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EPA Ground Water Issue

Performance Evaluations of Pump-and-Treat Remediations

Joseph F. Keely

One of the most commonly used ground-water remediation technologies is to pump contaminated water to the surface for treatment. Evaluating 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 Superfund decision-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 ability to pump such contaminants to 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 evaluating the effectiveness of ground-water remediations. It has been reviewed by members of EPA's Robert S. Kerr Environmental Research Laboratory.

For further information contact Marion R. (Dick) Scalf, Chief, Applications and Assistance Branch, RSKERL-Ada, FTS 743-2312, or Randall R. Ross, Project Officer, RSKERL-Ada, FTS 743-2355.

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 the desired 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?

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Ada, OK

potentially destructive interactions between contaminants and subsurface formations, such as the dissolution of limestone and 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 opportunity for 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-water flow 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.

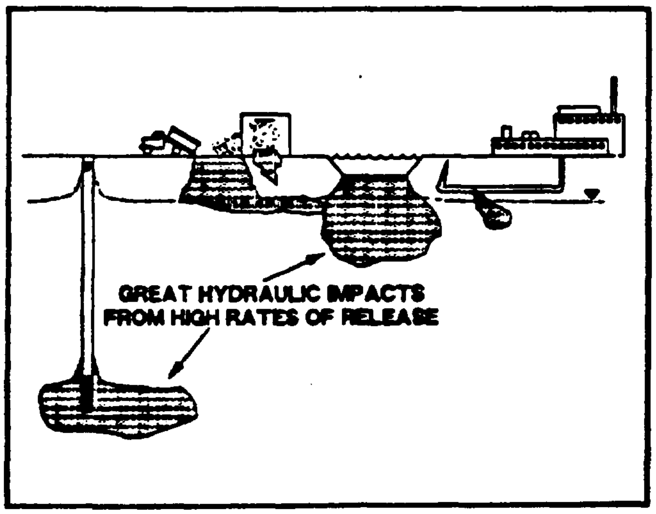

Figure 3. Hydraulic impacts of contaminant sources. Injection wells and surface impoundments may release fluids at a high rate, resulting in local mounding of the water table.

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.

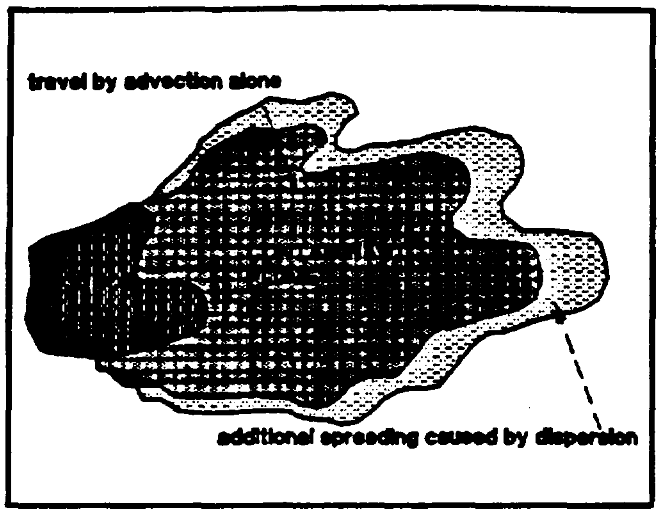

Figure 4. Bird's-eye view of contaminant plume spreading. Advection causes the majority of plume spreading in most cases Dispersion adds only marginally to the spreading.

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

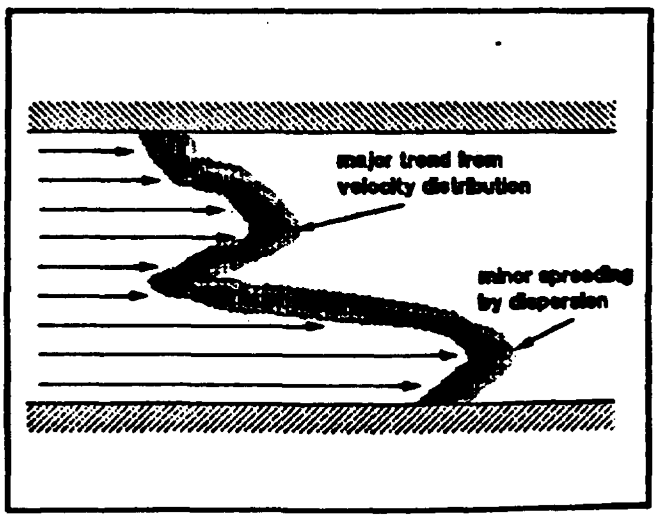

Figure 5. Cross-sectional view of contaminant spreading. Permeability differences between strata cause comparable differences in advection and, hence, plume spreading.

Cosolvation is the process by which the solubility 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.

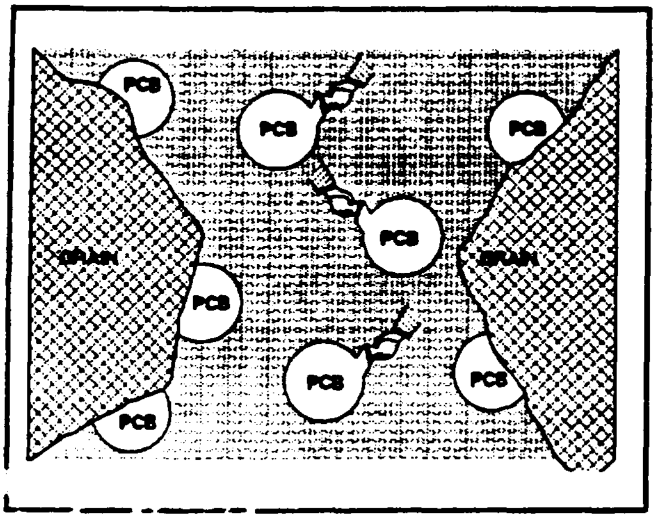

Figure 8. Conceptualization of transport by cosolvation. Insoluble contaminants may dissolve in ground water that contains solvents at high concentrations.

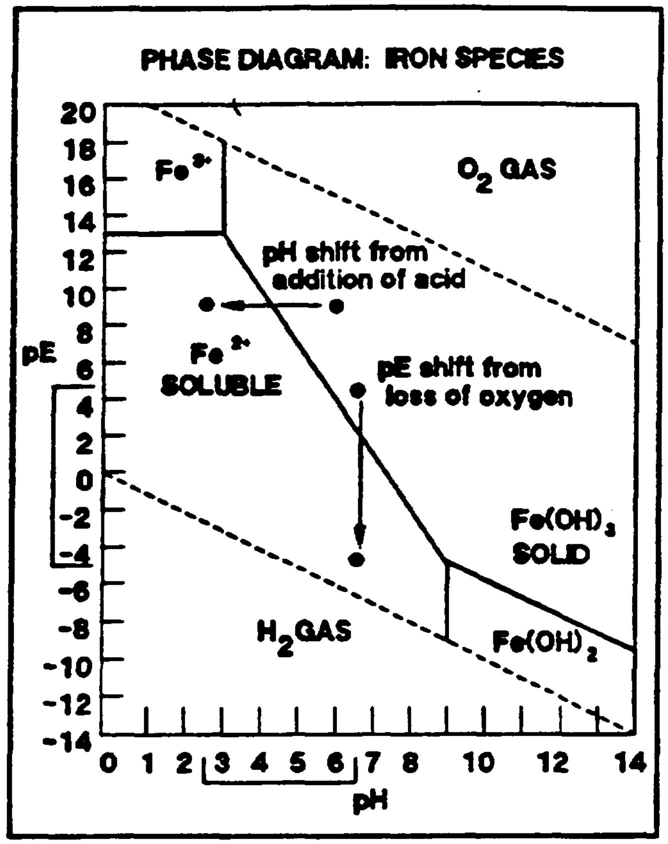

Figure 9. Facilitated transport by phase diagram shifts. Releases of acidic contaminants, or depletion of oxygen by biota, may solubilize precipitated metals or ionize organics.

... who design treatment strategies should anticipate the ne... to remove from ground water certain contaminants that are normally immobile, if the ground water 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.

...s between chemical phases (Figure 9) involve a large change in the pH or redox (reaction) potential of water, and can increase contaminant solubilities 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 components 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.

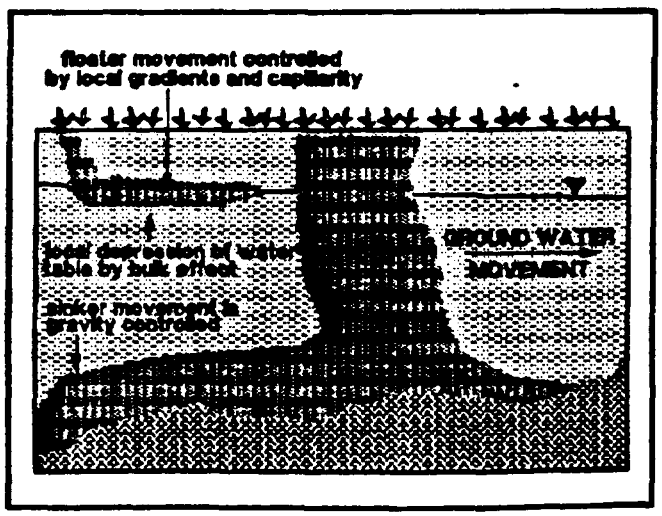

Figure 10. Dynamics of immiscible floater and sinker plumes. Buoyant plumes migrate laterally on top of the water saturated zone. Dense plumes sink and follow bedrock slopes.

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 intervals, 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 intervals, 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 may be 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 a 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 evaluations of monitoring data incorporate allowances for statistical variations in the reported 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 may be 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 latter stages (Figure 12). At that point, large volumes of water are treated to remove small amounts of contaminants.

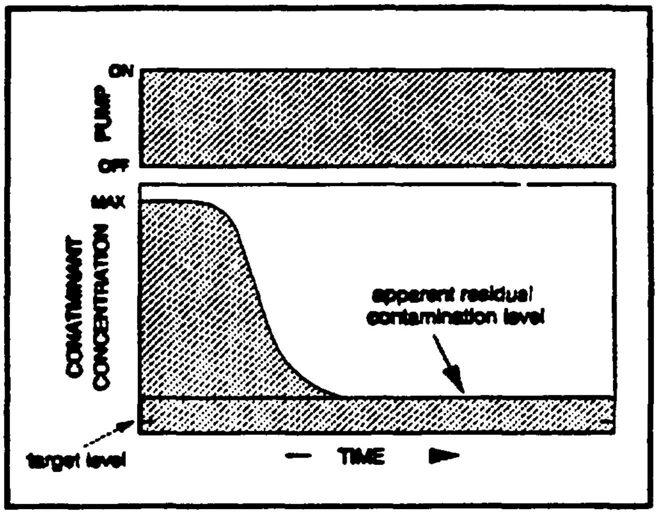

Figure 12. Apparent clean-up by pump-and-treat remediation. Contamination concentrations in pumped water decline over time, to an apparently irreducible level.

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 a remediation wellfield include:

(1) diffusion of contaminants in low permeability sediments,

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

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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-water flow 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.

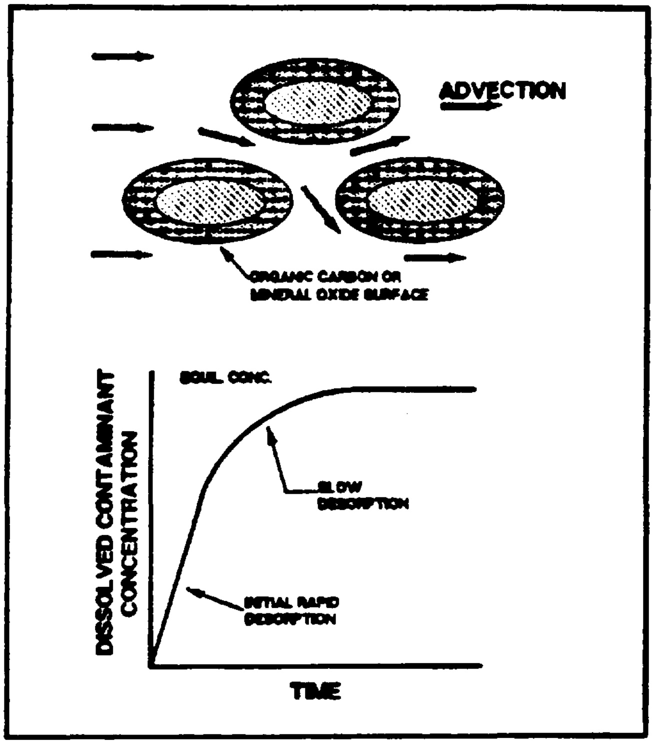

Figure 15. Sorption limitation of pump-and-treat remediations. Increased flow velocities caused by pumpage may not allow for sufficient time to reach chemical equilibrium locally.

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-water flow 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 levels 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.

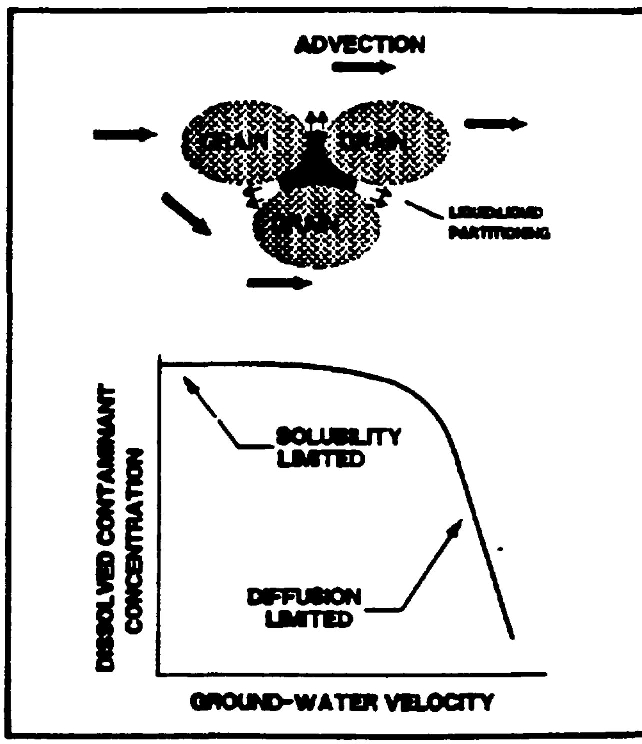

Figure 16. Partitioning limits pump-and-treat effectiveness. Less than solubility levels of contaminants may be released from trapped solvents if pumpage increases flow velocities.

Again, this process generates large volumes of mildly contaminated water where small volumes of highly contaminated water would otherwise 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 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 may or 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 remediation wellfield, such as occasionally turning off individual pumps, allows for some flushing of stagnant zones. That approach may not be as 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, all 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 poorly soluble 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 evaluation of the performance of a remediation, the presence of a multilayer 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 evaluating 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. If capping can 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 all 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 evaluation 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 qualitatively, as well as quantitatively, incorrect. If done properly, however,

Figure 20 illustrates another means of producing readily recognizable patterns of the milli-equivalence values of major cations and anions in a ground-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) may be evaluated in terms of its contribution to the total organic chemical contamination load, or against other specific contaminants, so that some differentiation of source contributions to the overall plume can be obtained.

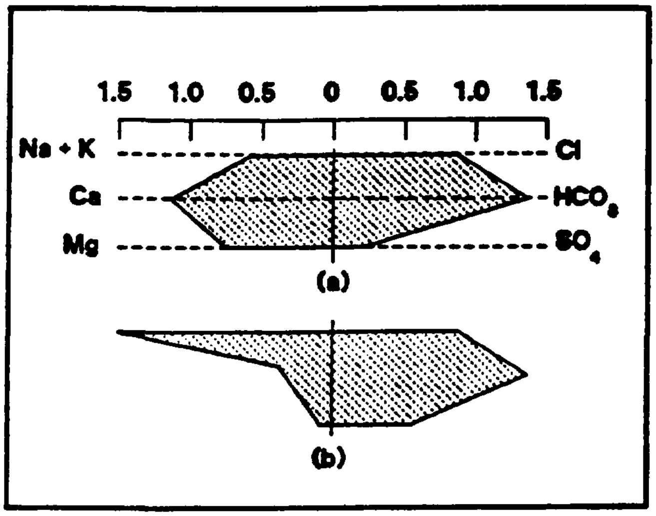

Figure 20. Stiff diagrams of major ions in two samples. The concentrations of the ions are plotted in the manner shown in (a); the uniqueness of another water type is shown by (b).

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.

Characterization 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 may be misunderstood
- Selected remedial 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 substantially 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.

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 wellfields, 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.

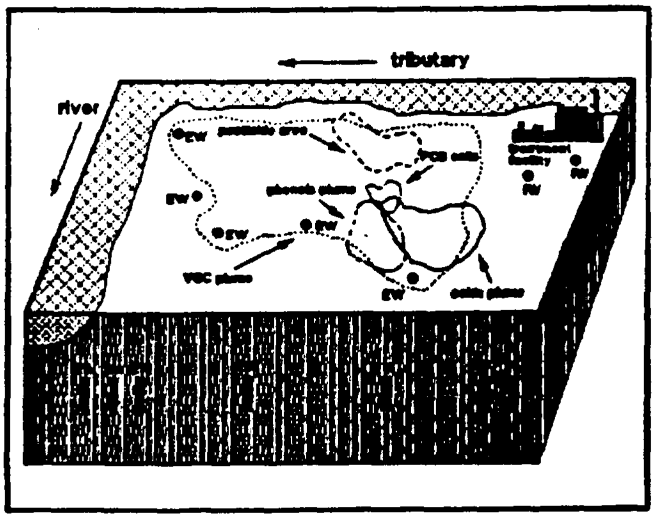

Figure 22. Conventional clean-up of the hypothetical site. EW's are extraction wells. IW's are injection wells; all are screened at the same elevation and have identical flowrates.

Information obtained from the drilling logs and samples of the monitoring wells would be inadequate to do more than position all of the screened sections of the remediation wells at the same shallow depth. 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-art 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, wellscreen 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 it would 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

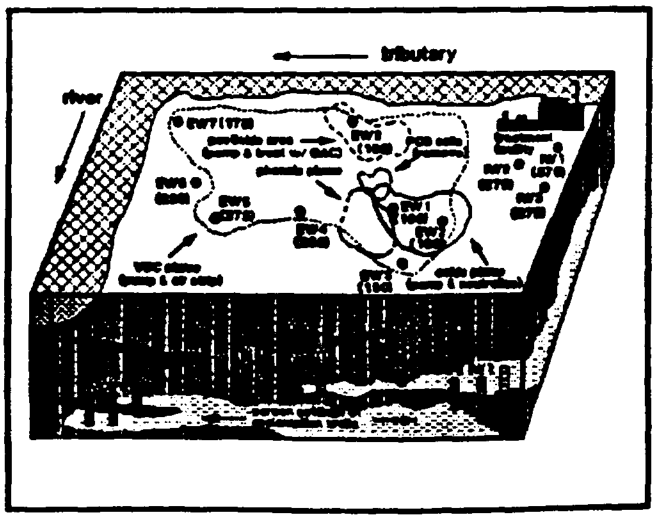

Figure 23. Moderate state-of-the-art remediation. Clusters of vertically-separated monitoring wells and an aquifer test were used to tailor the remedy to the site hydrogeology.

Additional Considerations

The foregoing discussion highlights generic 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 may be 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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AR003602