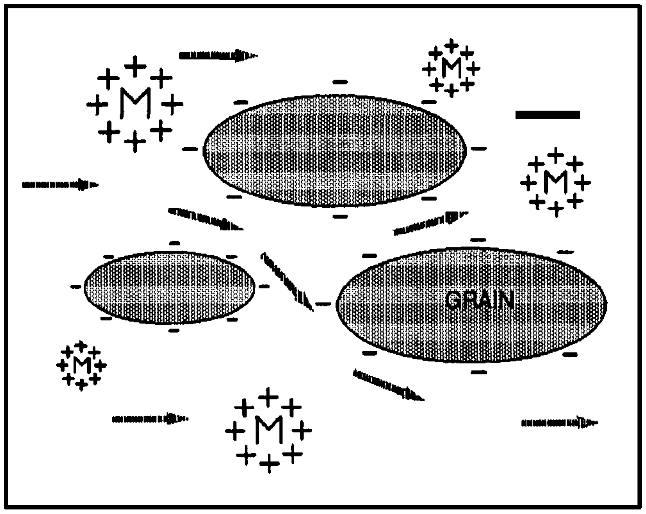

Figure 7. Retardation of metals by ion exchange. Metal ions carrying positive charges are attracted to negatively charged surfaces, where they may replace existing ions.

Cosolvation is the process by which the volubility and mobility of one contaminant are increased by the presence of another (Figure 8), usually a solvent present at levels of a few percent (note: 1 percent= 10,000 parts per million). Such phenomena are most likely to occur close to contamination sources, where pure solvents and high dissolved concentrations are often found.

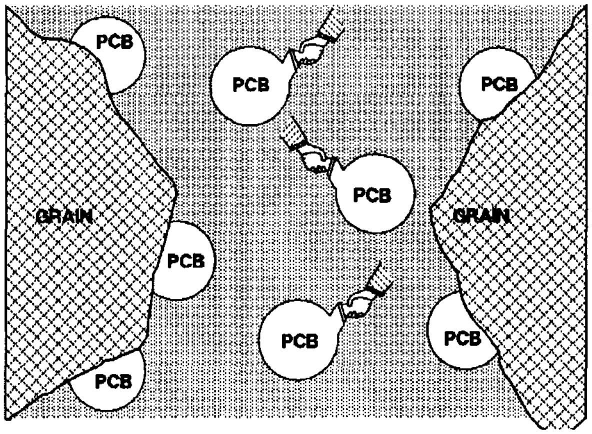

Figure 8. Conceptualization of transport by cosolvation. Insoluble contaminants may dissolve in ground water that contains solvents at high concentrations.

Those who design treatment strategies should anticipate the need to remove from ground water certain contaminants that are normally immobile, if the groundwater is to be extracted in areas that are close to a source of contamination. Those who make health risk estimates should attempt to factor in the increased mobility and exposure potential generated by cosolvation.

Shifts between chemical phases (Figure 9) involve a large change in the pH or redox (reaction) potential of water, and can increase contaminant solubilties and mobilities by ionizing neutral compounds, reversing precipitation reactions, forming complexes with other chemical species, and limiting bacterial activity. Phase shifts may occur as the result of biological depletion of the dissolved oxygen normally present in ground water, or as the result of biological mediation of oxidation-reduction reactions (e.g., oxidation of iron II to iron III). Phase shifts may also result from raw chemical releases to the subsurface.

Some ground-water contaminants are conponents of immiscible solvents, which may be either floaters or sinkers (Figure 10). The floaters generally move along the upper surface of the saturated zone, although they may depress this surface locally, and the sinkers tend to move downward under the influence of gravity. Both kinds of immiscible fluids leave residual portions trapped in pore spaces by capillary tension. This is particularly troublesome when an extraction well is utilized to control local gradients such that free product (drainable gasoline) flows into its cone of depression.

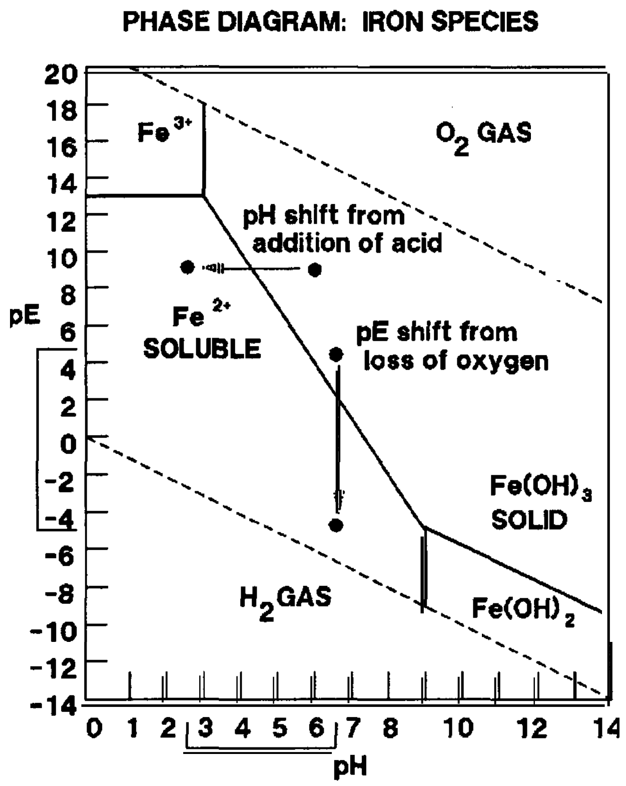

Figure 9. Facilitated transport by phase diagram shifts, Releases of acidic contaminants, or depletion of oxygen by biota, may solubilize precipitated metals or ionize organics.

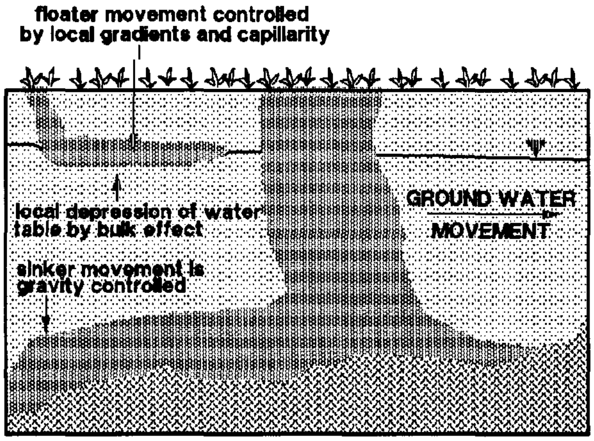

Figure 10. Dynamics of immiscible floater and sinker plumes. Buoyant plumes migrate laterally on top of the water saturated zone. Dense plumes sink and follow bedrock slopes.

The point of concern is that the cone of depression will contain trapped residual gasoline below the water-table (Figure 11). That residual will become a continuous some of contamination, which will persist even when the extraction well is turned off. The extent of the contamination that is generated by the residual gasoline in the cone of depression may exceed that generated by the gasoline resting in place above the saturated zone prior to the onset of pumping.

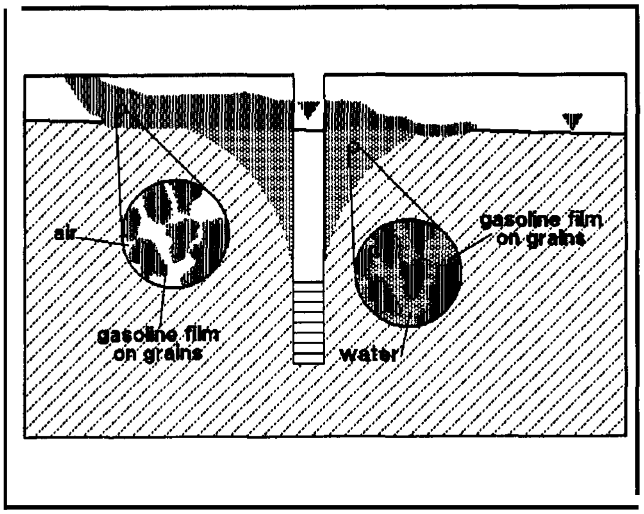

Figure 11. Zone of contaminant residuals caused by pumping. Pumping creates a cone of depression to trap gasoline for removal but also leaves residues below the water table.

Reliable prediction of the future movement of contaminant plumes under natural flow conditions is difficult because of the need to evaluate property the many processes that affect contaminant transport in a particular situation. Remediation evacuations are even more difficult because of extensive redirection of pre-remediation transport pathways by pump-and-treat wellfields. Hence, to prepare for remediation, it is important to determine the potential transport pathways during the site investigation.

Monitoring for Remediation Performance Evaluations

Ground-water data are collected during remediations to evaluate progress towards goals specified in a ROD. The key controls on the quality of these data are the monitoring criteria that are selected and the locations at which those criteria are to be applied. Ideally, the criteria and the locations would be selected on the basis of a detailed site characterization, from which transport pathways prior to remediation could be identified, and from which the probable pathways during remediation could be predicted.

The monitoring criteria and locations should also be chosen in such a way as to provide information on what is happening both downgradient of the plume boundary and inside the plume. Monitoring within the plume makes it possible to determine which parts of the plume are being effectively remediated and how quickly. This facilitates management of the remediation wellfield for greatest efficiency; for example, by reducing the flowrates of extraction wells that pump from relatively clean zones and increasing the flowrates of extraction wells that pump from zones that are highly contaminated. By contrast, the exclusive use of monitoring points downgradient of the plume boundary does not allow one to gain any understanding about the behavior of the plume during remediation, except to indicate out-of-control conditions when contaminants are detected.

There are many kinds of monitoring criteria and locations in use today. The former are divided into three categories: chemical, hydrodynamic, and administrative control. Chemical criteria are based on standards reflecting the beneficial uses of ground water (e.g., MCL'S or other health-based standards for potential drinking water). Hydrodynamic monitoring criteria are such things as:

(1) prevention of infiltration through the unsaturated zone,
(2) maintenance of an inward hydraulic gradient at the boundary of a plume of ground-water contamination, and
(3) providing minimum flows in a stream.

Administrative controls maybe codified governmental rules and regulations, but also include:

(1) effective implementation of drilling bans and other access-limiting administrative orders,
(2) proof of maintenance of site security, and
(3) reporting requirements, such as frequency and character of operational and post-operational monitoring.

Combinations of chemical, hydrodynamic, and administrative control criteria are generally necessary for specific monitoring points, depending on location relative to the source of contamination.

Natural Water Quality Monitoring Points

Natural water quality (or "background") sampling locations are the most widely used monitoring points, and are usually positioned a short distance downgradient of the plume. The exact location is chosen so that:

(1) it is neither in the plume nor in adjacent areas that may be affected by the remediation,
(2) it is in an uncontaminated portion of the aquifer through which the plume would migrate if the remediation failed, and
(3) its location minimizes the possibility of detecting other potential sources of contamination (e.g., relevant to the target site only).

Data gathered at a natural water quality monitoring point indicate out-of-control conditions when a portion of the plume escapes the remedial action. The criteria typically specified for this kind of monitoring point are known natural water quality concentrations, usually established with water quality data from wells located upgradient of the source.

Public Supply Monitoring Points

Public water supply wells located downgradient of a plume are another kind of monitoring point. The locations of these points are not negotiable; they have been drilled in locations that are suitable for water supply purposes, and were never intended to serve as plume monitoring wells. The purpose of sampling these wells is to assure the quality of water delivered to consumers, as related to specific contaminants associated with the target site. The criteria typically specified for this kind of monitoring point are MCL'S or other health-based standards.

Gradient Control Monitoring Points

A third kind of off-plume monitoring point frequently established is one for determinations of hydraulic gradients. This kind may be comprised of a cluster of small diameter wells that have very short screened intevals, and is usually located just outside the perimeter of the plume. Water level measurements are obtained from wells that have comparable screened intervals and are then used to prepare detailed contour maps from which the directions and magnitudes of local horizontal hydraulic gradients can be determined. it is equally important to evaluate vertical gradients, by comparison of water level measurements from shallow and deeper screened intevals, because a remediation wellfield may control only the uppermost portions of a contaminant plume if remediation wells are too shallow or have insufficient flow rates.

[Internal] Plume Monitoring Points

Less often utilized is the kind of monitoring point represented by monitoring wells located within the perimeter of the plume. Most of these are installed during the site investigation phase, prior to the remediation, but others maybe added subsequent to implementation of the remediation; they are used to monitor the progress of the remediation within the plume. These can be subdivided into on-site plume monitoring points located within the property boundary of the facility that contains the source of the contaminant plume, and off-site plume monitoring points located beyond the facility boundary, but within the boundary of the contamination plume.

interdependencies of Monitoring Point Criteria

Each kind of monitoring point has a specific and distinct role to play in evaluating the progress of remediation. The information gathered is not limited to chemical identities and concentrations, but includes other observable or measurable items that relate to specific remedial activities and their attributes. in choosing specific locations of monitoring points, and criteria appropriate to those locations, it is essential to recognize the interdependency of the criteria for different locations.

In addition to the foregoing, one must decide the following: Should evacuations of monitoring data incorporate allowances for statistical variations in the repotted values? if so, then what cut-off (e.g., the average value plus two standard deviations) should be used? Should evaluations consider each monitoring point independently or use an average? Finally, what method should be used to indicate that the maximum clean-up has been achieved? The zero-slope method, for example, holds that one must demonstrate that contaminant levels have stabilized at their lowest values prior to cessation of remediation and that they will remain at that level subsequently, as shown by a flat (zero-slope) plot of contaminant concentrations versus time,

Limitations of Pump-and-Treat Remediations

Conventional remediations of ground-water contamination often involve continuous operation of an extraction-injection wellfield. In these remedial actions, the level of contamination measured at monitoring wells maybe dramatically reduced in a moderate period of time, but low levels of contamination usually persist. In parallel, the contaminant load discharged by the extraction wellfield declines over time and gradually approaches a residual level in the latterstages (Figure 12). At that point, large volumes of water are treated to remove small amounts of contaminants.

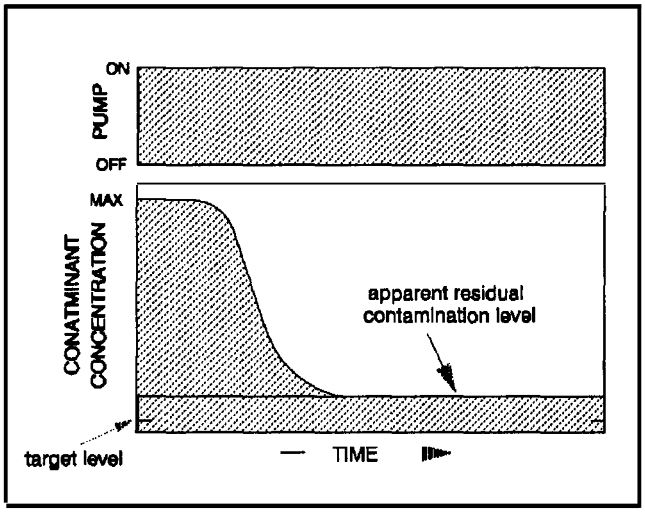

Figure 12. Apparent clean-up by pump-and-treat remediation. Contamination concentrations in pumped water decline overtime, to an apparently irreducible level.

Depending on the reserve of contaminants within the aquifer, this may cause a remediation to be continued indefinitely, or it may lead to premature cessation of the remediation and closure of the site. The latter is particularly troublesome because an increase in the level of ground-water contamination may follow (Figure 13) if the remediation is discontinued prior to removal of all residual contaminants,

There are several contaminant transport processes that are potentially responsible for the persistence of residual contamination and the kind of post-operational effect depicted in Figure 13. To cause such effects, releases of contaminant residuals must be slow relative to pumpage-induced water movement through the subsurface.

Transport processes that generate this kind of behavior during continuous operation of remediation wellfield include:

(1) diffusion of contaminants in low permeability sediments,

(2) hydrodynamic isolation ('dead spots') within wellfields,

(3) resorption of contaminants from sediment surfaces, and
(4) liquid-liquid partitioning of immiscible contaminants.

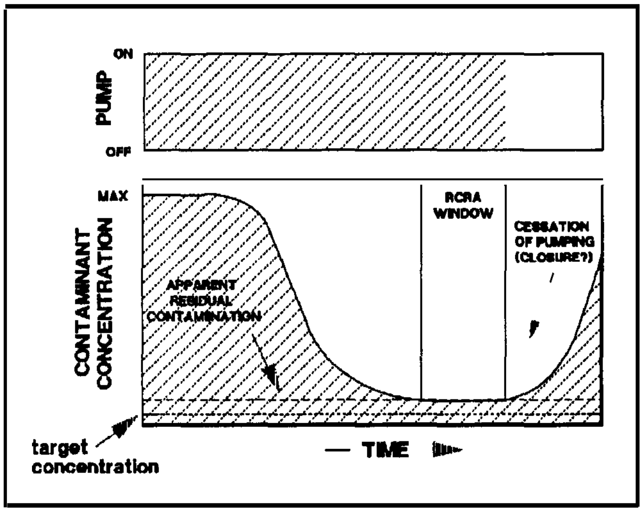

Figure 13. Contaminant increases after remediation stops. Contaminant levels may rebound when pump-and-treat operations cease, because of contaminant residuals.

Advection vs. Diffusion

Localized variations in the rate of ground-waterflow (advection) arise in heterogeneous settings because of interlayering of high-and low-permeability sediments. When operating a remediation wellfield, these advection variations result in rapid cleansing of the higher permeability sediments, which conduct virtually all of the flow (Figure 14). By contrast, contaminants are removed from the lower permeability sediments very slowly, by diffusion. The specific rate at which this diffusive release occurs is dependent on the difference in contaminant concentrations within and external to the low permeability sediments.

When the higher permeability sediments are cleaned up, the chemical force drawing contaminants from the lower permeability sediments is at its greatest. This force is exhausted only when the chemical concentrations are nearly equal everywhere.

Low permeability sediments have orders-of-magnitude greater surface area per volume of material than high permeability sediments. Much greater amounts of contaminants may thus accumulate in a given volume of low permeability sediments, as compared with contaminant accumulations in a like volume of high permeability sediments. The thicker the low permeability stratum, the more contaminant reserves it can hold, and the more diffusion controls contaminant movement overall. Thus the majority of contaminant reserves in heterogeneous settings may be available only under just such diffusion-controlled conditions.

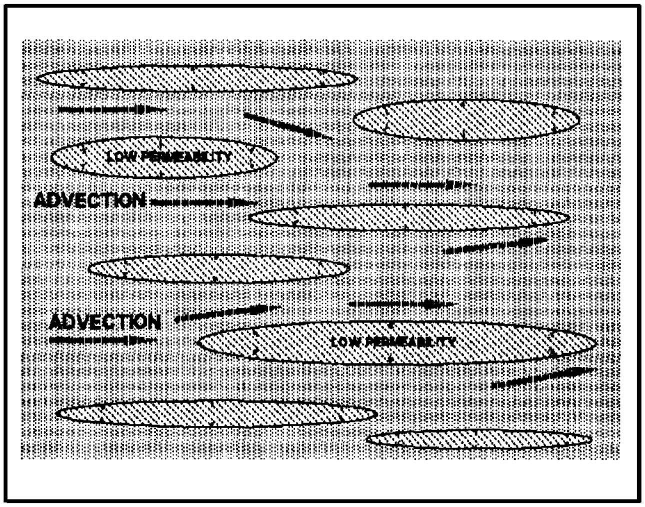

Figure 14. Permeability variations limit remediations. High permeability sediments conduct most of the flow; low permeability sediments act as leaky contaminant reservoirs.

The situation is similar, though reversed, for in-situ remediations that require the injection and delivery of nutrients or reactants to the zone of intended action: access to contaminants in low permeability sediments is restricted to that provided by diffusion.

Hydrodynamic Isolation

The operation of any wellfield in an aquifer containing moving fluid results in the formation of stagnation zones downgradient of extraction wells and upgradient of injection wells. The stagnation zones are hydrodynamically isolated from the remainder of the aquifer, so mass transport into or out of the isolated water may occur only by diffusion. If remedial action wells are located within the bounds of a contaminant plume, such as for the removal of contaminant hot-spots, the portion of the plume lying within their associated stagnation zone(s) will not be effectively remediated. The flowline pattern must be altered radically, by major changes in the locations of pumping wells, or by altering the balance of flowrates among the existing wells, or both, if the original stagnation zone(s) are to be remediated.

Another form of hydrodynamic isolation is the physical creation of enlarged zones of residual hydrocarbon (Figure 11). This occurs when deep wells are used to create cones of drawdown into which underground storage tank and pipeline leaks of gasoline can flow, so that skimmer pumps can remove the accumulated product. When the deep water pump is turned off, the watertable will rise to its pre-pumping position. This will allow the aquifer waters that then fill the cone of depression, and any subsequent ground-waterflow through the former cone of depression, to become highly contaminated with BTEX compounds (benzene, toluene, the ethyl benzenes, and the xylenes) as a result of contact with the gasoline remaining there on the aquifer solids. Gasoline in residual saturation may occupy as much as 40 percent of the pore space of the sediments.

Sorption Influences

The number of pore volumes of contaminated water to be removed during a remediation depends on the sorptive tendencies of the contaminant. The number of pore volumes to be removed also depends on whether ground-waterflow velocities during remediation are too rapid to allow contaminant levels to build up to equilibrium concentrations locally (Figure 15). If insufficient contact time is allowed, the affected water is advected away from sorbed contaminant residuals prior to achieving a state of chemical equilibrium and is replaced by fresh water from upgradient.

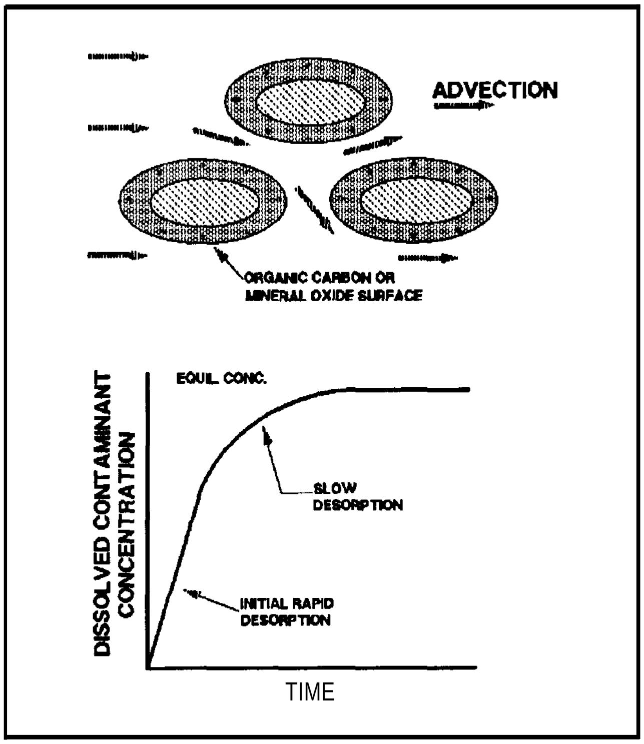

Figure 15. Sorption limitation of pump-and-treat remediations. Increased flow velocities caused by pumpage may not allow for sufficient time to reach chemical equilibrium locally.

Hence, continuous operation of pump-and-treat remediations may result in steady releases of contaminants at substantially less than their chemical equilibrium levels. With less contamination being removed per volume of water brought into contact with the affected sediments, it is clear that large volumes of mildly contaminated water are recovered, where small volumes of highly contaminated water would otherwise be recovered.

Unfortunately, this is all too likely to occur with conventional pump-and-treat remediations and with those in-situ remediations that depend upon injection wells for delivery of nutrients and reactants. This is because ground-waterflow velocities within wellfields may be many times greater than natural (non-pumping) flow velocities. Depending on the sorptive tendencies of the contaminant, the time to reach maximum equilibrium concentrations in the ground water may simply be too great compared with the average residence time in transit through the contaminated sediments.

Liquid-Liquid Partitioning

Subsequent to gravity drainage of free product that has been discharged to the subsurface, immiscible or non-aqueous phase liquids (NAPL’s) remain trapped in the pores of subsurface sediments by surface tension to the grains that bound the pores. Liquid-liquid partitioning controls the dissolution of NAPL residuals into ground water.

As with sorbing compounds, flow rates during remediation may be too rapid to allow aqueous saturation level of partitioned NAPL residuals to be reached locally (Figure 16). If insufficient contact time is allowed, the affected water is advected away from the NAPL residuals prior to reaching chemical equilibrium and is replaced by fresh water from upgradient. “

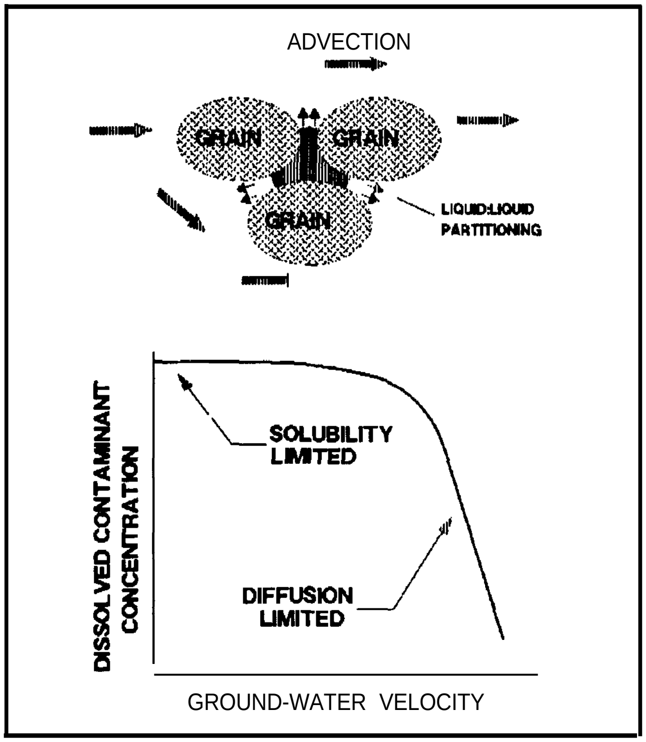

Figure 16. Partitioning limits pump-and-treat effectiveness. Less than solubility levels of contaminants maybe released from trapped solvents if pumpage increases flow velocities.

Again, this process generates large volumes of mildly contaminated water where small volumes of highly contaminated water would other wise result, and this means that it will be necessary to pump and treat far more water than would otherwise be the case. The efficiency loss is generally two-fold, because much of the pumped water will contain contaminant concentrations that are below the level at which optimal treatment is obtained.

Design and Analysis Complications

Contaminant concentrations and ground-waterflow velocities can be highly variable throughout the zone of action, which is that portion of an aquifer actively affected by the remediation wellfield. Consequently, monitoring strategies should be focussed on detection of rapid, sporadic changes in contaminant concentrations and flow velocities at any specific point in the zone of action. In practice, this means that tracking the effectiveness of pump-and-treat remediations by chemical samplings is quite complicated.

Decisions regarding the frequency and density of chemical samplings should take into account the detailed flowpaths generated by the remediation wellfield, including changes in contaminant concentrations that result from variations In the influences of transport processes along those flowpaths. The need to reposition extraction wells occasionally, to remediate portions of the contaminated zone that were previously subject to slow flowlines, means that the chemical samplings may generate results that are not easily understood. It also means that it may be necessary to move the chemical monitoring points during the course of a remediation.

Evaluations of the hydrodynamic performance of remediation wellfields are also data intensive. For example, It is usually required that an inward hydraulic gradient be maintained at the periphery of a contaminant plume undergoing pump-and-treat remediation. This requirement Is imposed to ensure that no portion of the plume is free to migrate away from the zone of action. To assess this performance adequately, the hydraulic gradient should be measured accurately in three dimensions between each pair of adjacent pumping or injection wells. The design of an array of piezometers (small diameter wells with very short screened Intervals, that are used to measure the hydraulic head of selected positions in an aquifer) for this purpose is not as simple as one might first imagine. Many points are needed to define the convoluted water-table surface that develops between adjacent pumping or Injection wells. Not only are there velocity divides in the horizontal dimension near active wells, but in the vertical dimension, too, because the hydraulic Influence of each well extends to only a limited depth in practical terms.

Innovations in Pump-and-Treat Remediations

One of the promising innovations in pump-and-treat remediations is pulsed pumping. Pulsed operation of hydraulic systems is the cycling of extraction or injection wells on and off in active and resting phases (Figure 17). The resting phase of a pulsed-pumping operation can allow sufficient time for contaminants to diffuse out of low permeability zones and into adjacent high permeability zones, until maximum concentrations are achieved In the higher permeability zones. For sorbed contaminants and NAPL residuals, sufficient time can be allowed for equilibrium concentrations to be reached In local ground water. Subsequent to each resting phase, the active phase of the cycle removes the minimum volume of contaminated ground water, at the maximum possible concentrations, for the most efficient treatment. By occasionally cycling only select wells, stagnation zones may be brought into active flowpaths and remediated.

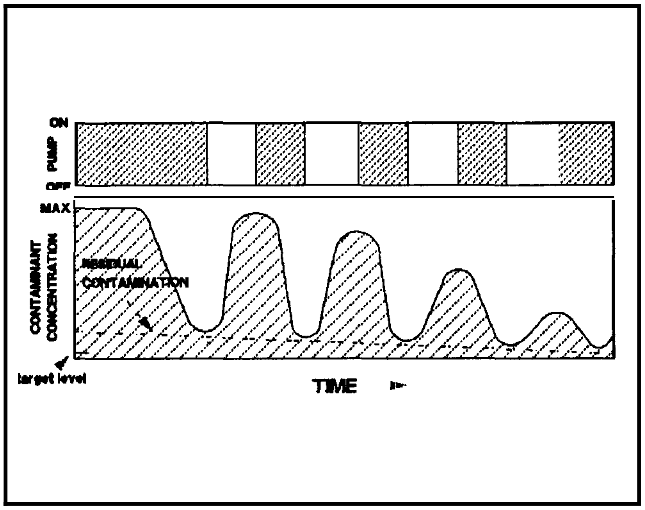

Figure 17. Pulsed pumping removal of residual contaminants. Repetitive removal of pulses of highly contaminated water ensures effective depletion of contaminant residuals.

Pulsed operation of remediation wellfields incurs certain additonal costs and concerns that must be compared with its advantages forsite-specific applications. During the resting phase of pulsed-pumping cycles, peripheral gradient control may be needed to ensure adequate hydrodynamic control of the plume. In an ideal situation, peripheral gradient control would be unnecessary. Such might be the case where there are no active wells, major streams, or other significant hydraulic stresses nearby to influence the contaminant plume while the remedial action wellfield is In the resting phase. The plume would migrate only a few feet during the tens to hundreds of hours that the system was at rest, and that movement would be rapidly recovered by the much higher flow velocities back toward the extraction wells during the active phase.

When significant hydraulic stresses are nearby, however, plume movement during the resting phase may be unacceptable. Irrigation or water-supply pumpage, for example, might cause plume movement on the order of several tens of feet per day. it might then be impossible to recover the lost portion of the plume when the active phase of the pulsed-pumping cycle commences. In such cases, peripheral gradient control during the resting phase would be essential. If adequate storage capacity is available, it may be possible to provide gradient control in the resting phase by injection of treated waters downgradient of the remediation wellfield. Regardless of the mechanics of the compensating actions, their capital and operating expenses must be added to those of the primary remediation wellfield to determine the complete cost.

Pump-and-treat remediations are underway today that Incorporate some of the principles of pulsed pumping. For instance, pumpage from contaminated bedrock aquifers and other low permeability formations results in Intermittent wellfield operations by default; the wells are pumped dry even at low flow rates. In such cases, the wells are operated on demand with the help of fluid-level sensors that trigger the onset and cessation of pumpage. This simultaneously accomplishes the goal of pumping ground water only after it has reached chemical equilibrium, since equilibrium occurs on the same time frame as the fluid recharge event in low permeability settings. in settings of moderate to high permeability, the onset and cessation of pumpage could be keyed to contaminant concentration levels in the pumped water, independent of flow changes required to maintain proper hydrodynamic control. Peripheral hydrodynamic controls mayor may not be necessary during the resting phase of the cycle.

Other strategies to improve the performance of pump-and-treat remediations include:

(1) scheduling of wellfield operations to satisfy simultaneously hydrodynamic control and contaminant concentration trends or other performance criteria,
(2) repositioning of extraction wells to change major transport pathways, and
(3) integration of wellfield operations with other subsurface technologies, such as barrier walls that limit plume transport and minimize pumping of fresh water, or infiltration ponds that maintain saturated flow conditions for flushing contaminants from previously unsaturated soils and sediments.

Flexible operation of a mediation wellfield, such as occasionally turning off individual pumps, allows for some flushing of stagnant zones. That approach may not baas hydrodynamically efficient as one that involves permanently repositioning or adding pumping wells to new locations at various times during remediation. Repositioned and new wells require access for drilling, however, and that necessarily precludes capping of the site until after completion of the pump-and-treat operations. The third approach cited above, combining pump-and-treat with subsurface barrier walls, trenching, or in-situ techniques, ail of which may occur at any time during remediation, may also require postponement of capping until completion of the remediation.

The foregoing discussion may raise latent fears of lack of control of the contaminant source, something almost always mitigated by isolation of the contaminated soils and subsoils that remain long after manmade containers have been removed from the typical site. Fortunately, vacuum extraction of contaminated air/vapor from soils and subsoils has recently emerged as a potentially effective means of removing volatile organic compounds (VOC'S). Steam flooding has shown promise for removal of the more retarded organics, and in-situ chemical fixation techniques are being tested for the isolation of metals wastes.

Vacuum extraction techniques are capable of removing several pounds of VOC'S per day, whereas air stripping of VOC'S from comparable volumes of contaminated ground water typically results in the removal of only a few grams of VOC'S per day because VOC'S are so poor insoluble in water. Similarly, steam flooding is an economically attractive means of concentrating contaminant residuals, as a front leading the injected body of steam. Steam flooding or chemical fixation have potential for control of fluid and contaminant movement in the unsaturated zone and should thus be considered a potentially significant addition to the list of source control options. in addition, soils engineering and landscape maintenance techniques can minimize infiltration of rainwater in the absence of a multilayer RCRA-style cap.

In terms of evacuation of the performance of a remediation, the presence of a multliayer RCRA-styled cap could pose major limitations. The periodic removal of core samples of subsurface solids from the body of the plume and the source zone, with subsequent extraction of the chemical residues on the solids, is the only direct means of evacuating the true magnitude of the residuals and their depletion rate. Since this must be done periodically, capping would conflict unless Postponed until closure of the site. Ifcappingcan be postponed or foregone, great flexibility for management of pump-and-treat remediations (e.g., concurrent operation of a soil vapor extraction wellfield, and sampling of subsoils) can be used to improve effectiveness.

Modeling as a Performance Evaluation Technique

Subsurface contaminant transport models incorporate a number of theoretical assumptions about the natural processes governing the transport and fate of contaminants, in order for solutions to be made tractable, simplifications are made in applications of theory to practical problems. A common simplification for wellfield simulations is to assume that air flow is horizontal, so that a two-dimensional model can be applied, rather than a three-dimensional model, which is much more difficult to create and more expensive to use. Two-dimensional model representations are obviously not faithful to the true complexities of real world pump-and-treat remediations since most of these are in settings where three-dimensional flow is the rule. Moreover, most pump-and-treat remediations use partially penetrating wells, which effect significant vertical flow components, whereas the two-dimensional models assume that the remediation wells are screened throughout the entire saturated thickness of the aquifer, and therefore do not cause upconing of deeper waters.

Besides the errors that stem from simplifying assumptions, applications of mathematical models to the evacuation of pump-and-treat remediations are also subject to considerable error where the study site has not been adequately characterized. It is essential to have appropriate field determinations of natural process parameters and variables (Figure 18), because these determine the validity and usefulness of each modeling attempt. Errors arising from inadequate data are not addressed properly by mathematical tests such as sensitivity analyses or by the application of stochastic techniques for estimating uncertainty, contrary to popular beliefs, because such tests and stochastic simulations assume that the underlying conceptual basis of the model is correct. One cannot properly change the conceptual basis (e.g., from an isolated aquifer to one that has strong interaction with a stream or another underlying aquifer) without data to justify the change. The high degree of hydrogeological, chemical, and microbiological complexity typically present in field situations requires site-specific characterization of various natural processes by detailed field and laboratory investigations.

Hence, both the mathematics that describe models and the parameter inputs to those models should be subjected to rigorous quality control procedures. Otherwise, results from field applications of models are likely to be quatitatively, as well as quantitatively, incorrect, if done properly, however,

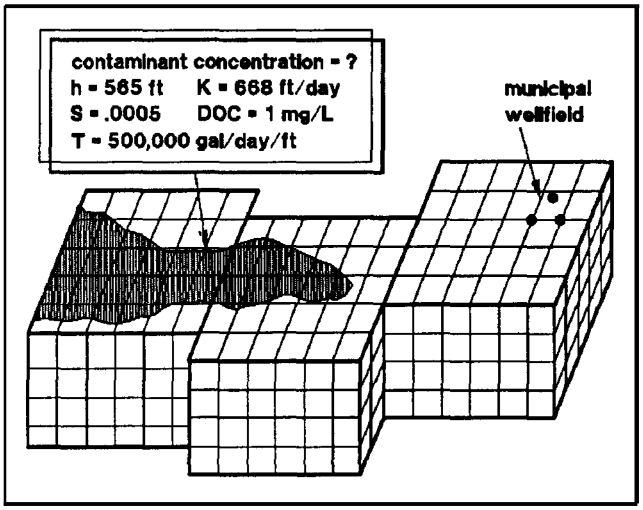

Figure 18. Grid of points for a contaminant transport modal. Known values of water level and other inputs are used to predict concentration changes at each grid intersection (node).

mathematical modeling may be used to organize vast amounts of disparate data into a sensible framework that will provide realistic appraisals of which parts of a contaminant plume are being effectively cleansed, when the remediation will meet target contaminant reductions, and what to expect in terms of irreducible contaminant residuals. Models may also be used to evaluate changes in design or operation, so that the most effective and efficient pump-and-treat remediation can be attained.

Other Data Analysis Methods for Performance Evacuations

Mathematical models are by no means the only methods available for use in evaluating the performance of pump-and-treat remediations. Two other major fields of analysis are statistical methods and graphical methods. The potential power of statistical methods has been tapped infrequently in ground-water contamination investigations, aside from their use in quality assurance protocols. The uses are many, however, as shown in Table 1. While data interpretation and presentation methods vary widely, many site documents lack statistical evaluations; some also present inappropriate simplifications of datasets, such as grouping or averaging broad categories of data, without regard to the statistical validities of those simplifications.

Graphical methods of data presentation and analysis have been used heavily in both ground-waterflow problems (e.g., flowline plots and flownets) and water chemistry problems (e.g., Stiff kite diagrams). Figure I, for example, is a flowline plot for a single well. From analysis of such plots, it is possible to estimate the number of pore volumes that will be removed over a set period of time of constant pumpage, at different locations in the contaminant plume. Figure 9 is a chemical phase diagram for iron, which may be used to relate pH and redox measurements to the most stable species of iron.

Analysis of Variance (ANOVA) Techniques

ANOVA techniques maybe used to segregate errors due to chemical analyses from those errors that are due to sampling procedures and from the intrinsic variability of the contaminant concentrations at each sampling point.

Correlation Coefficients

Correlation coefficients can be used to provide justification for lumping various chemicals together (e.g., total VOC'S), or for using a single chemical as a class representative, or to link sources by similar chemical behavior.

Regression Equations

Regression equations may be used to predict contaminant loads based on historical records and supplemental data, and may be used to test cause-and-effect hypotheses about sources and contaminant release rates.

Surface Trend Analysis Technique

Surface trend analysis techniques maybe used to identify recurring and intermittent (e.g., seasonal) trends in contour maps of ground-water levels and contaminant distributions, which may be extrapolated to source locations or future plume trajectories.

Table 1. Statistical methods useful in performance evaluations.

Figure 19 presents one means of producing readily recognizable patterns of the major ion composition of a water sample, so that it maybe differentiated from other water types. At sites of subsurface contamination, the major ion composition often differs greatly from the natural quality of water in adjacent areas. Water quality specialists have used such plots for decades to differentiate zones of brackish water from zones of potable water, in studies of saltwater intrusion into coastal aquifers, and in studies of the upconing of saline water from shales during pumping of overlying sandstone aquifers.

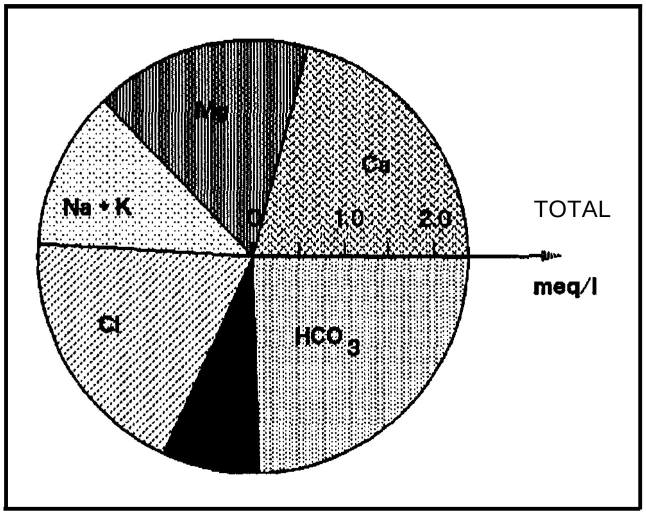

Figure 19. Pie chart of major ions in aground-water sample. The mini-equivalence values of the major ions are computed and plotted to generate patterns specific to the source.

Figure 20 illustrates another means of producing readily recognizable patterns of the milli-quivalence values of major cations and anions in aground-water sample. Geochemical prospectors have used this graphical technique as an aid in the identification of waters associated with mineral deposits. These graphical presentation techniques have been adapted recently to the display of organic chemical contaminants. For example, a compound of interest such as trichloroethene (TCE) maybe evaluated interms of its contribution to the total organic chemical contamination load, or against other specific contaminants, so that some differentiation of some contributions to the overlll plume can be obtained.

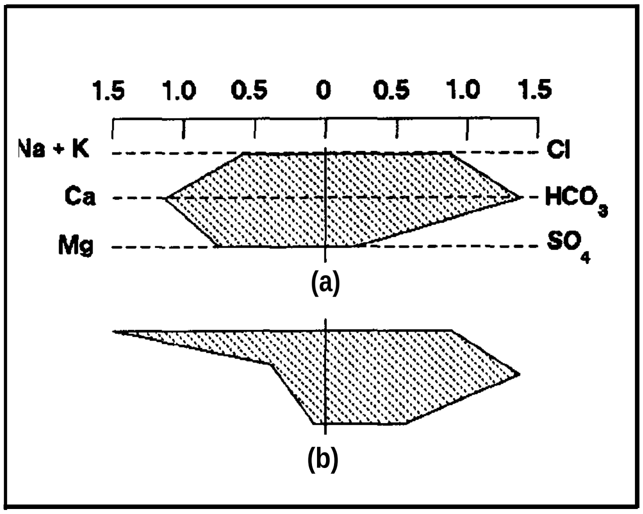

Figure 20. Stiff diagrams of major ions in two samples. The concentrations of the ions are plotted in the manner shown in (a); the uniqueness of another water type is shown by (b).

Perspectives for Site Characterizations

Concepts pertinent to investigating and predicting the transport and fate of contaminants in the subsurface are evolving. Additional effort devoted to site-specific characterizations of preferential pathways of contaminant transport and the natural processes that affect the transport behavior and ultimate fate of contaminants may significantly improve the timeliness and cost-effectiveness of remedial actions at hazardous waste sites.

Characterzation Approaches

To underscore the latter point, it is useful to examine the principal activities, benefits, and shortcomings of increasingly sophisticated levels of site characterization approaches: conventional (Table 2), state-of-the-art (Table 3), and state-of-the-science (Table 4). The conventional approach to site characterizations is typified by the description given in Table 2.

Each activity of the conventional approach can be accomplished with semi-skilled labor and off-the-shelf technology, with moderate to low costs. It may not be possible to characterize thoroughly the extent and probable behavior of a subsurface contaminant plume with the conventional approach.

Key management uncertainties regarding the degree of health threat posed by a site, the selection of appropriate remedial action technologies, and the duration and effectiveness of the remediations all should decrease significantly with the implementation of more sophisticated site characterization approaches.

Actions Typically Taken

- install a few dozen shallow monitoring wells
- Sample ground-water numerous times for 129+ priority pollutants
- Define geology primarily by driller's logs and drill cuttings
- Evaluate local hydrology with water level contour maps of shallow wells
- Possibly obtain soil and core samples for chemical analyses

Benefits

- Rapid screening of the site problems
- Costs of investigation are moderate to low
- field and laboratory techniques used are standard
- Data analysis/interpretation is straightforward
- Tentative identification of remedial alternatives is possible

Shortcomings

- True extent of site problems maybe misunderstood
- Selected remadial alternatives may not be appropriate
- Optimization of final remediation design may not be possible
- Clean-up costs remain unpredictable, tend to excessive levels
- Verification of compliance is uncertain and difficult

Table 2. Conventional approach to site characterization.

it will probably cost substantiality more to implement state-of-the-art and state-of-the-science approaches in site characterizations, but the increased value of the information obtained is likely to generate offsetting cost savings by way of improvements in the technical effectiveness and efficiency of the site clean-up.

Obviously, it is not possible to test these conceptual relationships directly, because one cannot carry site characterization and remediation efforts to fruition along each approach simultaneously. One can infer many of the foregoing discussion points, however, by observing the changes in perceptions, decisions, and work plans that occur when more advanced techniques are brought to bear on a site that has already undergone a conventional level of characterization. The latter situation is a fairly common occurrence, because many first attempts at site characterization turn up additional sources of contamination or hydrogeologic complexities that were not suspected when the initial efforts were budgeted.

Hypothetical Example

It is helpful to examine possible scenarios that might result from the different site investigation approaches just outlined.

Recommended Actions

- Install depth-specific clusters of monitoring wells
- Initially sample for 129+ priority pollutants, be selective subsequently
- Define geology by extensive coring/sediment samplings
- Evaluate local hydrology with well clusters and geohydraulic teats
- Perform limited tests on sediment samples (grain size, day content, etc.)
- Conduct surface geophysical surveys (resistivity, EM, ground-penetrating radar)

Benefits

- Conceptual understandings of the site problems are more complete
- Prospect are improved for optimization of remedial actions
- Predictability of remediation effectiveness is increased
- Clean-up costs maybe lowered, estimates are more reliable
- Verification of compliance is more soundly based

shortcomings

- Characterization costs are higher
- Detailed understandings of site problems are still difficult
- Full optimization of remediation is still not likely
- Field tests may create secondary problems (disposal of pumped waters)
- Demand for specialists is increased, shortage is a key limiting factor

Table 3. State-of-the-art approach to site characaterization.

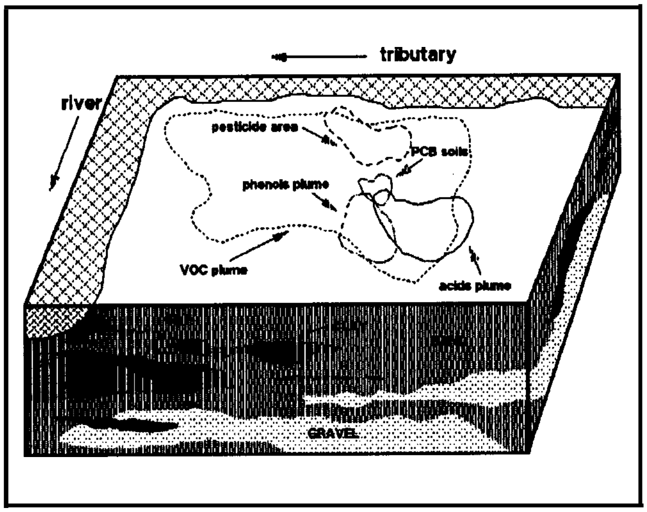

Figure 21. Hyothetical contamination site in an alluvial setting. Ground-water contamination at the site includes a variety of plumes; the setting is complex geologically and hydrologically.

Idealized Approach

- Assume state-of-the-art as starting point
- Conduct soil vapor surveys for volatile% fuels
- Conduct tracer teak and borehole geophysical surveys (neutron and gamma)
- Conduct karat stream tracing and recharge studies, if appropriate to the setting
- Conduct bedrock fracture orientation and interconnectivity studies, if appropriate
- Determine the percent organic carbon and cation exchange capacity of solids
- Measure redox potential, pH, and dissolved oxygen level of subsurface
- Evaluate sorption-desorption behavior by laboratory column and batch studies
- Assess the potential for biotransformation of specific compounds

Benefits

- Thorough conceptual understandings of site problems are obtained
- Full optimization of the remediation is possible
- Predictability of the effectiveness of remediation is maximized
- Clean-up cost maybe lowered significantly, estimates are reliable
- Verification of compliance is assured

Shortcoming

- Characterization costs may be much higher
- Few previous applications of advanced theories and methods have been completed
- field and laboratory techniques are specialized and are not easily mastered
- Availability of specialized equipment is low
- Need for specialism is greatly increased (it may be the key limitation overall)

Table 4. state-of-the-science approach to site characterization.

Figure 21 depicts a hypothetical ground-water and soil contamination situation located in a mixed residential and light industry section of a town in the Northeast. As illustrated, there are three major plumes: an acids plume (e.g., from electrolytic plating operations), a phenols plume (e.g., from a creosoting operation that used large amounts of pentachlorophenol), and a volatile organics plume (e.g., from solvent storage leaks). in addition, soils onsite are heavily contaminated in one area with spilled pesticides, and in another area with spilled transformer oils that contained PCB'S in high concentrations.

The hydrogeologic setting for the hypothetical site is a productive alluvial aquifer composed of an assortment of sands and gravels that are interfingered with clay and silt remnants of old streambeds and floodplain deposits. The latter have been continually dissected by a central river as the valley matured over geologic time. The deeper portion of the sediments is highly permeable and is the zone most heavily used for municipal and industrial supply wells, whereas the shallow portion of the sediments is only moderately permeable since it contains many clay and silt lenses. The predominant ground-water flow direction in the deeper zone parallels the river (which is also parallel to the axis of the valley), except in localized areas around municipal and industrial wellfields. The predominant direction of flow in the shallow zone is seasonally dependent, having the strongest component of flow toward the river during periods of low flow in the river, and being roughly parallel to the river during periods of high flow in the river.

Strong downward components of flow carry water from the shallow zone to the deeper zone throughout municipal and industrial weilfields, as well as along the river during periods of high flow. Slight downward components of flow exist elsewhere due to local recharge by infiltrating rainwaters.

Conventional Characterization Scenario

A conventional site characterization would define the horizontal extent of the most mobile, widespread plume. However, it would provide only a superficial understanding of variations in the composition of the sediments. An average hydraulic conductivity would be obtained from review of previously published geologic reports and would be assumed to represent the entire aquifer for the purpose of estimating flow rates. The kind of clean-up that would likely result from a conventional site investigation is illustrated in Figure 22. The volatile organics plume would be the most important to remediate, since it is the most mobile, and an extraction system would be installed. Extracted fluids would be air-stripped of volatiles and then passed through a treatment plant for removal of non-volatile residues, probably by relatively expensive filtration through granular activated carbon.

Extraction wells would be placed along the downgradient boundary of the VOC plume to withdraw contaminated ground water. A couple of injection wells would be placed upgradient and would be used to return a portion of the extracted and treated waters to the aquifer. The remainder of the pumped and treated waters would be discharged to the tributary under an NPDES permit.

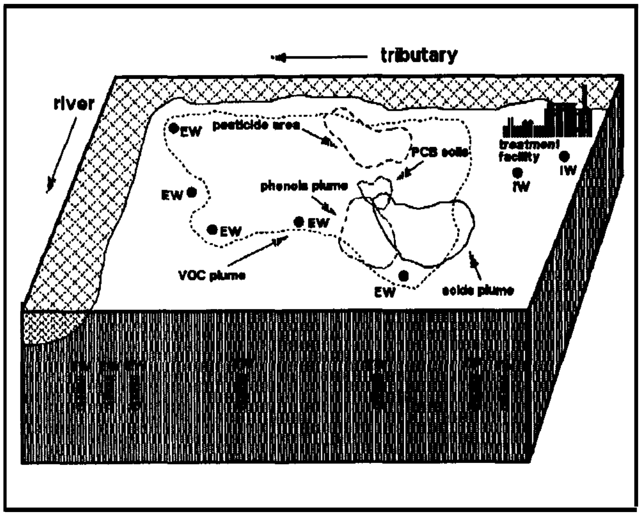

Figure 22. Conventional dean-up of the hypothetical site. EW's are extraction wells. IW's are injection wells; all are screened at the same elevation and have identical flowrates.

information obtained from the drilling logs and samples of the monitoring wells wouldbe inadequate to do more than position all of the screened sections of the remediation wells at the same shallowdepth. The remediation wellfield would operate for the amount of time needed to remove a volume of water somewhat greater than that estimated to reside within the bounds of the zone of contamination, allowing for average retardation values (from the scientific literature) for contaminants found at the site. The PCB-laden soils would be excavated and sent to an incinerator or approved waste treatment and disposal facility. The decision makers would have based their approval on the presumption that the plume had been adequately defined, and that if it had not, that the true magnitude of the problem does not differ substantially, except for the possibility of perpetual care.

State-of-the-Art Characterization Scenario

incorporation of some of the more common state-of-the-ail site investigation techniques, such as pump tests, installation of vertically-separated clusters of monitoring wells (shallow, intermediate, and deep) and river stage monitors, and chemical analysis of sediment and soil samples would likely result in the kind of remediation illustrated in Figure 23. Since a detailed understanding of the geology and hydrology would be obtained, optimal selection of well locations, well screen positions and flowrates (the values in the parentheses in Figure 23, in gallons per minute) for the remediation wells could be determined, A special program to recover the acid plume and neutralize itwould be instituted. A special program could also be instituted for the pesticide plume. This approach would probably lower treatment costs overall, despite the need for separate treatment trains for the different plumes, because substantially lesser amounts of ground water would be treated with expensive carbon filtration for removal of non-volatile contaminants.

The screened intervals of the extraction wells would be placed at deeper positions towards the river, if water quality data from monitoring well clusters show that the plume is migrating beneath shallow accumulations of clays and silts to

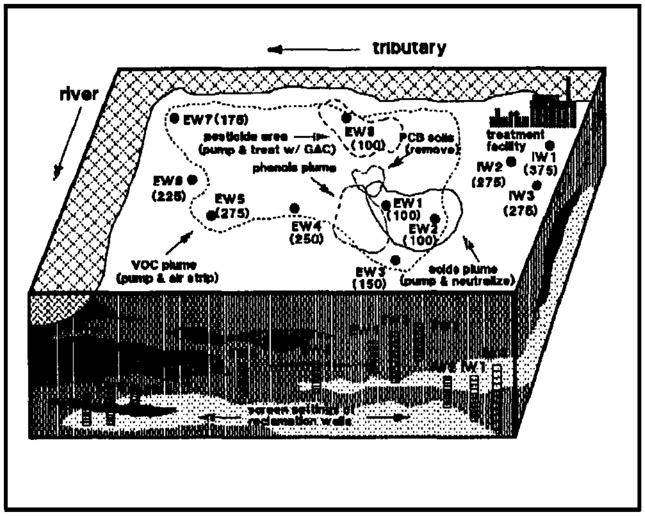

Figure 23. Moderate state-of-the-art remediatlon. Clusters of vertically-separated monitoring wails and an aquifer test are used to tailor the remedy to the site hydrogeology.

the deeper, more permeable sediments. All or most of the extracted and treated ground water could be returned to the aquifer through injection wells. The well screens would need to be positioned (e.g., deeper) to avoid diminishing the effectiveness of nearby extraction wella. As in the conventional remedy, the remediation weilfield would operate for the amount of time needed to remove a volume of water that is determined from average contaminant retardation values and the rate of flushing of groundwater residing in the zone of contamination. The detailed geologic and hydrologic information acquired would result in an expectation of more rapid cleansing of portions of the contaminated zone than others.

One could conclude that this remediation is optimized to the point of providing an effective clean-up, and decision makers would be reasonably justified in giving their approval. One should note, however, that the efficiency (esp., duration) of the remediation maybe less than optimal.

Advanced State-of-the-Art Characterization Scenario

if ail state-of-the-art investigation too ls were used at the site, there would be an opportunity to evaluate the desirability of using a subsurface barrier wall to enhance remediation efforts (Figure 24). The wall would not entomb the plumes, but would limit pumping to contaminated fluids, rather than having the extracted waters diluted with fresh waters, as was true of the two previous approaches. The volume to be pumped could be lowered because the barrier wall will increase the drawdown at each well by hydraulic interference effects, thereby maintaining the same effective hydrodynamic control with less pumping (note the lower flowrates for each well in Figure 24). Treatment costs should be less, also, because the pumped waters should contain higher concentrations of contaminants and treatment efficiencies are often greatest at moderate to high concentrations. soil washing techniques could be used on the pesticide contaminated area minimize future source releases to ground water.

Both the effectiveness and the efficiency of this remediation might therefore appear to be optimizable, but that is a perception that is based on the presumption that the contaminants will be released readily. Given the potential limitations to pump-and-treat remediations discussed previously, it is doubtful that even this advanced state-of-the-art site investigation precludes further improvement. Much attention could be devoted to the chemical and biological peculiarities, just as has been given to the geologyand the hydrology. For example, detalledevaluation of sorption or other contaminant retardation processes at this site, rather than the use of average retardation values from the literature, should generate additional improvements ineffectiveness and efficiencyof the remediation. Likewise, detailed examination of the potential for biotransformation would be expected to lead to improved effectiveness and efficiency.

State-of-the-Science Characterization Scenario

At the state-of-the-science level of site characterization, tracer tests could be undertaken which would provide good information on the potential for diffusive restrictions in low permeability sediments and on anisotropic biases in the flow regime, Sorption behavior of the VOC'S could be evaluated in part by determining the total organic carbon content of selected subsurface sediments. Similarly, the cation exchange capacities of subsurface sediment sampes could be determined to obtain estimates of release rates and nobilities of toxic metals. The stabilities of various possible forms of elements and compounds could be evaluated with measurements of pH, redox potential, and dissolved oxygen. Contemporary research indicates that the acids plume and the phenols plume might be better addressed with such measurements (e.g., chemical speciation modeling). Finally, if state-of-the-science findings regarding potential biotransformations could be taken advantage of, it might be possible to effect in-situ degradation of the phenols pluma, and remove volatile residues too (Figure 25).

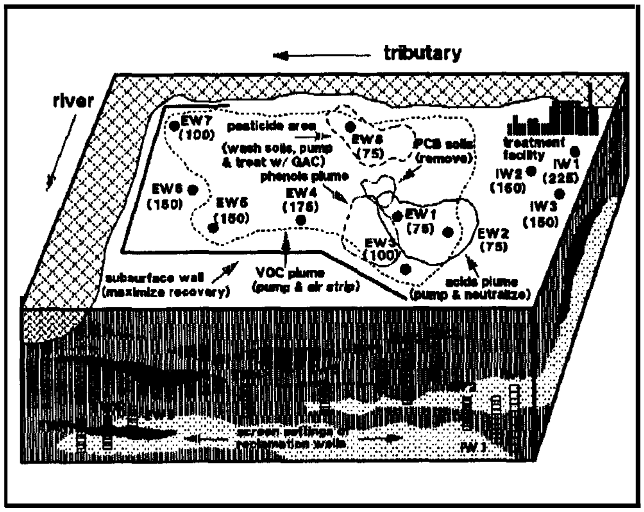

Figure 24. Advanced state-of-the-art remediation. Subsurface barrier walls or other technologies can be integrated with pump and-treat operations.

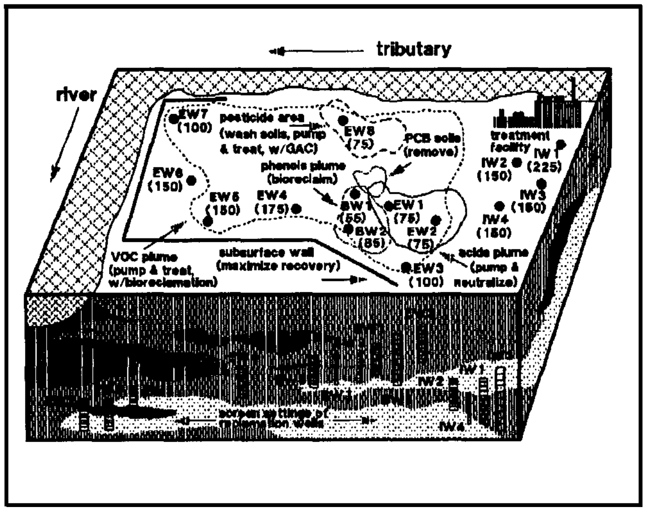

Figure 25. State-of-the-science remediafion. Bioremediation and other emerging technologies could be tested and Implemented with reasonable oertainty of effects.

Additional Considerations

The foregoing discussion highlights genetic gains In effectiveness and efficiency of remediation that should be expected by better defining ground-water contamination problems and using that information to develop site-specific solutions.

Because the complexities of the subsurface cannot fully be delineated even with “state-of-the-science” data collection techniques and many of these techniques are not fully developed nor widely available at this time, it Is important to proceed with remediation in a phased process so that information gained from initial operation of the system can be incorporated into successive stages of the remedy. Some considerations that may help to guide this process include the following:

1. In many cases, it maybe appropriate to initiate a response action to contain the contaminant plume before the remedial investigation is completed. Containment systems (e.g., gradient control) can often be designed and implemented with less information than required for full remediation. In addition to preventing the contamination from migrating beyond existing boundaries, this action can provide valuable Information on aquifer response to pumping.

2. Early actions might also be considered as a way of obtaining information pertinent to design of the final remedy. This might consist of installing an extraction system in a highly contaminated area and observing the response of the aquifer and contaminant plume as the system is operated.

3. The remedy itself might be Implemented In a staged process to optimize system design. Extraction wells might be installed incrementally and observed for a period of time to determine their range of influence, This will help to identify appropriate locations for additional wells and can assure proper sizing of the treatment systems as the range of contaminant concentrations in extracted ground water is confirmed.

4. In many cases, ground water response actions should be initiated even though it is not possible to assess the restoration time frames or ultimate concentrations achievable. After the systems have been operated and monitored over time, it should be possible to better define the final goals of the action.

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