Hazardous Waste Site Investigations

Toward Better Decisions

Edited by

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characterization and early warning detection, and providing adequate data for remedial design or remedial performance assessment is problematic. The designer of monitoring networks is caught in a conundrum: the need for a large number of wells to satisfy the demands of complex ground water systems, with the reality of high cost per well often limiting wells in the network to an inadequate number relative to the complexity of the problem.

Mackay[1] provided a vivid description of the problem facing the designer of ground water monitoring networks:

> Envision an extremely complex maze in which are lost a variety of chemicals — some concentrated and localized, and some dilute and spread out. Imagine further that the chemicals are all moving at different rates and directions as a result of gravity and/or the flow of air and water through the maze. Then imagine that the internal walls of the maze are porous, like a hedge, and that the chemicals, air or water can move into and even through them at rates that vary throughout the maze. Lastly, imagine that you must find all of the chemicals but cannot enter the maze to do so.

In the first part of this chapter, the author considers the implications for ground water monitoring of some recent studies pertaining to contaminant behavior in ground water. The overall emphasis is on organic chemicals. The discussion focuses on three facets of site hydrogeology: transverse dispersion in heterogeneous sandy aquifers, fractures in aquitards, and heavier-than-water immiscible industrial liquids. These are the main areas of the author's site-investigation experience in the past decade.

The term "conventional monitoring well" is used frequently in this chapter. This refers to a single well in a single borehole. The well has a screen of moderate or short length at the bottom, a sand or gravel pack is placed around the screen, and the entire portion of the borehole annulus above the sand pack is sealed to surface with an impervious material such as cement grout or bentonite slurry.

HYDRODYNAMIC DISPERSION

Dispersion has received much attention from the ground water research community in the past three decades. Lehr[2] argued that excessive attention has been paid to this topic and that it is no longer worthy of priority in research. Regardless of the issue of priority, research findings of the past decade on dispersion have immense implications for ground water monitoring. The following consideration of the topic pertains to contaminant transport in porous media such as sand and gravel rather than fractured rock.

Plumes of dissolved-phase contamination generally travel more or less horizontally through sand or gravel aquifers because these aquifers, as broad geologic deposits, are typically close to horizontal. Therefore, it is convenient to consider dispersion in terms of the following three principle directions:

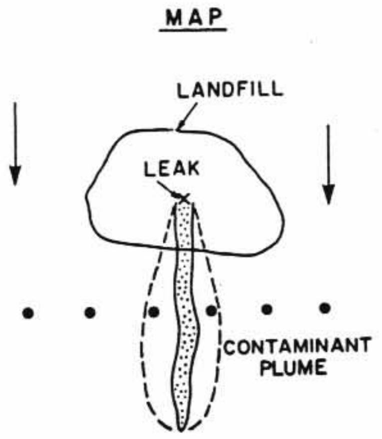

FIGURE 1. Schematic diagram showing a narrow contaminant plume from a landfill leak not being detected by a row of down gradient monitor wells because of a weak transverse dispersion (solid outline); dashed line represents strong transverse dispersion.

some plumes, the difference between detecting or missing a concentration zone orders of magnitude above a regulatory limit is the difference in positioning in depth of the critical well by only a meter or two.

At a landfill where the monitoring network is used for early warning of contamination, a likely prospect for contamination to enter ground water would be a hole in the liner. The width of the contaminant entry-area to ground water beneath the landfill would tend to be narrow. Due to weak transverse dispersion, the spacing between monitoring wells down-gradient would need to be equally narrow to provide much probability that the network would eventually detect the leak. Consideration of spacing between monitoring wells then becomes almost entirely dependent on estimates of the width of the contaminant entry-area at the source. From this, it follows that at many waste disposal or industrial sites, the spacing of wells in both the vertical and horizontal directions is too large to detect the main impacts of the type of leakages or spills most likely to cause ground water contamination (Figure 1). If transverse dispersion were to have as strong a spreading effect as was previously believed, this monitoring problem would be much less severe because plumes would spread out rapidly in the transverse directions as the plume front advances, thereby being at least detectable (but not necessarily mappable) by widely spaced wells.

DENSE NON-AQUEOUS PHASE LIQUIDS

Dense non-aqueous phase liquids (DNAPLs) are now recognized as one of the most common and complex causes of ground water contamination in

The problems referred for DNAPL site monitoring pertain to the spatial and temporal resolution of concentration distributions. However, an even more difficult DNAPL monitoring problem is the installation of monitor wells in areas of DNAPL without causing lenses or pools of DNAPL to drain liquid-DNAPL down the borehole or well to deeper levels in the aquifer. Many DNAPLs have a specific gravity between 1.2 and 1.6, low viscosity and low interfacial tension. This gives them strong propensity to move downward through small openings created by drilling or well installation. In hydrogeologic settings where no major aquitard exists into which casing can be keyed at the bottom of a DNAPL pool, there is no proven technology for drilling through such DNAPL zones without draining liquid DNAPL deeper in the aquifer or otherwise inducing artificial complexities in the monitoring data.

The worst circumstances are generally found in fractured rock. Extreme precautions can be taken which may minimize these problems in some cases. However, without detailed prior knowledge of the locations of the lenses or pools of DNAPL, the precautions can be futile. Such prior knowledge must derive from drilling, a Catch-22 situation. Considering the inadequacy of present drilling technology in this context. It is often inadvisable to drill in areas of known or suspected DNAPL. Unconventional strategies for site investigation should be pursued. Specialized equipment suitable for this challenge is needed.

FRACTURED AQUITARDS

In the simplest conceptualization, hydrogeological systems are comprised of aquifers and aquitards. Aquifers are normally the focus of attention because they are the source of water supply and are the zones where large contaminant plumes develop. At waste disposal or industrial sites, however, aquitards are often as important as the aquifers. The problems of monitoring aquitards are much different than those of aquifers.

In sedimentary terrain, aquitards typically are strata comprised of silt, clay, siltstone, or shale in which nearly all ground water flows through fractures (the term fracture is used here for all types of secondary openings such as joints, fissures, and bedding planes). In many aquitards, vertical fractures exist and in situations where the fractures extend from top to bottom, these fractures often provide pathways for contaminants to move through the aquitard into underlying aquifers. One of the reasons why ground water contamination is now so common in industrial regions is the leakiness of aquitards due to fractures, primarily vertical fractures.

Using numerical simulations, Sudicky and McLaren[16] and Harrison et al.[17] showed major impacts of dissolved contaminants, such as chloride and trichloroethylene, on an underlying aquifer due to movement through small vertical fractures in an overlying clay aquitard. Vertical fractures as small as 10 or be on hand. There is now much standardization in ground water monitoring and, with this, much improvement in the quality of data provided by individual monitoring wells. With these improvements in well design, well materials, sampling pumps, and field and laboratory protocols, has come a large increase in the cost of each chemical data point. A major implication in site investigations of the three factors previously described (dispersion, DNAPL, and fractured aquitards) is recognition of the need for much more detailed three-dimensional hydraulic and chemical data. The recent advances in monitoring technologies and protocols have done little to fulfill this need. To meet this need, the cost per chemical data point must decline rather than continue to increase.

At some sites, the cost of a single nest of monitoring wells (several wells in the nest or an equivalent modular multilevel device in a single borehole) with one full chemical data set from the nest exceeds $50 thousand or even $100 thousand. This includes the cost of handling and disposing of contaminated borehole cuttings and water. If the site is a DNAPL site or is a site on fractured rock, one nest is usually an insignificant step towards achievement of the level of understanding necessary for a reliable risk assessment or remedy selection. Many tens of nests per site or many more may be necessary to achieve these practical goals. It is entirely feasible at many sites (such as SUPERFUND or RCRA sites) to spend millions of dollars on a monitoring network without producing the site data necessary for the goals to be accomplished. This is not to say that the achievements in monitoring of the past decade have been ill-advised; rather, it is that they have been primarily unidirectional, leaving an urgent need for advances of a much different nature in the 1990s.

SOME DIRECTIONS FOR DEVELOPMENT OF NEW TECHNOLOGY

This consideration of needs in monitoring technology and strategy focuses on three-dimensional complexities in ground water systems caused by weak dispersion, fractures, DNAPL, or combinations thereof. The challenge is to develop efficient means for achieving adequate spatial and temporal distributions of data so that the level of understanding of the ground water system is commensurate with the needs of site risk assessment or remedy selection/design. The practical goal should be to reduce the cost per data point and to increase the probability of acquiring data points from the important or essential locations over the most relevant time scale.

Detailed spatial snapshots of hydraulic head and ground water concentrations can often provide an adequate data base for risk assessment or remedy selection because ground water flow is typically so slow that spatial distributions change little over months or even years. It can be argued that sampling over months is necessary to establish credible analyses following the formation disturbance caused by drilling. The need, however, is for drilling techniques that minimize formation water disturbance so that immediate sampling has validity.

Technically advanced versions of the piezo-cone and the screened hollow-stem auger are examples of recent technologies for obtaining head and chemical data at many depths in boreholes as drilling proceeds. The screened auger is used in permeable sand or gravel to depths generally not greater than 40 or 50 m. The piezo-cone functions best in soft silty or clay deposits in which the cone can be pushed under heavy load applied at surface. Because these techniques perform well only in a few types of overburden deposits and because of depth limitations, they can only be used in some regions. They offer possibilities for drilling in DNAPL zones because frequent sampling and analysis is done as the hole advances. This provides for drilling to cease when concentrations indicative of DNAPL are encountered. However, these methods, like other drilling methods, do not prevent DNAPL from draining deeper in the hole if the hole penetrates below a DNAPL zone. The piezo-cone and the screened auger have yet to be connected to field analysis equipment to produce laboratory-grade analyses on-site as drilling proceeds.

The technically advanced piezo-cone has sensors positioned near the tip of the drive-point penetrating the geologic material. The advantages of these tip sensors are many. There is a need for other drilling methods to have chemical and pressure sensors on or near the drill bit.

Use of Conventional Monitoring Wells for Contamination Scanning

Sampling of conventional wells using the standard protocol involves purging of several well-casing volumes before sampling. The purging is intended to produce samples of formation water free of artifacts related to reactions with well materials or gas transfer at the top of the water column. Normally, only one sampling is done after purging. The objective of this standard protocol is to produce a sample representative of the formation water in the immediate vicinity of the well screen. This type of sample is referred to here as a point sample. If the monitoring is being done to locate plumes that could be narrow and therefore difficult to locate or to locate local high-concentration zones within large complex plumes, point sampling has minimal probability of accomplishing these objectives.

An alternative use of the conventional monitoring well is to sample the well at the well screen using a down-hole point sampler (e.g., canister or cartridge sampler) or deep pump with a packer to avoid well casing and gas-

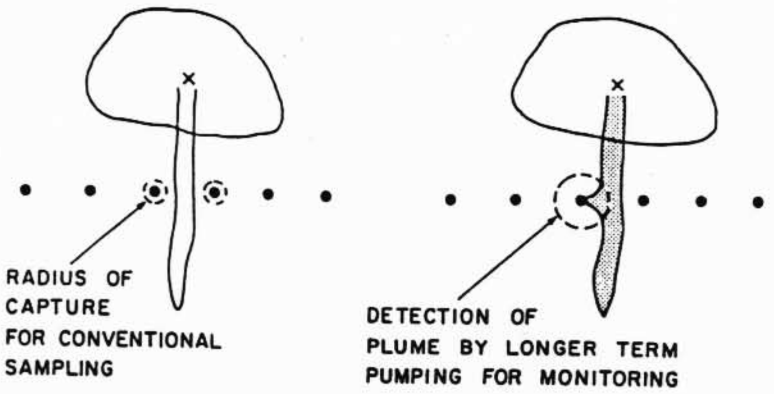

FIGURE 4. Schematic maps showing the radius of water withdrawal for a monitor well subjected to a standard sampling protocol (left) and the expanded radius for a protocol based on aquifer scanning (right).

Investigation of Fractured Aquitards

The fractures in aquitards that are generally the most important in ground water contamination are vertical or near-vertical. The usefulness of vertical boreholes/vertical monitoring wells is often very limited because of the low probability of detecting the critical fractures. Angle or horizontal boreholes provide much greater probability of obtaining data from critical fractures. In clay or silt aquitards, continuous cores from angled holes can be divided into numerous segments for analysis of extracted pore water or solids. The main limitations in this approach are in the drilling. The methods normally available for drilling angle holes in clay deposits, such as hollow stem augering, provide little control at depth on the angle of the lead augers, and therefore poor information on the subsurface location of the bit. The position of deep cores is poorly known. Technologies solving this problem in the petroleum industry have not been widely used in hydrogeology. Angled boreholes in clay aquitards are rare in hydrogeology even though the need is apparent. Technology transfer in this area is lagging. Perhaps this is due to the difficulty of installing monitor wells in angled holes. However, in many cases, few wells are needed if sufficient angle cores are taken for analysis of contaminant concentrations in core samples.

Investigations of contaminant migration in vertical or near vertical fractures in fractured-rock aquitards have much different problems than those in clay aquitards. Continuous cores of fractured rock usually provide little data on contaminant occurrence on the fracture surfaces. Water or air and water are circulated in the borehole at all times during the coring operation. With available rock coring methods this circulation flushes contaminants from the fracture surfaces. In low matrix-porosity crystalline rock such as granite, there obtain concentration vs. time relations for the ports. This provides insight on concentration patterns in the fracture network.

The main limiting factor in the use of the modular systems is the cost and turnaround time of analyses. On-site analytical systems that do laboratory-grade analyses with fast turn-around are needed to bring modular monitoring systems into the mainstream of ground water contamination studies. Until this happens, investigations of contaminant occurrence and migration in fractured rock at many sites will remain hampered by inadequate spatial distribution of data points.

The modular systems described above can only be installed in boreholes open from top to bottom at the time the system is lowered down the borehole. Therefore, these systems, like conventional wells, do not circumvent the propensity for DNAPL to run down the borehole if the hole penetrates a zone of free liquid-phase DNAPL.

CONCLUSION

The major advances in ground water monitoring at waste disposal and industrial sites made during the past decade pertain primarily to the design, construction, and installation of conventional monitoring wells and to the equipment and protocols for sampling these wells. Also, advanced protocols used for routine laboratory analyses, particularly for organic chemicals, have achieved common use. The importance of these advances notwithstanding, little progress has been made in the development of cost-effective technologies for detailed determination of the spatial distribution of contamination in most types of hydrogeologic systems. This deficiency severely impedes progress towards reliable risk assessments of ground water contamination, selection of site remedies, and monitoring of progress of remedial action. Recent studies of dispersion in sand and gravel aquifers show weak transverse dispersion. This magnifies the difficulty of achieving adequate understanding of the spatial distribution of contaminants using conventional wells.

To decrease the cost of chemical analyses in site investigations and to provide greater insight on the location and internal character of contaminant plumes, there is an urgent need for new technologies for reliable and accurate on-site chemical analyses, preferably technologies with a high degree of automation and ease-of-use. These technologies should fulfill many needs such as rapid turn-around time so that field decisions can be made during drilling, development of concentration-vs.-time relations for monitor wells and modular multilevel systems, automated analyses for pumping tests and pump-and-treat remediation, and scanning of aquifers for contamination.

Many waste or industrial sites within SUPERFUND and RCRA and other sites such as those on military land have DNAPL in the ground water zone. The monitoring methods used in DNAPL areas are generally poorly suited

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