Title

Conjunctive Vadose and Saturated Zone Monitoring for Subsurface Contamination

Journal

Environmental Monitoring and Assessment, 59(1)

ISSN

0167-6369

Authors

Hudak, Paul F
Loaiciga, Hugo A

Publication Date

1999-11-01

DOI

10.1023/a:1006066516432

CONJUNCTIVE VADOSE AND SATURATED ZONE MONITORING FOR SUBSURFACE CONTAMINATION

PAUL F. HUDAK[1]* and HUGO A. LOAICIGA[2]

[1] *Department of Geography and Environmental Science Program, University of North Texas, Denton, TX 76203-5279, U.S.A.;* [2] *Department of Geography and Environmental Studies Program, University of California, Santa Barbara, CA 93106, U.S.A.*
(author for correspondence, e-mail: hudak@unt.edu)*

(Received 9 February 1998; accepted 26 May 1998)

Abstract. A comprehensive subsurface monitoring program should include contaminant detectors in both the vadose and saturated zones. Vadose zone detectors can provide an early warning of an impending groundwater contamination problem, and also yield information relevant to placing groundwater monitoring wells. Moisture probes, gas monitoring wells, and pore-liquid samplers deployed in the vadose zone complement groundwater detection wells. The objective(s) of a monitoring program, spatial-scales, and hydrogeology are important considerations for designing subsurface monitoring networks. Often, these networks are used to detect potential releases or characterize existing contamination beneath land-based waste storage facilities. A case study in Santa Barbara, California, U.S.A., illustrates the utility of vadose zone monitoring in characterizing a gasoline contamination problem and guiding the placement of groundwater monitoring wells.

Keywords: saturated zone, subsurface monitoring, vadose zone

1. Introduction

Groundwater quality monitoring networks are used to characterize the physical, chemical, and biological properties of groundwater. Contaminants applied at the land surface migrate through the vadose zone before being advected and dispersed by flowing groundwater. Therefore, vadose zone detectors should be an integral component of a comprehensive subsurface monitoring program. The behavior and fate of chemicals in the vadose zone is rather complex (Everett *et al*., 1982), influencing the subsequent spatial and temporal evolution of contaminants in groundwater. Unfortunately, many subsurface monitoring networks either neglect or consider the vadose zone only indirectly (e.g., as a delay in contaminant transport). However, in addition to providing an early warning of an impending groundwater contamination problem (Cullen *et al*., 1995), information obtained from a vadose zone monitoring system can be used to guide the placement of groundwater monitoring wells and determine an appropriate sampling frequency. This paper addresses the role of vadose zone monitoring in a comprehensive subsurface monitoring program. Key network design considerations include the objectives of a monitor-

Environmental Monitoring and Assessment **59:** 15–29, 1999.

ing program; spatial scales; and hydrogeologic considerations, both regional and site-specific.

2. Monitoring Objectives

A groundwater quality monitoring program typically has one or more of the following objectives (Todd *et al*., 1976): ambient monitoring, source monitoring, compliance monitoring, or research monitoring. The purpose of an ambient monitoring program is to characterize regional groundwater quality over time. This type of monitoring typically involves routine sampling of public water supply, industrial, or domestic wells distributed over a region. Source monitoring programs are designed to identify contaminants released from potential pollution sources. This type of monitoring typically entails placing upgradient and downgradient wells in the vicinity of a landfill. In contrast, compliance monitoring is carried out to verify the status of a site after contamination has occurred. As part of a compliance program, a stringent set of groundwater quality monitoring requirements may be enforced by regulatory agencies. Finally, research monitoring involves detailed spatial and temporal groundwater quality sampling designed to meet specific research goals (Mackay *et al*., 1986).

Conjunctive vadose and groundwater monitoring is relevant to the source, compliance, and research objectives outlined above. Source and compliance monitoring are most common in practice. Although vadose zone monitoring can be used to establish ambient conditions at a site, such monitoring is not typically conducted on a regional scale, in an ambient groundwater quality monitoring program.

In a source monitoring program, the primary role of vadose zone monitoring is to quickly document a contaminant release. Neutron moisture probes deployed in access tubes beneath the leachate collection system of a landfill, gas sampling points, and pore-liquid samplers can detect contaminants that have escaped a landfill before they reach the groundwater domain (Cullen *et al*., 1995). In some cases, early documentation of a developing pollution problem can motivate source control efforts that minimize or effectively eliminate impending groundwater contamination (Kirschner and Bloomsburg, 1988). If an effectively designed vadose zone monitoring program does not detect the movement of pollutants, the requirement for extensive groundwater monitoring may be reduced, which can yield significant cost savings. A secondary role of vadose zone monitoring in a source monitoring program is characterizing the temporally evolving extent of contamination above the main water table. The term ‘main water table’ is used to distinguish the zone of continuous saturation from perched groundwater, the latter being considered part of the vadose zone. In assessing the domain of contamination above the main water table, the utility of a vadose zone monitoring network is not limited to the area directly beneath a contaminant source. Suction cup lysimeters have been used at depths up to 50 feet (15 m) and can be effective in detecting and characterizing the extent of deeper moving pollutants (Everett and Wilson, 1984). In a developing groundwater contamination problem, the area of vadose zone contamination directly above the main water table can be used to assess the initial extent of groundwater contamination beneath the contaminant source. Knowledge of the spatial distribution of this ‘capillary fringe source area’ can be used to evaluate the utility of an established groundwater monitoring network and to guide the placement of additional groundwater monitoring wells.

In practice, detailed subsurface monitoring often takes place after soil and groundwater have been polluted. At sites where a source monitoring network is absent, the contamination may be documented by declining fuel levels in underground storage tanks, leachate seeps on the sides of landfills, vapors from volatile organic compounds (VOCs), or pollution of downgradient water supply wells. In a post-contamination, or compliance monitoring program, the emphasis is on characterizing spatial and temporal variations in subsurface pollution (Loaiciga *et al.*, 1992). A vadose zone monitoring component should be installed before the groundwater component, its primary role being spatial delineation of contamination above the main water table. The extent of vadose zone contamination can then be used to infer the possible extent of groundwater contamination and to guide the placement of groundwater monitoring wells used to document actual concentrations in groundwater. Soil gas surveying can be effective in the early phases of a post-contamination assessment if volatile contaminants are present (Robbins *et al.*, 1990).

3. Spatial Scales

The overall objective of a groundwater quality monitoring program determines the spatial scale, or coverage of the sampling network. While ambient monitoring is often synonymous with regional groundwater quality monitoring, source and compliance monitoring programs typically imply a more localized coverage. The spatial scale affects the types of data needed in the process of network design as well as spatial and temporal sampling frequency. For example, a regional scale groundwater monitoring program typically requires annual or semi-annual sampling, and emphasizes the geographic distribution of monitoring wells relative to population centers (Hsueh and Rajagopal, 1988). In contrast, source or compliance monitoring programs require detailed local scale information on aquifer properties to characterize potential migration pathways (USEPA, 1986).

Both pattern and spacing characterize the spatial structure of a monitoring configuration. The pattern of a configuration reflects the roles of detection and characterization. Instrument spacing is primarily dependent on spatial variations in soil or aquifer properties. A monitoring network with detection capability is comprised of a series of sampling locations arranged in a manner that optimizes the potential for contaminant leak detection. Detection capability generally requires a closelyspaced arrangement of sampling locations. Characterization, on the other hand, refers to the capability of a network to document the three-dimensional extent of evolving subsurface contamination. A network with adequate characterization potential typically exhibits some degree of separation between sampling sites over the extent of a potentially polluted area, particularly away from the contaminant source. With migration away from the source, mechanical dispersion and diffusion spread contaminants, and a coarser instrument spacing is needed to characterize the spatial distribution of contaminant concentrations.

In general, monitoring configurations exhibiting a pattern of relatively close sampling point separation near a contaminant source and a progressive increase in spacing away from the source are potentially effective for both detection and characterization (Hudak *et al.*, 1995). However, this generalization does not apply to cases where preferential migration pathways dictate narrower contaminant distributions with distance from the source. For groundwater monitoring, the pattern of increased well spacing away from the contaminant source typically operates along a horizontal orientation, especially in two-dimensional flow systems. In contrast, the vertical direction is of primary significance in determining an optimal configuration of sampling sites within the vadose zone. Gravitational forces considerably accelerate the movement of percolating effluent in the downward direction, although movement in all directions is possible (Bear, 1979).

In the initial stages of a post-contamination compliance monitoring program, where characterization is an important issue, it may be effective to lay out vadose zone monitoring sites along a uniform grid to ensure unbiased coverage over a region of interest. For example, a regularly-spaced configuration of sampling sites is typically employed in soil-gas surveys (Karp, 1990).

In addition to overall pattern, spacing between sampling points is an important characteristic of a network configuration. Spatial variations in soil properties, in particular, have a significant impact on potential contaminant distributions and influence the effective layout of sampling points within the vadose zone. Previous studies attest to a high degree of spatial variability in unsaturated field soil properties and transport characteristics (Biggar and Nielsen, 1976; Butters *et al.*, 1989; Roth *et al.*, 1991).

The high degree of variability inherent in soil properties has led to the application of quantitative geostatistical techniques in which the spatial dependence of soil properties is investigated through the variogram. An important product of the variogram is the correlation length scale, defined as the average distance over which spatial variability in soil properties is correlated (Gelhar and Axness, 1983). Field estimates of this parameter range from less than 1 m to more than 20 m (Byers and Stephens, 1983; Russo and Jury, 1987). To adequately characterize spatial variability in soil properties within a geostatistical framework, a vadose zone sampling program must employ an instrument spacing that is within the relevant correlation length scale.

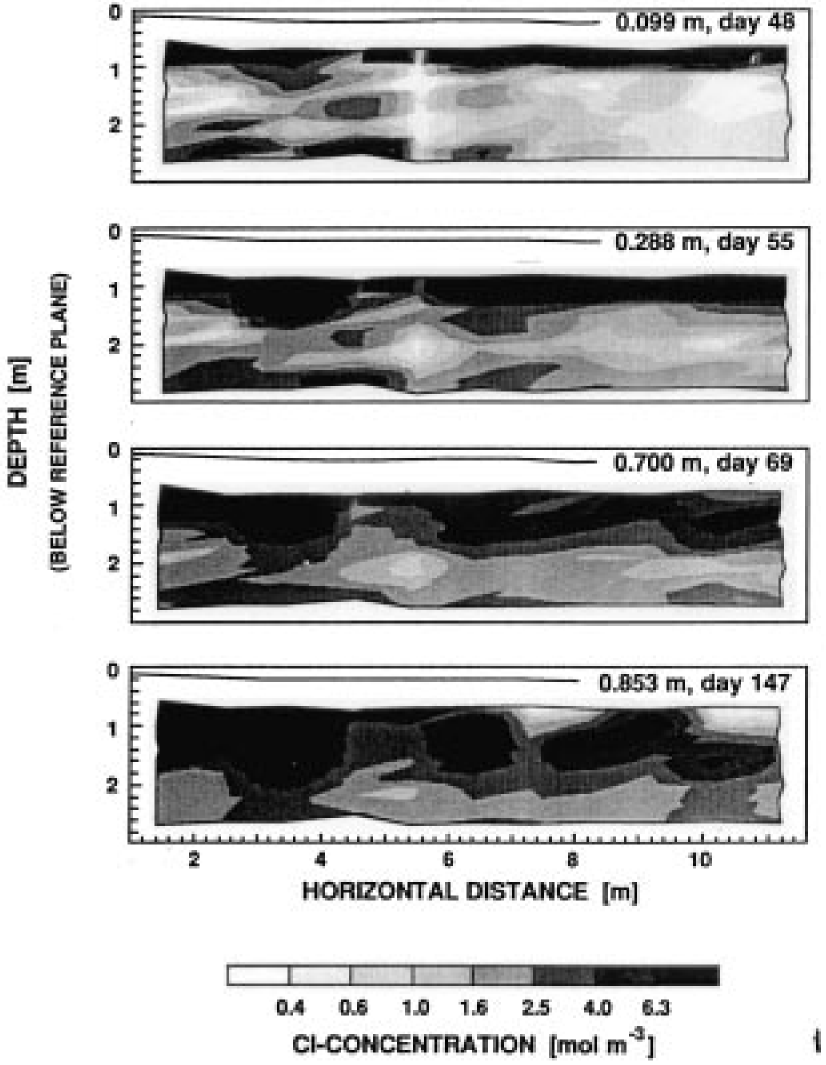

Figure 1. Spatial distribution of tracer after various values of cumulative infiltration (Roth *et al.*, 1991).

Statistical and mathematical approaches to unsaturated transport have demonstrated that variation in hydraulic conductivity, water flux, pore water velocity and dispersion produce substantial variations in water and solute distribution in the soil profile (Wagenet, 1985). Large variations in soil water and solute distributions have also been documented in experimental field studies (Biggar and Nielsen, 1976; Van de Pol *et al.*, 1977; Butters *et al.*, 1989). These field results indicate a three dimensional transport process with a wide distribution of local velocities.

Where present, heterogeneities introduced by macropores can have a significant impact in the transport process. Infiltration and flow through macropores can be substantially different from that in relatively homogeneous material (Bouma, 1981; Nielsen *et al.*, 1986). Roth *et al.* (1991) documented preferential pathways for tracer transport in a structured, layered soil along a 12 m long, 2.4 m deep trench wall. Some of the results of that study are illustrated in Figure 1. The results indicate a highly irregular solute movement pattern. In many areas of the cross-section, order-of-magnitude variations in tracer concentrations occur over distances of only a few tens of centimeters.

Variations in soil properties and transport characteristics have important implications for instrument spacing in a vadose zone monitoring network. To adequately characterize spatial variability in soil transport properties and contaminant concentrations in a heterogeneous soil, a vadose zone monitoring network may require an instrument spacing on the order of 0.1 m in the vertical direction and 1.0 m in the horizontal direction. The spatial resolution in instrument spacing required for detailed characterization of contaminant concentrations may be unattainable in many cases due to limited financial resources. Larger instruments can be deployed to provide greater detection capability, while sacrificing characterization potential. For example, pan type lysimeters may be more appropriate than suction cup lysimeters for detecting contaminants in structured soils containing numerous macropores.

The domain of influence of individual sampling devices should be considered when designing monitoring networks. For many subsurface detectors, the sphere of influence is not well known. Consequently, determining the number and depths of sampling devices requires subjective, professional judgement. The range of influence of suction lysimeters is less than one meter (USEPA, 1987). A horizontal sampling horizon consisting of uniformly spaced suction cup lysimeters used for release detection may be particularly ineffective directly beneath a contaminant source. However, the same horizon could be more effective further downward if conditions dictated an increase in plume size with depth.

Monitoring wells tapping perched groundwater provide integrated, bulk samples which are more representative of regional conditions than are small point samples (Wilson and Schmidt, 1978). Because of spatial variability in soil properties, point water samples may not reflect the average chemical composition of a soil solution (Biggar and Nielsen, 1976). Point sampling is particularly inappropriate for determining the regional impacts of diffuse contaminant sources such as irrigation return flow on groundwater (Wilson and Schmidt, 1978).

In addition to defining appropriate sampling locations, a comprehensive vadose zone monitoring program should establish a suitable temporal sampling frequency. Sampling frequency for suction lysimeters depends on factors such as the matric potential in the surrounding porous matrix. Very dry conditions dictate that water enters at a slow rate. As a result, it takes weeks or longer to accumulate a sample size sufficiently large to chemically analyze. Factors which affect the amount of time required for a monitoring device to detect a leak can be addressed by modeling solute transport (USEPA, 1987). Sampling frequency cannot be explicitly defined until field units are installed and operating. Lysimeters and perched groundwater should be sampled weekly, or as frequently as possible, until quality trends are established. Thereafter, samples could be obtained at greater time intervals (Everett, 1985).

The potential for aliasing should be considered when defining a temporal sampling frequency (Quinlan *et al*., 1992). Aliasing occurs when the sampling interval is not small enough to properly characterize short-term fluctuations in water quality. This problem can lead to erroneous interpretations of water quality trends.

4. Hydrogeologic Considerations

Hydrogeologic information is fundamentally important to designing subsurface monitoring networks. Complex spatial variations in soil properties often lead to non-uniform contaminant migration which must be accounted for in the network design process. It is generally infeasible to characterize details in heterogeneous aquifers by direct mapping due to the excessive volume of data which would typically be required. Spatial patterns in aquifer properties can be inferred with an understanding of the geological processes that created the system under study. As these processes are regional in scale, an understanding of regional hydrogeology can facilitate a local-scale analysis.

4.1. REGIONAL CHARACTERIZATION

A regional hydrogeologic characterization can yield information on the geometry of major geologic units and geologic structures, groundwater circulation patterns, and water chemistry. The distribution of major hydrostratigraphic units of varying hydraulic conductivity influences spatial variations in groundwater velocity which, in turn, influence the choice of appropriate monitoring strategies. The distribution of perching horizons within the vadose zone is an important consideration in regional scale characterization.

Over a regional scale, groundwater circulation is controlled by the distribution of recharge and discharge areas. These areas can be inferred from variations in topography and from surface features such as vegetation, streams, and lakes. For example, flat sites may induce high infiltration rates and warrant detailed vadose zone monitoring, both beneath and immediately downgradient of the waste cells. Depth to groundwater, storage and attenuation characteristics, and geologic characteristics of the vadose zone in recharge areas influence regional circulation transit times, which can be used to assess natural attenuation and migration patterns.

Observations of regional groundwater chemistry, a function of rock-water interactions along flow paths, can elucidate the potential for geochemical and biological attenuation of contaminants. Within this context, vadose zone monitoring devices may document chemical evolution patterns of water percolating through the vadose zone in groundwater recharge areas.

4.2. SITE SPECIFIC CHARACTERIZATION

The detection and characterization capability of a vadose zone monitoring network should be applicable to a variety of site hydrogeologic conditions. Early release detection is important in shallow groundwater systems due to short travel times and a low potential for pollutant attenuation. But early detection is also important for a deep groundwater condition, because travel times are typically long (decades or centuries) (Wilson and Schmidt, 1978), storage potential is high, and massive amounts of leachate would be required before the onset of groundwater quality degradation. Quality degradation would reflect pollution a substantial time after it was initiated. By this time, the groundwater system would have been essentially destroyed.

Site-specific hydrogeologic information determines the configuration of sampling locations that will provide effective detection and characterization capability in a local-scale monitoring program. Contaminant migration pathways are controlled by site geology, which influences soil and aquifer properties. Geostatistical methods can be used to estimate inter-sampling point heterogeneity and uncertainty in complex environments (Journel and Huijbregts, 1978). These methods have been applied effectively to both saturated and unsaturated environments. However, in extremely complex environments such as karst aquifers, poorly defined or unknown migration pathways may dictate a need for tracer tests to assess the suitability of well locations (Quinlan *et al.*, 1992). Successful site description requires an integrated approach consisting of several tasks including geologic characterization, borehole and surface geophysics, measurement of hydraulic properties, stochastic estimation of heterogeneity, and modeling of unsaturated and saturated flow and transport. Such a comprehensive analysis typically requires the input of several specialists.

The vadose zone component of a site-specific analysis should yield information on various soil properties, such as hydraulic conductivity at various degrees of saturation, soil water characteristic curves, porosity, field capacity, and soil attenuation properties. The analysis should also provide information on hydrogeologic characteristics such as the distribution of perching horizons and depth to groundwater across a site. Effective perching layers can retard vertical flow and transmit fluid laterally, in many cases well beyond the actual boundaries of a contaminant source. Field studies have shown that perching layers intercepting downward moving water may transmit the water laterally at substantial rates (Wilson, 1971). The information outlined above can be used to infer contaminant flux rates and storage characteristics, which have bearing on both spatial and temporal sampling frequency. For example, high vadose zone flux rates, low storage potential, and low contaminant attenuation capability dictate a need for frequent sampling at vadose zone monitoring sites distributed throughout the interval from ground surface to the main water table and for an early initiation of groundwater sampling. If attenuation rates are high, large spatial variations in contaminant concentrations will likely occur within a shallow depth. A relatively dense arrangement of vacuum-operated lysimeters would be warranted in near surface horizons to characterize such variations.

The presence of macropores should also be assessed in the site-specific characterization. Macropore flow (i.e., the rapid transmission of free water through large, continuous pores or channels) can greatly accelerate net transit time to groundwater (Bouma, 1981; Nielsen *et al*., 1986). Macropores can be formed by several mechanisms, including channels along root cavities, animal and insect burrows, fractures in semi-consolidated soils, and ‘stringers’ of highly conductive material in heterogeneous soils. In bedrock vadose zones, the presence of fractures should be thoroughly assessed, as these features constitute important potential preferential contaminant migration pathways. Vadose zone monitoring in fractured rock systems requires a higher density of sampling units to compensate for extreme spatial variability of fluid transport (Everett *et al*., 1983). Trench excavations are typically required to facilitate a detailed assessment of in-situ soil or rock structure.

Site-specific hydrogeologic considerations also determine the suitability of various sampling methods. For example, soil gas surveys are best-suited for large, coarse-grained deposits with minimal organic carbon (Marrin, 1988). Coarse grained deposits are generally less susceptible than fine-grained deposits to partitioning, adsorption, and biodegradation, which can reduce concentrations in the vapor phase to levels that cannot be detected. Suction cup lysimeters are commonly used for vadose zone sampling. However, in cases where the site hydrogeologic analysis indicates that unsaturated hydraulic conductivity is very low, ceramic lysimeters may be inappropriate, as it takes too long to collect a sample.

5. Case Study

This section illustrates a local-scale, post-contamination monitoring network that was designed for a gasoline-contaminated site in Santa Barbara County, California, U.S.A. Deposits underlying the site (Figure 2) consist of unconsolidated sand, silt, and clay. The study focused on Property A (Figure 2). Prior to the study, areas designated Source A and Source B were each occupied by three 10 000-gallon underground gasoline storage tanks. Test results and observations made during tank removal indicated leaks in fuel piping at Source A. During the course of the study, a gasoline contamination problem was known to exist at Property B. Groundwater contamination and accumulation of free product had been confirmed in the area beneath Source B, but the extent of contamination was unknown. Boreholes were drilled around the vicinity of Source A to characterize underlying stratigraphy and

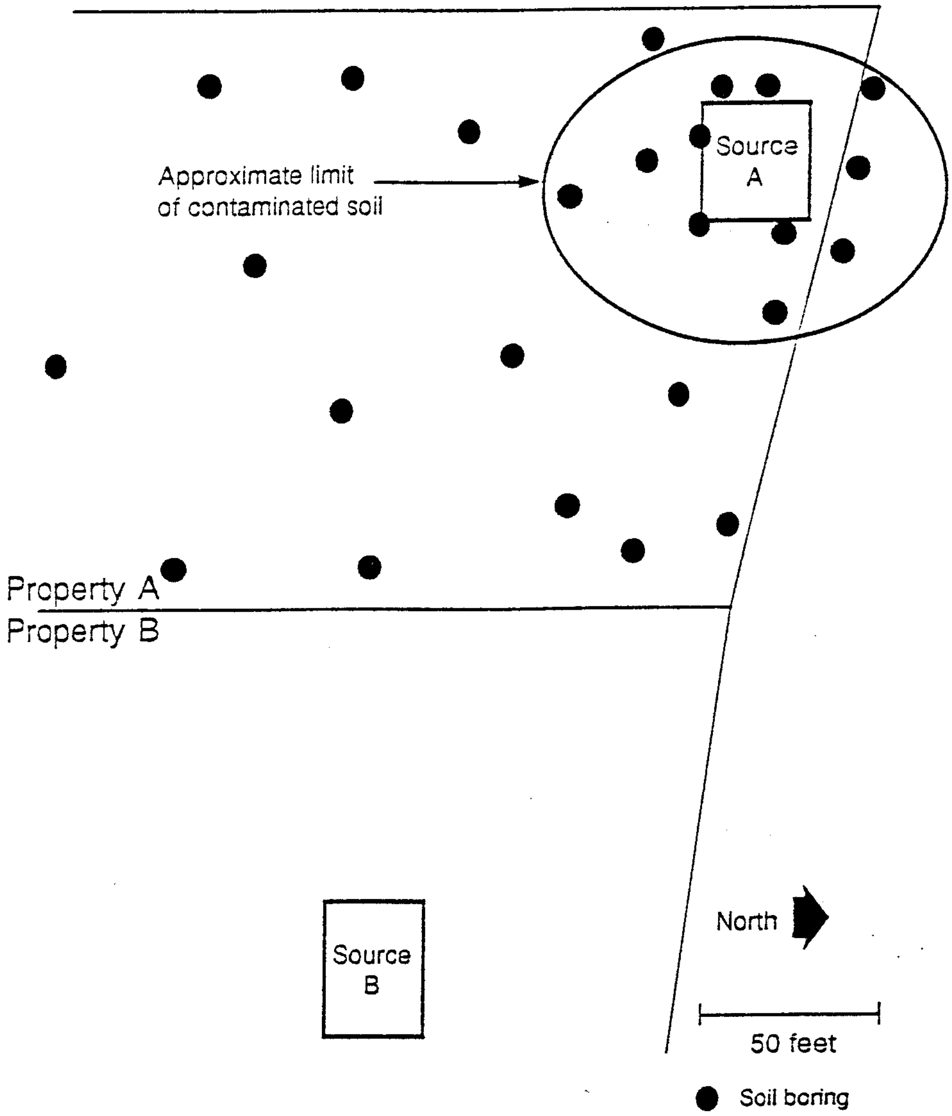

Figure 2. Map of study area illustrating locations of property lines, gasoline tank storage areas (Source A, Source B), soil boring locations, and extent of soil contamination; 1 foot = 0.31 m.

assess the extent of soil contamination (Figure 2). Split-spoon borehole samples were obtained at 5-foot (1.5 m) intervals from ground surface to the water table, approximately 50 feet (15 m) below ground surface. Samples were screened in the field with an organic vapor detector. Selected soil samples were then sent to an analytical laboratory for analysis of the presence of gasoline constituents such as benzene and toluene. The results were used to assess the spatial extent of soil contamination, as shown in Figure 2.

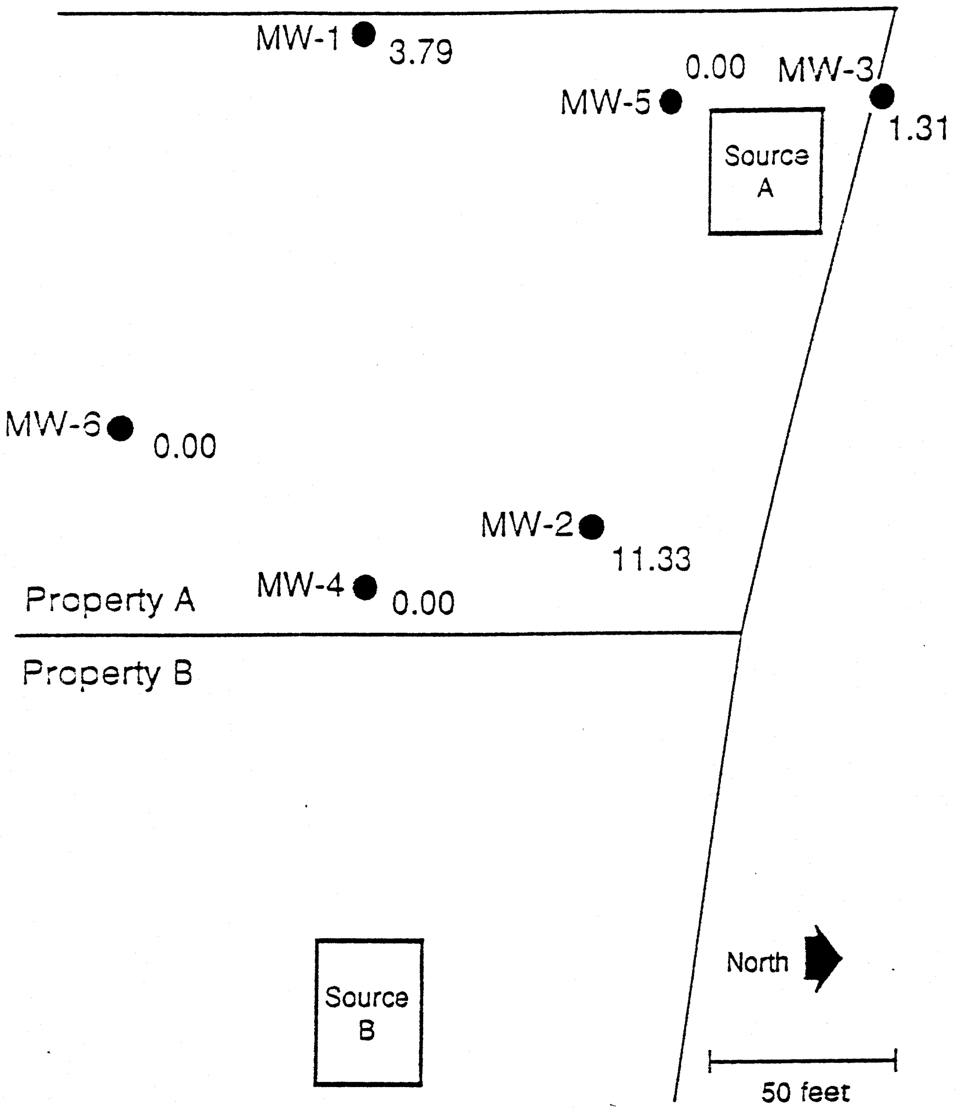

Figure 3. Locations of monitoring wells (dots), and product thickness values measured in wells (numbers next to dots, in feet); 1 foot = 0.31 m.

Six monitoring wells were drilled to establish the shape of the water table and the possible extent of free product accumulation (Figure 3). The areal extent of contamination above the water table, established by vadose zone monitoring, extends beyond the boundaries of Source A. This indicates lateral spreading with downward migration and a potentially large extent of free product accumulation. Free product was detected in three of the wells (MW-1,2,3) in thicknesses ranging from approximately 1–11 feet (0.3–3 m) (Figure 3). No product was encountered

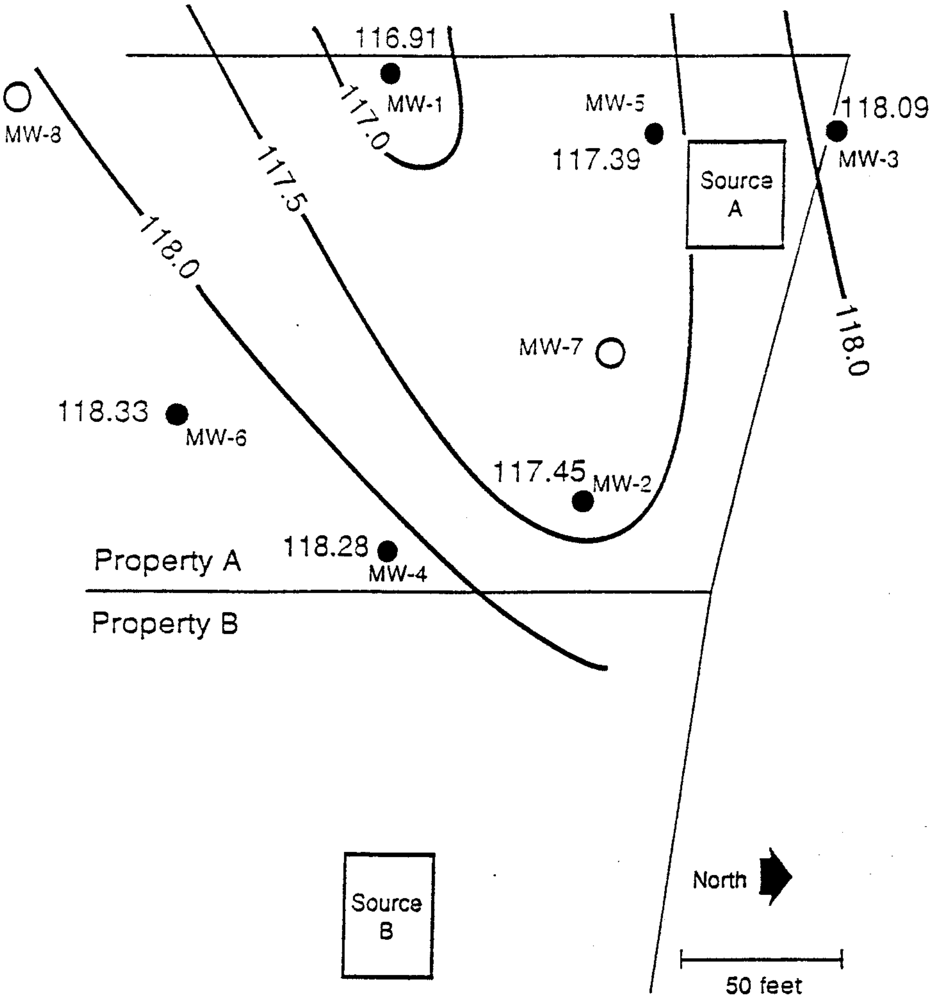

Figure 4. Water table configuration inferred from measurements at six monitoring wells and locations of confirmation wells (circles); elevations in feet above mean sea level; 1 foot = 0.31 m.

in the remaining wells. The shape of the ambient (undisturbed) water table was assessed from measurements at all six wells, applying correction factors (Testa and Pacskowski, 1989) to the wells containing free product (Figure 4).

Several conclusions can be drawn from the combined vadose and saturated zone observations. (1) Vadose zone contamination extends beyond the excavation pit boundaries. (2) Free product near well MW-2 most likely originated from Source B. (3) Product at well MW-1 could have originated from Source A and/or B. A plume originating at Source A and moving southward would be narrow in an east-west direction, or may have already moved past well MW-5 (based upon an absence of free product at that well). (4) Source B probably did not contaminate the area around well MW-3. The proximity of this well to Source A suggests that Source A is the more likely origin for the observed free product. Even though well MW-3 is hydraulically upgradient of the source, it could still be contaminated by lateral spreading of product within the vadose zone prior to accumulation on and within the capillary fringe. (5) Assuming that the free product in well MW-2 originated from Source B, and given the large amount of product encountered in this well, it is likely that a plume originating from Source B extends further west, along the axis of the water table trough. Furthermore, the axis of the trough is a low area in the water table that would attract a thick accumulation of free product. It would be a good area in which to focus remedial efforts.

Two additional wells were installed to provide more detail on the spatial distribution of free product accumulation. The locations of these wells are illustrated in Figure 4. Well MW-7 was drilled in the central area of the trough to provide data that might verify this area as a zone of free product accumulation. The second well (MW-8) was drilled near the southwest end of the site to provide information regarding the lateral extent of contamination. As expected, a relatively thick accumulation of free product, 7.11 feet (2.14 m), was detected in well MW-7. No product was observed in well MW-8. Based on these findings, the area along the axis of the water table trough, particularly the area around well MW-2, was recommended for focusing remedial action.

6. Conclusions

Vadose zone devices are an important component of a comprehensive subsurface monitoring program. The fundamental roles of vadose zone monitoring can be described in general terms as detection and characterization. For a given application, the role of vadose zone monitoring is dependent on several factors, including the overall objective of the monitoring program. There are four broad objectives for groundwater quality monitoring programs: source monitoring, compliance monitoring, ambient monitoring, and research monitoring. In practice, most network design problems involve source or compliance monitoring. In source groundwater monitoring programs, the primary role of vadose zone monitoring is to provide an early warning of groundwater pollution. A secondary role is to characterize the spatial extent of contamination above the main water table. This information can be used to assess the adequacy of existing groundwater monitoring well locations and guide the placement of new monitoring wells. In compliance monitoring programs, documented vadose zone contamination can be used to evaluate the possible extent of groundwater contamination and guide the placement of groundwater monitoring wells.

The objective of a groundwater monitoring program dictates the spatial scale of the sampling network. Instrument spacing is influenced by variations in soil properties and transport characteristics. Numerous experimental field studies attest to a high degree of spatial variability in unsaturated soil transport characteristics, even for apparently homogeneous soils. In designing a vadose zone monitoring network, one must examine trade-offs between the detailed spatial resolution offered by point sampling and the detection capability offered by larger instruments which yield integrated bulk samples. In most cases, a combination of different sampling devices is appropriate.

References

Bear, J.: 1979, *Hydraulics of Groundwater*, McGraw-Hill, N.Y.

Biggar, J. W. and Nielsen, D. R.: 1976, ‘Spatial variability of the leaching characteristics of a field soil’, *Water Resources Research* **12**(1).

Bouma, J.: 1981, ‘Soil morphology and preferential flow along macropores’, *Agricultural Water Management* **3**.

Butters, G. L., Jury, W. A. and Ernst, F. F.: 1989, ‘Field scale transport of bromide in an unsaturated soil, 1, Experimental methodology and results’, *Water Resources Research* **25**(7).

Byers, E. and Stephens, D. B.: 1983, ‘Statistical and stochastic analysis of hydraulic conductivity and particle-size in a fluvial sand’, *Soil Science Society of America Journal* **47**.

Cullen, S. J., Kramer, J. H. and Luellen, J. R.: 1995, ‘A systematic approach to designing a multiphase unsaturated zone monitoring network’, *Ground Water Monitoring and Remediation*, Summer Issue.

Everett, L. G. and Wilson, L. G.: 1984, *Permit Guidance Manual on Unsaturated Zone Monitoring for Hazardous Waste Land Treatment Units*. U.S. Environmental Protection Agency, Washington, DC.

Everett, L. G.: 1985, *Groundwater Monitoring Handbook for Coal and Oil Shale Development*, Elsevier, Amsterdam.

Everett, L. G., Wilson, L. G. and McMillion, L. G.: 1982, ‘Vadose zone monitoring concepts for hazardous waste sites’, *Ground Water* **20**(3).

Gelhar, L. W. and Axness, C. L.: 1983, ‘Three-dimensional stochastic analysis of macrodispersion in aquifers’, *Water Resources Research* **19**(1).

Hsueh, Y. W. and Rajagopal, R.: 1988, ‘Modeling ground-water quality decisions’, *Ground Water Monitoring Review* **8**(4).

Hudak, P. F., Loaiciga, H. A. and Marino, M. A.: 1995, ‘Regional-scale ground water quality monitoring via integer programming’, *Journal of Hydrology* **164**(1/4).

Journel, A. G. and Huijbregts, C. J.: 1978, *Mining Geostatistics*, Academic Press, London.

Karp, K. E.: 1990, ‘A surface-flux measurement method for screening contamination from volatile organic compounds’, *Groundwater Monitoring Review*, Summer Issue.

Kirschner, F. E. and Bloomsburg, G. L.: 1988, ‘Vadose zone monitoring: An early warning system’, *Groundwater Monitoring Review* **8**(2).

Loaiciga, H. A., Charbeneau, R. J., Everett, L. G., Fogg, G. E., Hobbs, B. F. and Rouhani S.: 1992, ‘Review of groundwater monitoring network design’, *Journal of Hydraulic Engineering* **118**(1), 11.

Mackay, D. M., Freyberg, D. L., Roberts, P. V. and Cherry, J. A.: 1986, ‘A natural gradient experiment on solute transport in a sand aquifer, 1. Approach and overview of plume movement’, *Water Resources Research* **22**(13).

Marrin, D. L.: 1988, ‘Soil-gas sampling and misinterpretation’, *Groundwater Monitoring Review* **8**(2).

Nielsen, D. R., van Genuchten, M. T. and Biggar, J. W.: 1986, ‘Water flow and solute transport processes in the unsaturated zone’, *Water Resources Research* **22**(9).

Quinlan, J. F., Davies, G. J. and Worthington, S. R. H.: 1992, 'Rationale for the design of cost-effective groundwater monitoring systems in limestone and dolomite terranes: Cost-effective as conceived is not cost-effective as built if the system design and sampling frequency inadequately consider site hydrogeology', in Proceedings, Waste Testing and Quality Assurance Symposium, American Chemical Society.

Robbins, G. A., Deys, B. G., Temple, M. R., Stuart, J. D. and Lacy, M. J.: 1990, 'Soil gas surveying for subsurface gasoline contamination using total organic vapor detection instruments, Part 1, Theory and laboratory experimentation', *Groundwater Monitoring Review*, Summer Issue.

Roth, K., Jury, W. A., Fluhler, H. and Attinger, W.: 1991, 'Transport of chloride through an unsaturated field soil', *Water Resources Research* **27**(10).

Russo, D. and Jury, W. A.: 1987, 'A theoretical study of the estimation of the correlation scale in spatially variable fields, 1, Stationary fields', *Water Resources Research* **23**(7).

Testa, S. and Pacskowski, M.: 1989, 'Volume determination and recoverability of free hydrocarbon', *Groundwater Monitoring Review* **9**(1).

Todd, D. K., Timlin, R. M., Schmidt, K. D. and Everett, L. G.: 1976, Monitoring Groundwater Quality: Monitoring Methodology. United States Environmental Protection Agency, Las Vegas, N.V.

USEPA (United States Environmental Protection Agency): 1986, RCRA Groundwater Monitoring Technical Enforcement Guidance Document. U.S. Environmental Protection Agency, Washington, D.C.

USEPA (United States Environmental Protection Agency): 1987, Processes Affecting Subsurface Transport of Leaking Underground Tank Fluids. CR810052.

Van de Pol, R. M., Wierenga, P. J. and Nielsen, D. R.: 1977, 'Solute movement in a field soil', *Soil Science Society of America Journal* **41**(1).

Wagenet, R. J.: 1985, 'Measurement and interpretation of spatially variable leaching processes', in *Soil Spatial Variability*, Pudoc-Wageningen, The Netherlands.

Wilson, L. G. and Schmidt, K. D.: 1978, 'Monitoring perched groundwater in the vadose zone', in *Establishment of Water Quality Monitoring Programs*, American Water Resources Association, Herndon, V.A.

Wilson, L. G.: 1971, 'Observations on water content changes in stratified sediments during pit recharge', *Ground Water* **9**(3).