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A Strategy for Improving Pump and Treat Ground Water Remediation

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A STRATEGY FOR IMPROVING PUMP AND TREAT GROUND WATER REMEDIATION

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ABSTRACT. Established pump and treat ground water remediation has a reputation for being too expensive and time consuming, especially when cleanup standards are set at very low levels, e.g., <10 parts per billion (ppb) for volatile organic compounds (VOCs). Although other ground water remediation technologies are currently being examined and show intriguing promise, pump and treat remains the only dependable technology for cleanup of deep (i.e., >50 ft below ground surface) widespread ground water contamination. The perceived shortcomings of pump and treat result from the (1) tendency of most contaminants to sorb to formation materials, thus retarding contaminant removal; (2) geologic complexity, which requires detailed characterization for the design of optimal extraction systems within available resources; and (3) failure to apply dynamic well field management techniques.

An alternative strategy for improving pump and treat ground water remediation consists of (1) detailed characterization of the geology, hydrology, and chemistry; (2) use of computer-aided data interpretation, data display, and decision support systems; (3) removal of sources, if possible; (4) initial design for plume containment and source remediation; (5) phased installation of the well field; (6) detailed monitoring of the remediation; (7) active ongoing re-evaluation of the operating well field, including redesign as appropriate (dynamic management); (8) re-injection of treated ground water to speed the flushing of contaminants; and (9) setting of appropriate cleanup levels or goals. Use of some or all of these techniques can dramatically reduce the time required to achieve cleanup goals and thus the cost of ground water remediation.

Cost versus Cleanup Model

Ground water remediation, by any known methodology, is expensive and time consuming. This is especially true in California, U.S.A., where the State's non-degradation policy requires that ground water in an aquifer that is or could be used for drinking water be remediated to meet the highest potential beneficial use, usually drinking water standards. This requirement applies even if there is no current use of the aquifer in the vicinity of the contamination and even if public health risk assessments indicate that there is no meaningful risk. Under these conditions, the ground water project at Lawrence Livermore National Laboratory (LLNL) has created a cost versus cleanup model (Fig. 1). This is a generic model generally based on LLNL experience and planning.

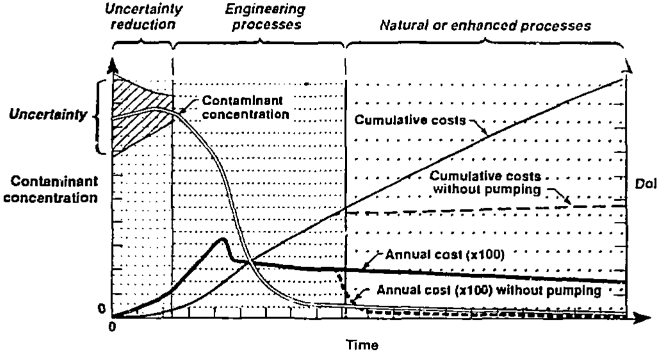

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Figure 1. Cost versus cleanup model comparing costs of the cleanup project with reduction in contaminant concentration in each of the three stages of the remediation.

The most significant feature of this model is that 50% of the total cost of the project is spent removing the last few percent of the contaminants. Another feature is the division of the approximately 50-year time frame into three distinct periods:

- *Characterization or uncertainty reduction.* Costs related to this period are quite small compared to the entire project. Although contaminant reduction is small during this period, optimal site characterization makes large savings possible during succeeding periods.
- *Engineering processes.* This period begins with the achievement of the optimal reduction in uncertainty. At this point, remediation is designed, facilities are constructed, and cleanup operations are begun. As of this writing (May 1992), the only viable technology for remediating widespread ground water contamination in deep aquifers is pump and treat. The period ends when the contaminant concentrations have been dramatically decreased and the remediation efforts have reached a point of greatly diminishing returns. The primary goals of pump and treat systems to date have been to (1) achieve hydraulic control of the contaminant plume such that downgradient movement toward water-supply wells is arrested, and (2) remove the maximum amount of contaminant mass from the areas of high concentration as soon as possible.
- *Natural or enhanced natural processes.* The premise of this period is that a number of natural processes are at work that continue to reduce the contaminant concentrations in ground water to levels below drinking water standards in the absence of continued engineering processes, usually pump and treat. If pump and treat were to continue into this period, 50% of the cost of the entire project could be expended for minimal benefit compared to the other periods. Natural processes operating during this period are: biotic and abiotic degradation of contaminants, and reduction of contaminant concentration by dispersion, diffusion, and adsorption. Processes that may be enhanced through future technologies include bioremediation, chemical abiotic degradation, and enhanced sorption.

The challenge of this model to ground water scientists and engineers is to determine the point where characterization activities are sufficient to design, construct, and operate the engineering facilities such that the point of diminishing returns is reached as soon as possible. The final challenge is to convince the public and the regulatory agencies that, based upon realistic public health and environmental risk assessments, we can terminate the period of engineering processes and rely upon the existing natural processes to finish the job. A number of decision support systems have been and are continuing to be developed that will help decide the optimal level of characterization (Hoffman, 1992a). A number of innovative cleanup technologies are also being researched, developed, and demonstrated. The remainder of this paper focuses on improving pump and treat technologies to reduce the operational lifetime of engineering processes.

Transport and Retardation of Contaminants in Ground Water

Contaminants in ground water are transported by advection and diffusion (Fig. 2). Advection is the physical transport of the contaminants along with the water. Conservative contaminants, i.e., contaminants that are in solution and have very little tendency to sorb onto the geologic formation materials, move at a velocity similar to that of the ground water. Because of the complexity of the interconnection of the pore spaces in the formation materials, contaminants will also spread as they move. Dispersion is the spreading of contaminants along and perpendicular to the direction of flow. Because ground water flow is laminar and relatively slow, the ratio of longitudinal to transverse dispersion is commonly on the order of 10:1.

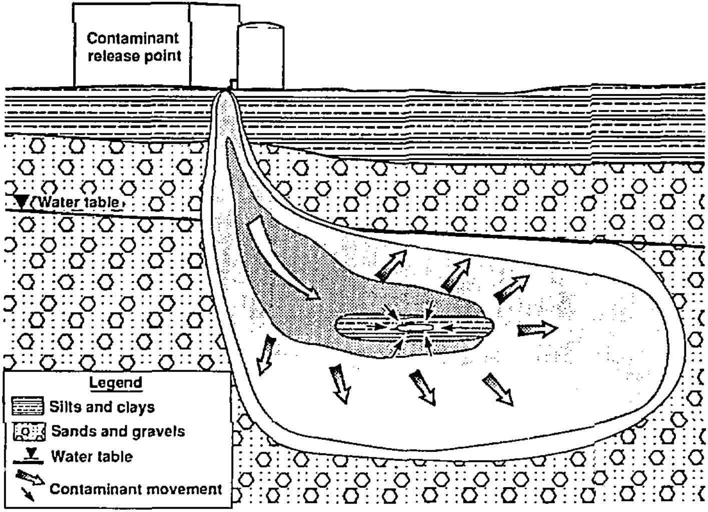

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Figure 2. Schematic view of contaminants moving by advection and diffusion into the clay lens in the center of the figure.

Diffusion is a chemical phenomenon by which contaminants in solution move from areas of higher concentration to areas of lower concentration. The speed with which diffusion takes place is dependent on the chemical characteristics of the contaminants and the water, the physical and chemical characteristics of the formation materials, and the concentration gradient.

Retardation of contaminants is primarily the result of adsorption/desorption of contaminants on to and off of the formation materials. Adsorption is dependent on the chemical characteristics of the contaminants and the physical and chemical characteristics of the formation materials. Some of these characteristics are cation exchange capacity, organic carbon content, and grain size. As a rule of thumb, the smaller the grain size the greater the adsorption. The result is that clay-sized and colloidal particles are particularly strong adsorbers. Some of the colloids are small enough that they too are advected with the ground water movement and, because of the contaminants sorbed to them, provide an additional means of contaminant transport.

As contaminants are advected through the ground water, they will strongly sorb to the fine-grained materials that they encounter and less so to the coarser grained materials. If the contaminants are moving through a sandy gravel and encounter a clay lens, they will be advected around the clay lens, but will also begin to diffuse into the clays, driven by their concentration gradient (Fig. 2). The process of diffusion will occur slowly and continue as long as there is a positive concentration gradient. If the concentration gradient should reverse, such as after cleanup of the higher permeability zones, the contaminants which earlier diffused into the clays will then diffuse out of them (Fig. 3).

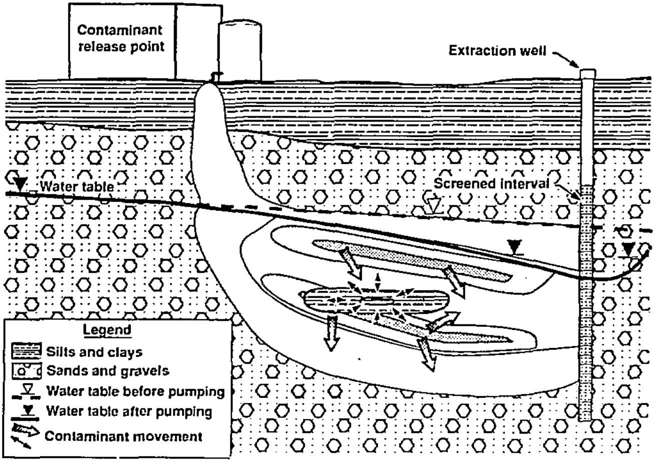

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Figure 3. Same situation as in Figure 2 after a period of ground water cleanup with an extraction well. The concentration gradients have changed, altering the direction of contaminant diffusion. Within the clay lens, diffusion continues into the center of the lens and back out of the lens at its margins.

Reasons for Perceived Failure of Pump and Treat

Pump and treat ground water remediation technologies have been reviewed by the U.S. Environmental Protection Agency (EPA, 1989) and have been described and criticized in U.S. environmental literature (Travis and Doty, 1990). These criticisms, for the most part based upon pump and treat remediations which have been operating for 10 years or less, are based upon the fact that none of the projects studied have achieved drinking water standards in the aquifer and all have been very expensive. In many cases, after pumping has stopped, concentrations in the extraction wells returned to their original contaminant concentrations of and, in some cases, exceeded those concentrations. Despair that pump and treat ground water remediation projects may never clean up the ground water to drinking water standards may be realistic for sites where dense non-aqueous phase liquids are present in fractures in consolidated materials. However, for sites with dissolved contaminants in alluvial materials, new pump and treat strategies hold great promise for improvement over more traditional remediation projects (Hoffman, 1992b).

The primary reason for the poor reputation of pump and treat is the unrealistic expectation that chemicals that have contaminated an aquifer over years or decades can be cleaned up to parts per billion concentrations in a short time. Contaminants that have taken decades to contaminate large areas of aquifer systems cannot be expected to be remediated quickly. Almost all aquifer restoration projects that are available for study have been operating as a static flow field for less than 10 years. These systems may not have been designed to achieve optimal contaminant mass removal or specified concentration levels. In addition, most ground water remediations are projected to require several decades for cleanup, and 10 years or less is insufficient time to evaluate the ultimate performance of the system. In fact, given enough time and a properly designed and operated extraction system, pump and treat can clean up ground water to any desired contaminant concentration. Our challenge is to design and operate a pump and treat system that will clean ground water to *appropriate* concentrations in an *acceptable* time frame. Understanding the reasons for the observations that have resulted in the criticisms of pump and treat is the first step in developing an improved strategy.

CONTAMINANT DIFFUSION INTO AND OUT OF FINE-GRAINED MATERIALS

Figure 3 shows that contaminants will sorb to fine-grained materials and then slowly diffuse back into the more permeable zones where they can be more readily remediated. In an active well field, most of the water is withdrawn from the coarse-grained, high-permeability materials. Under stressed conditions, flow through these systems is usually of relatively high velocity and contaminant concentrations may be reduced relatively quickly. This condition creates the concentration gradient reversal discussed above, and contaminants diffuse back into the more permeable materials from the bounding finer grained materials. Contaminant concentrations in water from extraction wells typically show this relatively rapid reduction followed by a much slower rate of decline as this diffusion process takes place.

Mitigation of this impediment to rapid remediation involves detailed characterization of the geologic formations. With a good understanding of the subsurface geology, we can strategically place monitor wells to improve our knowledge of the details of contaminant distribution. Extraction wells can then be located, and pumping managed, to minimize the diffusion of contaminants into the fine-grained materials and to maximize the diffusion out of them.

CREATION OF ZONES OF STAGNATION

Most pump and treat remediation projects install the extraction wells, turn on the system, and monitor ground water quality. This static pumping creates stagnant areas within the aquifer from which contaminants can only slowly diffuse into the body of the aquifer. This results in a longer than necessary cleanup time. It also accounts in part for the rise of contaminant concentration following the cessation of pumping. Figure 4 is a map of the LLNL site with the initial conceptual design for the extraction well field (Dresen *et al.*, 1991). The extraction wells have been located such that the downgradient migration of contaminants has been halted and the high concentration areas are being remediated. Additional wells have been placed such that no contaminants can flow through the area of the contaminated plume and not be drawn into one of the extraction wells. The flow lines shown on Figure 4 are from a semi-analytical capture zone model. Under equilibrium pumping conditions, stagnation zones, or areas of very slow ground water movement, will be created and are shown by the concentric circles.

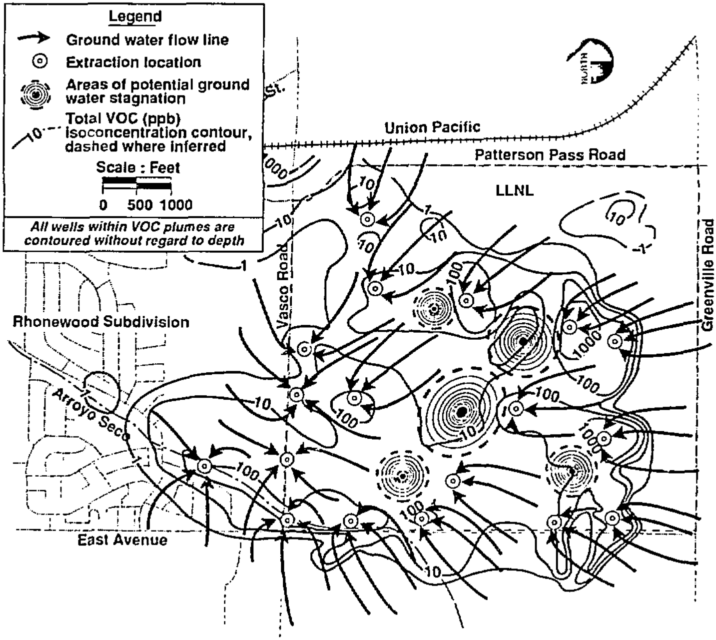

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Figure 4. Map of the conceptual cleanup plan for LLNL, showing locations of extraction wells, flow lines to the wells, and areas of potential ground water stagnation under steady-state pumping conditions.

The way to overcome the problem of stagnation zones is to vary the pumping rates of existing wells and/or to place new extraction wells in the zones of stagnation. Then, based upon the chemical and hydrologic measurements made on the ground water in the extraction wells and monitor wells, we can manage the operation of the extraction well field. Extraction wells can be pumped or rested to achieve the most efficient removal of contaminant mass and contaminant concentration reduction.

CONTAMINANTS CAN BE LEFT BEHIND IN NEWLY UNSATURATED AREAS

Aggressive pumping may also dewater portions of the aquifer, leaving contaminants sorbed to the formation materials (Fig. 5). When pumping ceases, the water levels return, desorbing some of the residual contaminants and causing contaminant concentrations in ground water to rise.

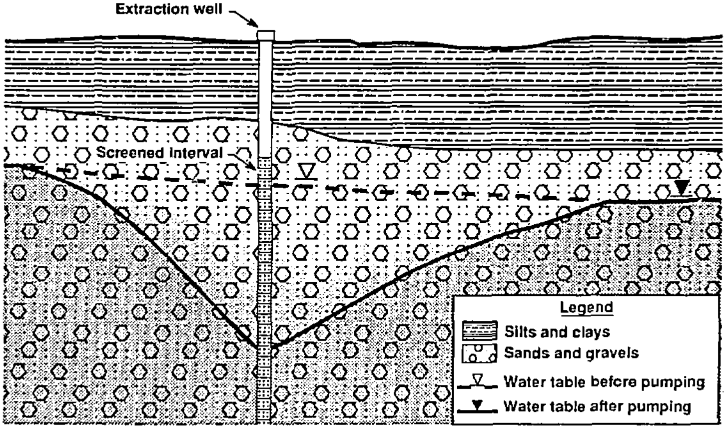

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Figure 5. Schematic view of water table drawdown in the vicinity of an extraction well, leaving contaminants behind absorbed to the newly unsaturated formation materials.

This problem can be overcome by managing extraction well pumping rates such that drawdown of the water table is not exaggerated. Another technique would be to periodically allow the extraction well to rest so that the water table could recover, allowing the contaminants to desorb, be re-entrained in the ground water, and be extracted for treatment. The area of drawdown can also be reduced by the injection of clean water into the same formation upgradient of the extraction well.

LOCATION OF EXTRACTION WELLS RELATIVE TO THE AXIS OF THE PLUME CAN COMPLICATE OBSERVATIONS AND REMEDIATION

In a geologically and chemically heterogeneous medium, pumping can set up a complex flow field in the vicinity of an extraction well. Figure 6 illustrates three examples of extraction wells placed in different orientations to a contaminant plume.

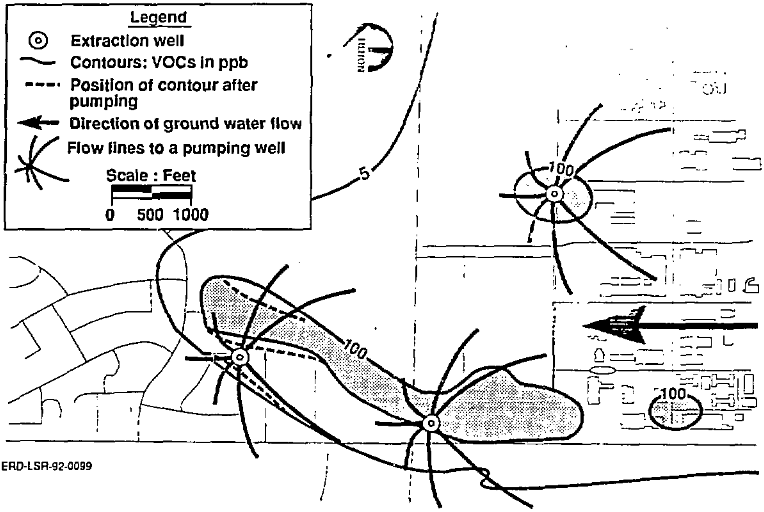

Figure 6. Map of three extraction wells in different orientations to a contaiminant plume.

Extraction well "A" is located directly in the center of the 100-ppb contour of the plume. In a homogeneous isotropic geologic formation, the ground water from the extraction well and from nearby monitor wells will show a steady trend of contaminant removal and concentration reduction through time. Following the cessation of pumping, the only additional contaminants would be from nearby stagnant zones or from diffusion of contaminants from nearby fine-grained materials.

Extraction well "B" is located within an area of high contaminant concentration, but is also near the margin of the plume. Pumping will create a capture zone that will draw in the high concentration part of the plume as well as some cleaner water, resulting in contaminant concentrations in ground water from the extraction well that differ from concentrations in ground water from monitor wells near the extraction well. This variability of concentrations complicates the understanding of the spatial distribution of contaminants. However, careful interpretation of the chemical analyses of the well taken through time and compared to the analyses from nearby monitor wells can also greatly add to our understanding of the geometry of the contaminant plume (Keely and Wolf, 1983).

Extraction well "C" is located just outside the 100-ppb contour of the contaminant plume. Pumping of this well will result in the axis of the contaminant plume shifting to an area that previously had lower concentrations (Keely and Wolf, 1983). Cessation of pumping would once again allow the original flow field to reestablish itself (Keely, 1989), but the dispersion of the contaminants resulting from the pumping would remain.

Figure 7 illustrates the major components of an improved pump and treat system:

- *Characterization activities* (middle of Fig. 7) are the first to be initiated at the beginning of a ground water contamination investigation and continue throughout the life of the project.
- *Modifications activities* (right side of Fig. 7) begin with the initial design of the remediation systems and also continue throughout the life of the project.
- *Operations activities* (left side of Fig. 7) begin with the startup of the first facilities constructed and also continue throughout the life of the project.

Any ground water contamination project begins with some evidence that ground water is contaminated or that a release of contaminants that may pollute the ground water has

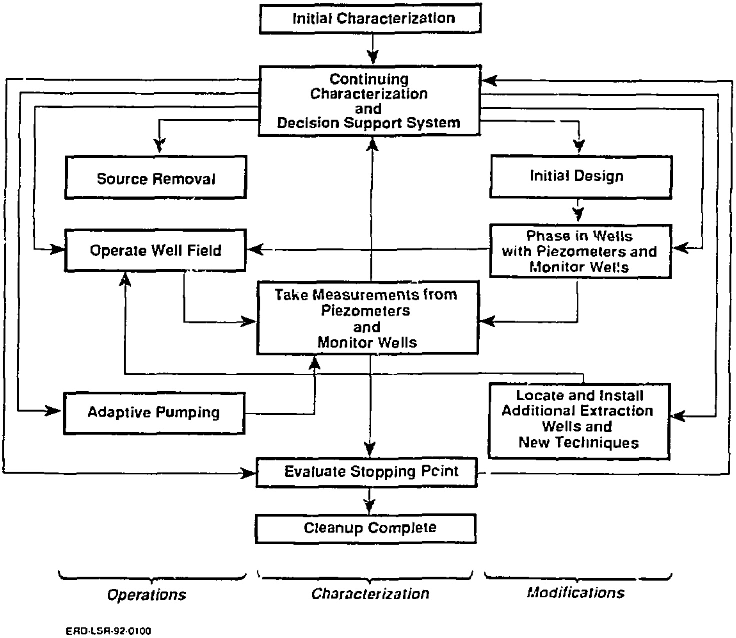

Figure 7. Diagram of the relationship of the major components of the strategy for improving pump and treat ground water remediation (after Hoffman, 1992b).

occurred. This discovery is followed by an initial characterization, which provides enough information to guide the investigators as to how to proceed. The next component is the continuing characterization, which usually proceeds with the installation of monitor wells. The monitor wells are sampled for chemical analyses, and water levels are measured on a regular basis. The collection of data continues until remediation is complete.

As soon as the project collects its first data, we begin to develop the decision support system. This system begins with a scientist examining the data and deciding what to do next. As the project proceeds, the decision support system grows with the size of the database and with the complexity of the decisions that are required, until it is a sophisticated collection of computer-aided systems that store and process the data, while allowing useful display of the data (Hoffman, 1992a).

In the early stages of the subsurface characterization, the goals of this stage of the project are to determine the distribution of the contaminants and to define the subsurface geology, hydrology, and geochemistry. In this way, we can begin the initial design of the cleanup facilities and discover any continuing sources of ground water contamination that can be quickly and easily remediated.

Following source removal and the initial design of the cleanup system, we begin to phase in the installation of the extraction wells. Each of the extraction wells will be monitored by a group of piezometers and monitor wells in its immediate vicinity. The first extraction well is installed, and the introductory well field operation begins. As pumping proceeds from the initial wells, hydrological and chemical measurements are taken from the piezometers and monitor wells and fed back into the decision support system. The output of the models in the decision support system is compared with the measurements taken under operating conditions, the models are modified to more closely reflect reality, the design of the system is modified, and the next extraction well is installed. We proceed in this manner, constantly improving our understanding of the subsurface environment and our remediation design to reflect the measurements taken in the field.

When the initial system has been installed, to arrest the downgradient movement of the plume and begin remediating areas of high contaminant concentration, we query the decision support system to find those areas of the plume where ground water stagnation is occurring or remediation is not proceeding according to plan. At this point, we can vary pumping rates of the existing wells and/or install new extraction wells in the stagnant areas or in other areas in which our continuing characterization activities indicate a need. With new extraction wells in place, we can proceed with adaptive pumping (Isherwood *et al.*, 1991). During adaptive pumping, some extraction wells are periodically shut off and others turned on, and pumping rates are varied to ensure that contaminant plumes are remediated at the fastest rate possible. This approach not only remediates the zones of stagnation, but also allows other portions of the flow field to rest while contaminants desorb and/or diffuse into the water in the portions of the aquifer that are more easily remediated.

At this point in the remediation, we can also consider the application of additional technologies. Treated ground water from an extraction well can be re-injected to help increase the ground water velocity in the vicinity of the well and facilitate the desorption of contaminants to speed the cleanup. At the same time, dewatering can be minimized or avoided. Although this approach increases the local gradient near the extraction well, thereby reducing the size of the capture zone of the well, it holds great promise for reducing the retardation of contaminants and speeding the attainment of cleanup goals. Other innovative technologies that might be deployed include:

- Introduction of heat by electrical heating or injecting hot water or steam.
- *In situ* air stripping.
- Bioremediation.
- Introduction of surfactants to reduce adsorption.
- Injection of chemical reagents to induce chemical degradation of the contaminant.

This brings us back to the large feedback loop (Fig. 7). We must continually evaluate "how clean is clean," both to create the optimal cleanup design and to know when to stop remediation. Appropriate levels will be different for each contaminated aquifer and can be determined with a high level of confidence if appropriate characterization of the problem has been accomplished and if realistic public health risk assessments have been performed.

Summary

There is an alternative to established systems of pump and treat ground water remediation. These systems can be greatly improved if they are based on a level of characterization that maximizes the understanding of the geologic, hydrologic, and chemical environment requiring remediation. Appropriate computer-aided data management, data interpretation, and flow and transport modeling are currently available and are being continuously improved. These tools, coupled with an intensive monitoring of the hydraulics and chemistry of the flow field, can be used to validate and/or change the existing conceptual and digital models. The results of this constantly improving understanding of the subsurface environment can provide the data for the decision support system necessary to properly construct and actively manage the extraction/injection well field. In this manner, cleanup levels can be achieved as quickly and inexpensively as possible. The establishment of realistic risk-based cleanup standards at levels that are protective of the public health and the environment and that ensure acceptable water quality at the point of use is also essential to the allocation of resources for maximum public benefit.

Acknowledgments

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