CHAPTER 5

HYDROGEOLOGIC SITE INVESTIGATIONS

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5.1 INTRODUCTION

The purpose of hydrogeologic site investigations is to characterize soil and ground water pollution problems in sufficient detail to facilitate design of a cost-effective corrective action program. For this purpose, the site investigation entails measurement of the physical parameters that control subsurface contaminant transport at a given site. Geologic, hydrologic, and chemical data must be acquired and integrated to define the nature and extent of soil and ground water contamination and the potential for migration of contaminants within the natural ground water flow system. To the extent practical, the remedy should be anticipated at the outset of an investigation so that design-basis information necessary for development of the corrective action program is obtained in a timely and cost-effective manner.

The preceding chapters of this book have reviewed the general principles of ground water occurrence and flow within geologic formations and the nature of the most common ground water contaminants. In this chapter, the engineering procedures involved in the acquisition and interpretation of ground water flow and contaminant information will be addressed. The following sections outline a systematic approach to planning and implementing soil and ground water contamination studies and summarize engineering standards for data evaluation and presentation.

5.2 DEVELOPMENT OF CONCEPTUAL SITE MODEL

Hydrogeologic processes are, by nature, complex, due to the heterogeneities of geologic formations and the transient effects of aquifer recharge and discharge phenomena. Additional complexity arises from the presence of contaminants that may be irregularly distributed in, and reacting with, subsurface formations and ground water. Consequently, detailed characterization of contaminant distribution and transport patterns throughout every inch of an aquifer system is impractical. From an engineering perspective, our objective is therefore to define subsurface contaminant transport processes to the degree necessary to allow us to design effective measures for control or reversal of these processes, as needed to protect public health and the environment.

Ultimately, protection of drinking water resources may require us to extract or "mine" the contaminated ground water mass from the affected aquifer. Therefore, it is helpful to approach a ground water contaminant delineation study in much the same manner as prospecting for hydrocarbons or precious metals. We do not need to know each twist and turn of every minor "ore" seam, but we do want to know how wide and how deep the play runs and, because our "ore" is a fluid, which way it is moving and how fast.

The hydrogeologic site investigation is the procedure by which we develop our understanding or our "working model" of contaminant plume migration within the ground water flow regime. In all cases, this model of the subsurface environment is constructed of three principal components of information:

1. **Geology**: the physical framework within which subsurface fluids collect and flow;
2. **Hydrology**: the movement of fluids through this physical framework; and
3. **Chemistry**: the nature of the chemical constituents that are entrained in this flow system and the chemical and physical interactions between the contaminants and the subsurface formation and ground water that may be occurring.

We build our model of the site by systematically addressing each of these principal components in turn. First, we must characterize the stratigraphic profile beneath the site and identify those strata serving as potential conduits for fluid flow and the geologic features that may influence the movement and accumulation of nonaqueous phase liquids (NAPLs). Second, we must measure the fluid hydraulic head distribution within the zone of saturation to determine the actual rate and direction of ground water movement through these conduits. Third, water samples are collected and analyzed to map the lateral and vertical extent of contaminant migration within the ground water flow regime.

There is significant overlap in the acquisition of these three classes of data, and in practice, they are collected simultaneously. For example, a soil boring may be drilled to characterize the geology of the site; it provides soil samples for laboratory analysis of contaminant concentration; and it may be converted to a monitoring well to permit collection of ground water samples and hydrologic data. A well designed site investigation will maximize the relevant information collected during each step of the work program. It is then the job of the project engineer or scientist to sort this information into a meaningful and accurate picture of subsurface ground water flow and contaminant transport processes.

5.3 STRATEGY FOR HYDROGEOLOGIC SITE INVESTIGATIONS

5.3.1 Overview and General Considerations

As a practical matter, site investigation workplans usually represent a compromise between the ideal of knowing as much as possible about a site and the realities imposed by a finite budget. For the purpose of economy and efficiency, every field and laboratory measurement conducted during the investigation must contribute to the conceptual model of the site. The key is to design a work program that provides the necessary data by making the maximum use of the available resources.

To achieve project objectives in a cost-effective manner, a clear strategy for mapping the contaminant zones must be established prior to commencement of field or laboratory work. At the outset, all available site information concerning subsurface geology, ground water flow, and the nature, extent, and timing of the contaminant release should be assembled to guide the selection of sampling locations. Data quality objectives and appropriate sampling and testing technologies must be identified to ensure collection of data that meet not only the engineering, but also the regulatory requirements of the project.

As a basis for a site investigation strategy, all subsurface contaminant problems should be viewed as two distinct zones of contamination: (1) contaminant source materials and contaminated soils in the unsaturated soil (or rock) zone; and (2) nonaqueous phase liquids (NAPLs) and/or ground water containing dissolved contaminants within the zone of saturation (Figure 5.1). For practical purposes, we can define the vertical boundary between these two zones as the surface of the uppermost water bearing unit beneath the site (e.g., a water-saturated stratum with hydraulic conductivity, $K \geq 1 \times 10^{-4}$ cm/sec). These two zones differ significantly in terms of their operant mechanisms of contaminant transport and the requisite corrective actions, and therefore should be addressed individually in the course of the hydrogeologic site investigation.

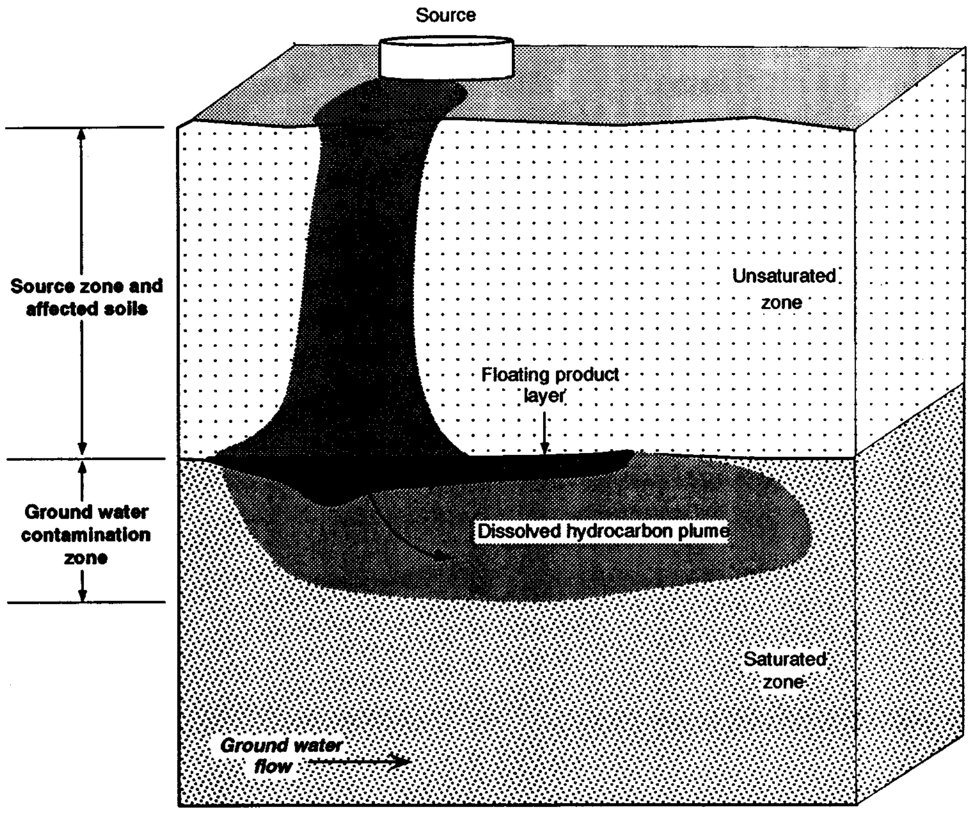

Figure 5.1 Zones of contamination for two-stage site investigation approach.

5.3.2 Unsaturated Source Zone Characteristics

Most incidents of hazardous chemical release to the subsurface environment occur as surface spills of products or wastes or leachate percolation from the base of waste landfills, surface impoundments, or material stockpiles. As the wetting front percolates downward through the unsaturated soil (or rock) zone underlying the source area, a significant portion of the contaminant mass may be retained in the unsaturated soil matrix due to the effects of filtration, sorption, or capillary retention. For many years thereafter, this contaminated soil can serve as a source of continuing contaminant release to stormwater flowing across the site surface or percolating downward through the unsaturated soil zone to the depth of underlying ground water.

Depending on the size and geological characteristics of this residual source zone and the nature and concentration of the contaminants, protection of surface water and ground water

resources could involve either complete excavation and removal of the contaminated soils, capping of the site to minimize rainfall contact and precipitation, or contaminant extraction by means of in-situ soil venting or rinsing. To support design of appropriate corrective measures, the hydrogeologic site investigation must therefore address the full lateral and vertical extent of residual contaminants within the unsaturated soil zone and the potential for future release of contaminants to local water resources.

5.3.3 Ground Water Plume Characteristics

Dissolved contaminants contained in waste leachate fluids penetrating to the depth of ground water occurrence will become entrained in the natural ground water flow system and spread laterally and vertically in accordance with local ground water flow gradients (Figure 5.1). Free-phase liquid contaminants may be subject to an additional "density gradient" with light non-aqueous phase liquids (LNAPLs, such as gasoline) floating atop the zone of saturation and collecting in the structural highs of confined water-bearing units. Alternatively, dense non-aqueous phase liquids (DNAPLs) can percolate downward through the water-bearing stratum to perch and spread atop underlying confining units (Chapter 11).

In all cases, ground water contamination problems are fluid problems. The contaminant enters the ground water system as a fluid and can therefore be removed or controlled as a fluid. Unlike contamination within the unsaturated soil zone, excavation and removal of the soil or rock mass from the zone of ground water contamination is neither practical nor necessary. The hydrogeologic site investigation must therefore provide definitive information on the current lateral and vertical extent of dissolved and free-phase contaminants within the ground water, as well as the hydraulic processes controlling contaminant migration.

5.3.4 Two-Stage Site Investigation Approach

In practice then, the hydrogeologic site investigation proceeds as a two-stage process: (1) delineate the unsaturated source zone, comprised of the chemical waste or product mass and the associated contaminated soils within the unsaturated soil column, and (2) investigate the presence and extent of contaminant migration within the underlying ground water system. Step-by-step strategies for implementation of these source zone and ground water contamination delineation studies are outlined below and illustrated on Figures 5.2 – 5.4.

Procedures for Unsaturated Source Zone Characterization. The objectives of the source zone characterization study are to locate the site of the release, identify the contaminants of concern and determine their concentrations, and delineate the source material or unsaturated soil mass that may act as a continuing source of contaminant release to surface water or underlying ground water. The principal steps required for delineation of the source zone are illustrated in Figure 5.2 and listed below.

As shown on the task flowchart, to commence the delineation study, available chemical information regarding the suspected source of the subsurface release (e.g., waste or product spill) must be compiled to provide a basis for design of the laboratory testing program. If

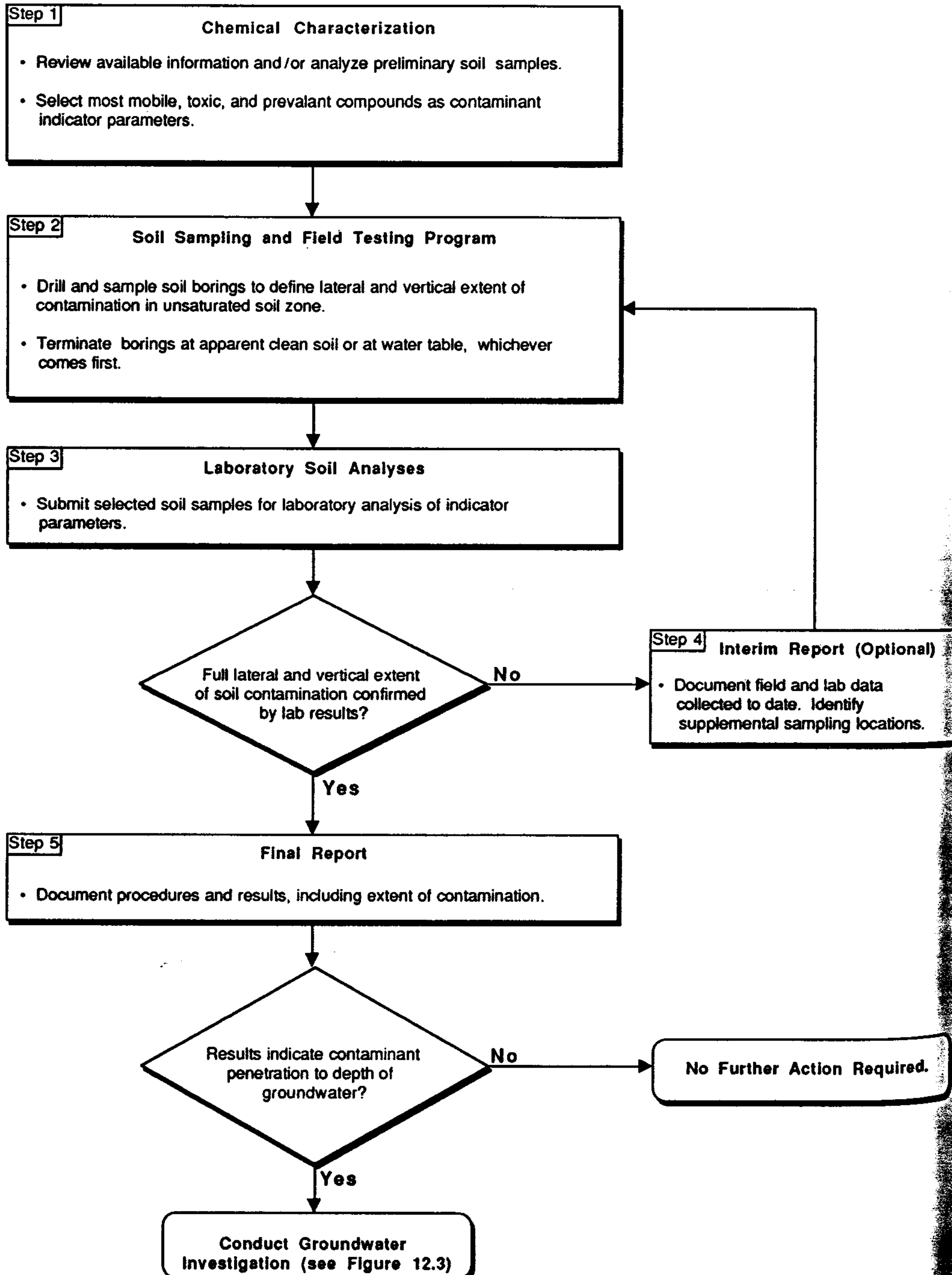

Figure 5.2 Procedures for source zone characterization.

such information is unavailable or inadequate, representative contaminated soil samples should be collected from the release site and analyzed for a broad suite of chemical compounds, as appropriate, to identify the principal contaminants of concern. Appropriate laboratory indicator parameters and field testing procedures should then be selected on the basis of the prevalence, mobility, and toxicity of the principal constituents identified.

In Step 2 of the source delineation, a field sampling and testing program is conducted to define the apparent lateral and vertical extent of contamination within the unsaturated soil zone. At each soil sampling location, sampling and field testing should be conducted continuously with depth until either clean soil or ground water infiltration is encountered. As discussed in Section 5.4, typical field test methods for hydrocarbon contamination include organic vapor headspace analyses and various colorimetric indicator tests.

To confirm the apparent lateral and vertical extent of contamination observed in the field, samples of the uppermost "clean" soils encountered at each sampling location should be submitted for laboratory analysis of indicator parameter content (see Step 3, Figure 5.2). Representative samples from within the contamination zone should also be submitted for analysis of total and leachable contaminant indicator concentrations in order to characterize contaminant mass and mobility.

Delineation of the contaminated soil zone is an iterative process, often requiring two or more field and laboratory cycles for completion. Should the results of the source zone investigation show contaminants to have penetrated to the depth of underlying ground water at concentrations exceeding relevant cleanup standards, a ground water contamination study will also be required.

Procedures for Ground Water Contaminant Plume Delineation. The objective of a ground water contaminant investigation is to determine the presence and extent of dissolved or free-phase contaminants, as well as the likely rate and direction of contaminant migration within the ground water flow system. Principal steps to be followed are shown on Figures 5.3 and 5.4.

As indicated on the task flowchart, the ground water investigation must be preceded by identification and characterization of all potential source zones in the study area. A detection monitoring program, involving installation of 1 to 3 ground water sampling points at each known or suspected source location, should then be completed to identify all sites of hazardous constituent release to ground water.

Ground water plume delineation should be conducted in a step-wise procedure in order to minimize the number of ground water sampling points required. First, based upon the suspected age of the release and the lateral ground water seepage velocity determined during the detection monitoring study, estimate the potential length of the contaminant plume (i.e., seepage rate × time = length) and space sampling points accordingly along the plume axis to locate the actual downgradient boundary. Second, to define the width of the contaminant plume, complete additional sampling points on 1 or 2 lines running transverse to the plume axis. Finally, to determine the vertical limit of contaminant migration, collect and analyze ground water samples from "nested" sampling points (i.e., samples collected in close lateral proximity, e.g., < 10 ft distance, but from different discrete depths within the water-bearing unit).

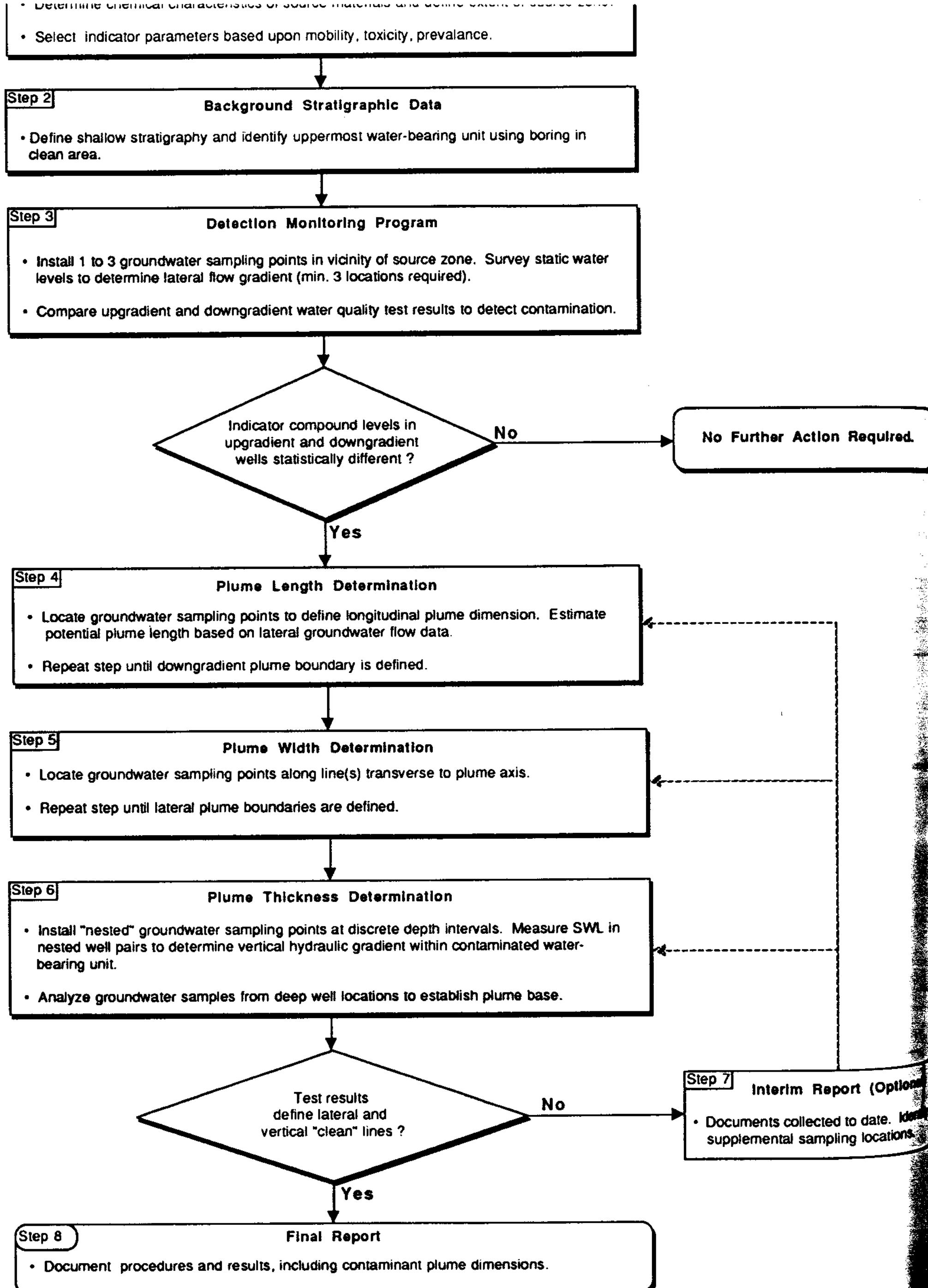

Figure 5.3 Procedures for ground water contaminant plume detection/delineation.

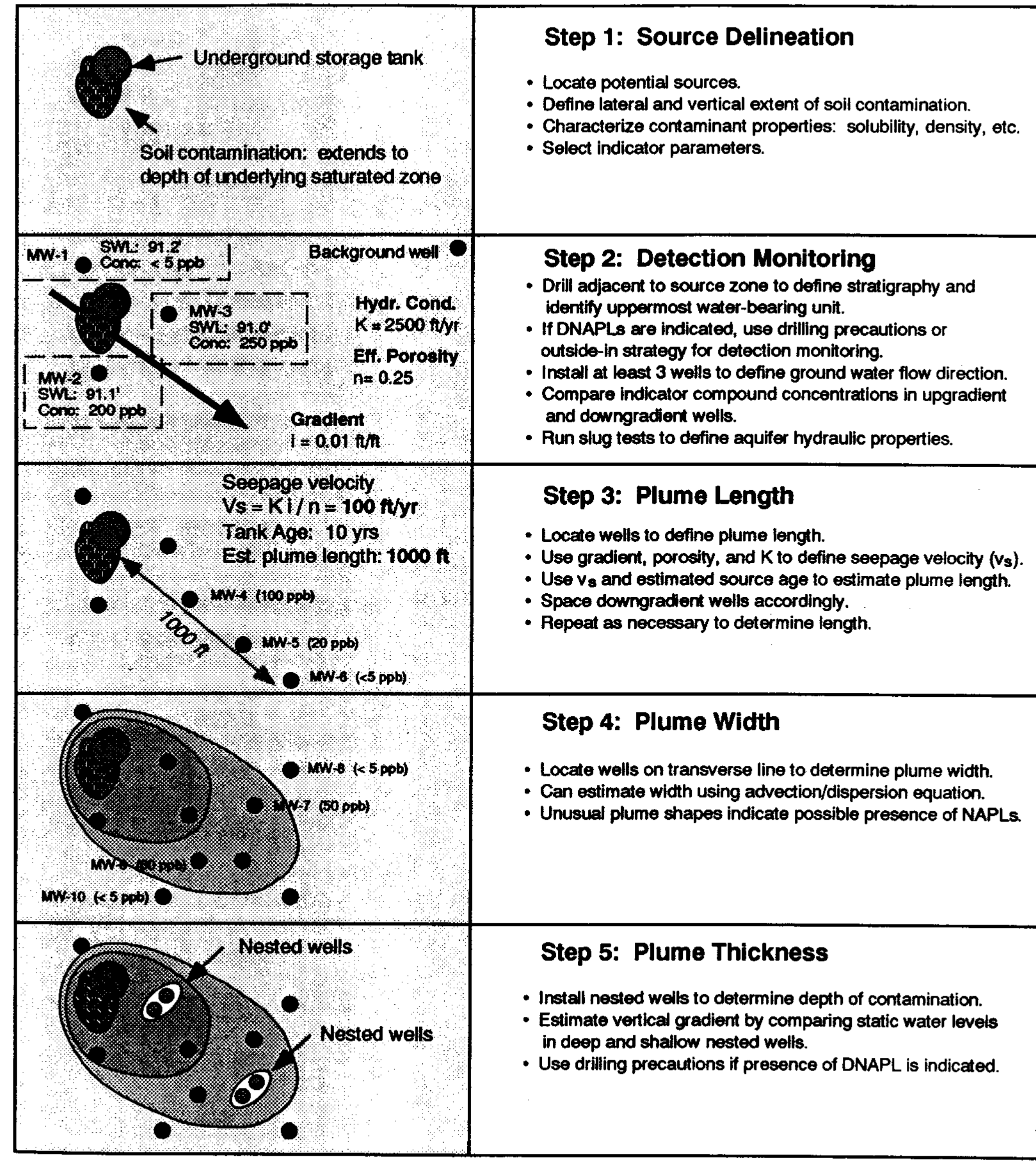

Figure 5.4 Typical work program for ground water plume delineation.

If the contaminant plume is found to extend through the full thickness of the uppermost water-bearing unit, sampling and analysis of ground water from the next underlying water-bearing stratum may be necessary to establish the vertical limit of contamination. In such case, it is critical that any observation points penetrating the confining layer separating

Apart from the inherent disadvantage of any indirect measurement (i.e., that the data are subject to interpretation), the major disadvantage of the cone rig is its size and weight, which can limit its mobility, particularly on unpaved sites.

5.6.7 Borehole and Surface Geophysical Methods

Subsurface geological conditions can also be evaluated indirectly using a variety of geophysical methods. Geologic strata or other buried features are differentiated by measuring the contrasting responses of differing geologic materials to physical forces such as electricity, magnetism, or seismic energy, or by measuring physical properties inherent in earth materials such as naturally occurring radioactivity. Geophysical methods are broadly divided into surface methods and borehole methods. Zohody et al. (1984) and Keys and MacCary (1971) provide guidelines for the applicability, acquisition, and interpretation of surface and borehole geophysical data, respectively.

In surface geophysical surveys, measurements are collected at regularly spaced intervals along a traverse or on a grid to produce a subsurface profile. Examples include conductivity surveys, most commonly used to identify salinity contrasts within an aquifer; magnetometer surveys, frequently used to identify buried drums, tanks, or ordnance, and ground penetrating radar (GPR), useful for identifying large scale buried geological or man-made features. The chief advantage of such methods is that broad regions of the subsurface can be surveyed rapidly in a noninvasive manner.

Borehole techniques utilize a variety of probes or sondes that measure physical properties of the soil or rock or contrasts between the drilling fluid and the fluids in the formation. Methods such as spontaneous potential and natural gamma ray logging are often used in lieu of core sampling to reduce costs, particularly when drilling conditions are difficult and required drilling depths are deep.

Application of surface and borehole geophysical methods to the environmental industry has been limited by the fact that a unique and definitive interpretation of the data is not generally possible. Because identical responses can be caused by a variety of conditions, the use of two or more types of measurements with interpretation by a highly knowledgeable specialist is frequently required to eliminate ambiguity. The need to run numerous tests, especially those employing the more sophisticated techniques, limits the ability of geophysical methods to compete cost-wise with drilling and sampling at shallow depths.

5.7 HYDROLOGIC DATA ACQUISITION

Assessment of the direction and rate of ground water flow beneath a site requires the following hydrologic data: lateral hydraulic gradient, hydraulic conductivity, and effective porosity. Of these, hydraulic gradient and conductivity are obtained by field measurements made in monitoring wells. Effective porosity (i.e., connected pore spaces through which ground water flows) is generally an estimated value (see Chapter 2). Because such determinations are most

commonly made from measurements in piezometers and monitoring wells, we begin with a description of monitoring well construction.

5.7.1 Monitoring Well Construction

The monitoring well is the primary source of hydrologic and ground water quality data used in hydrogeologic site assessments. Most of the special requirements for monitoring well construction are due to their use in the collection of ground water quality data. For collection of hydrologic data, a piece of slotted pipe inserted into a borehole would be sufficient in most instances, but because of the dual purpose monitoring wells serve, careful attention must be paid to the materials used and the methods of construction. Many state environmental regulatory agencies have very particular construction specifications and require that well installation be performed by licensed drillers.

Hydrogeologic site investigations frequently require installation of a permanent monitoring well network to permit resampling and evaluation of changing site conditions. However, monitoring well installation is fairly expensive. To reduce the cost of a ground water plume delineation program, the use of temporary ground water sampling points is becoming increasingly common. A variety of configurations may be installed using a drill rig, direct-push soil probe rig, or cone penetrometer rig to provide samples for lateral and vertical plume delineation in a fraction of the time required to install a well. Following delineation, a relatively small number of permanent wells can be installed at strategic locations and depths to confirm plume boundaries and facilitate future monitoring.

The essential elements of a monitoring well are the well screen and riser, the filter pack, and the annular seal (Figure 5.15). The well screen, typically a section of slotted pipe, allows water to flow from the formation into the well while screening out coarse soil particles. The riser is a solid-walled or "blank" pipe that connects the well screen with the surface. The filter pack, also referred to as the sand or gravel pack, limits the influx of fine surface. The filter pack, also referred to as the sand or gravel pack, limits the influx of fine sediment from the formation. Above the gravel pack, a seal composed of low permeability material prevents fluids from above the screened interval (including percolating rainwater) from entering the well.

Well Design. Monitoring wells should be designed on the basis of the purpose of the well, the hydrogeologic setting, and the expected contaminants in the ground water, as well as cost. Monitoring objectives will determine such factors as the length and placement of the screen interval. Construction materials that are selected should minimize the potential for reaction with the formation fluids and the expected contaminants while providing adequate strength to withstand the pressures exerted by the formation.

For measuring the potentiometric surface, wells screens are positioned to intersect the top of the aquifer in confined flow systems, or to straddle the expected zone of water table fluctuation in unconfined aquifers. Placement of the screen across the top of the water-bearing zone permits detection of floating accumulations of light nonaqueous phase liquids (LNAPLs), while for investigation of dense nonaqueous phase liquids (DNAPLs), intersec-

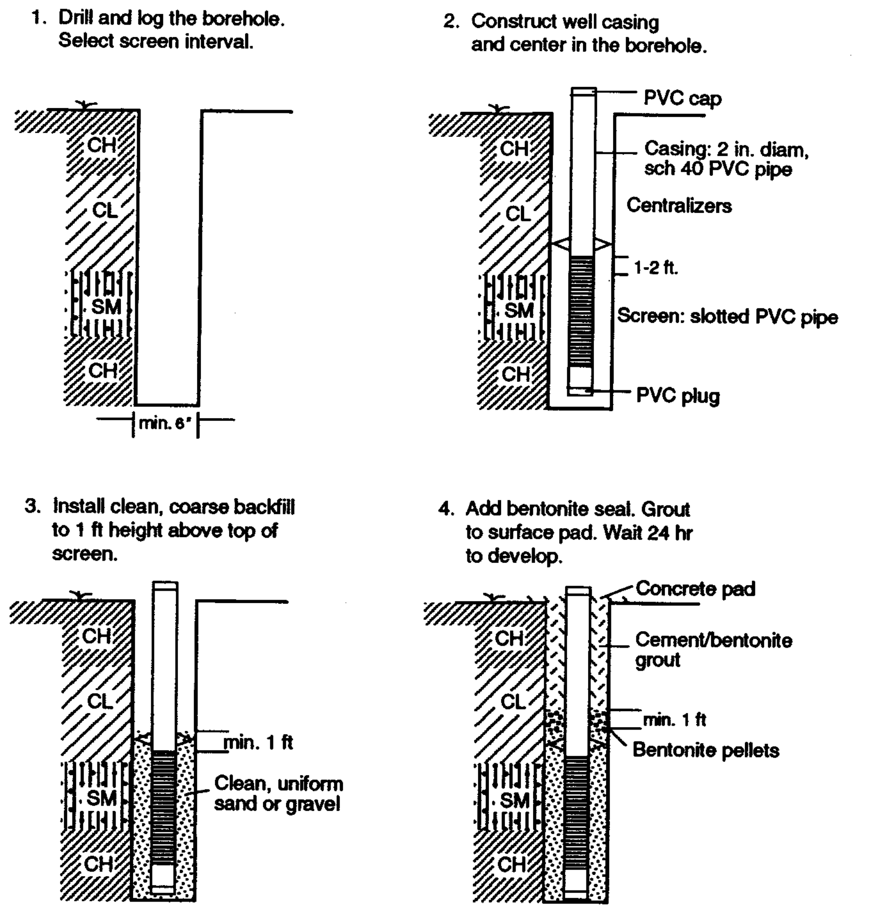

Figure 5.15 Typical monitoring well installation.

tion of the screen with the base of the aquifer is more appropriate. Long screen sections yiel water samples representing an average of conditions across their length; shorter screens (10 f or less) yield more depth-specific data and are generally preferred, since low levels of con tamination present over a limited depth interval may be overlooked due to dilution of the sample by uncontaminated water from elsewhere in the screen interval. In general screens in excess of 15 ft are avoided. Well diameters of 2 in. and 4 in., installed in 6 in. and 10 in diameter boreholes, are most common.

To establish the vertical extent of ground water contamination, it may be necessary t drill monitoring wells through a contaminated upper zone into an uncontaminated lowe zone. In such cases, it is necessary to first install isolation casing, consisting of a length o blank pipe sealed in place with cement or grout to prevent entrainment of contaminants fro

the upper zone to the lower zone during drilling. Once the casing is installed, drilling and well installation are resumed within the casing.

Materials of Construction. Well screens and risers are most commonly constructed of PVC. Threaded joints are generally specified, since the use of glues that contain organic solvents is discouraged. However, PVC reacts with some contaminants and is not always suitable. For example, high concentrations of chlorinated solvents can attack PVC, compromising ground water samples or damaging the well. In addition, the strength of PVC may not be adequate for very deep installations. Stainless steel is frequently used under such conditions, at significantly greater expense. Materials such as Teflon minimize reaction with contaminants, but their use is usually cost-prohibitive. Information on compatibility of various well materials with common contaminants can be found in Driscoll (1986).

Filter packs should be composed of graded silica sand. Blasting sand and other general-use sands may contain minerals that adsorb dissolved metals, potentially compromising the integrity of the ground water sample. The grain size interval of the filter pack material should be selected based on analysis of aquifer grain size distribution as described by Driscoll (1986).

Annular seals are most often composed of bentonite, frequently in combination with other materials. A 1 ft. to 2 ft. thick layer of bentonite pellets is usually placed atop the filter pack to protect the filter pack from invasion by the grout, which completes the seal to the ground surface. Grout may be composed of neat Portland cement, a mixture of cement and powdered bentonite, or other specialty materials such as Volclay.

Installation Procedures. In monitoring well installation, both the drilling and sampling equipment and the well construction materials must be free of contamination to prevent contamination of collection of ground water samples. Drilling equipment should be cleaned with pressurized hot water or steam and detergent, as needed, prior to drilling at each location. Well screen and riser should be packaged and handled to prevent fouling prior to well installation. Drilling and sampling personnel should handle the well pipe with clean gloves.

When wells are drilled using hollow-stem augers, the well screen and riser are lowered within the augers. For rotary drilled wells, the well is lowered within the open borehole. Drilling mud should be thinned by dilution with potable water to the extent practical prior to well installation to facilitate well development. A bottom cap or plug at the base of the well pipe prevents the flow of sediment into the bottom of the well. Silt traps or sumps, consisting of a short section of riser are frequently installed beneath the well screen to prevent fine sediment entering the well from accumulating in and clogging the screened interval. In deeper wells, "centralizers" may be placed above the screen section to maintain distance from borehole wall and ensure proper filter pack placement. Proper placement of the screen should be verified by careful measurement.

Once the screen and riser are in position, the filter pack is installed within the annulus around the well screen (Figure 5.15). The filter pack is generally placed from the base of the well to 1 ft to 2 ft above the top of the screen. In wells drilled by hollow-stem, the filter pack material is usually poured down the inside of the augers. The auger sections are pulled from the hole one at a time as the annulus is filled with sand. In deeper wells and wells drilled by wet rotary methods, it is frequently placed using the tremie method. Potable water is used to wash the filter material down a pipe lowered to the base of the well.

Following placement of the filter pack, the well is sealed to the ground surface to prevent migration of fluids from the surface or water-bearing zones above the screened interval down the borehole. Grout is frequently placed using the tremie method to ensure even placement up the borehole.

Monitoring wells are completed at the surface with a locking caps and/or casing to prevent tampering and a concrete surface pad to protect the annular seal. The elevations of the ground surface and top of well casings should be surveyed relative to a common datum such as mean sea level or an arbitrary datum established by a site benchmark. Top of casing elevations are required to convert depth to water measurements to static water level elevations and should be surveyed to the nearest 0.01 ft, and the point of measurement marked on the top of the well casing.

Well Development Procedures. Following installation, wells are developed to remove fine sediment and drilling mud from the filter pack and ensure collection of ground water samples that are representative of formation conditions, and prevent clogging of the well screen and pump damage. If the well has been installed in a low permeability aquifer using a dry drilling method, bailing out three to ten casing volumes may be sufficient to permit collection of representative ground water samples. If fluids have been introduced during drilling, larger volumes of water must be removed.

Development usually consists of a combination of pumping and surging. Surging the well, by running a close fitting cylinder up and down the inside of the well over the screened interval, causes a back-flushing action in the gravel pack, loosening fine sediment. Pumping from the well (preferably at a rate higher than the expected normal pumping rate) pulls fine sediment through the well screen into the well where it can be pumped to the surface.

5.7.2 Determination of Ground Water Flow Gradients

Ground water flow gradients are determined by measurement of water level elevations in site wells. In addition to the lateral gradient, determined by measurement of wells within the same water-bearing zone, the vertical gradient may be determined by measurement of closely spaced "nested pairs" of wells screened in different aquifers or within the upper and lower portions of the same aquifer. The presence of surface water features should be noted and surface water elevations determined to evaluate possible recharge/discharge relationships. The presence and discharge rate of any pumping wells on site should also be noted.

The water level in each well is measured to the nearest 0.01 ft using an appropriate instrument such as a water-sensitive probe on a graduated tape. The elevation of the potentiometric surface is obtained by subtracting the depth to water from the top of casing elevation. Ideally, water level surveys represent the potentiometric surface at one instant in time. Therefore, measurements should be made in as short a time frame as possible, since water levels within wells respond to such factors as barometric pressure or tidal influence. On sites with large numbers of wells, requiring several hours to survey, the first well measured should be remeasured at the end of the survey to detect possible changes in the potentiometric surface during the period of the survey. If more than one instrument is to be used in the survey, a common well should be measured simultaneously using each instrument to confirm that all instruments give the same reading.

On sites with LNAPLs, the water level survey should also include inspection of wells for the presence floating free-phase layers. If an LNAPL accumulation atop the water column is found, the water level must be corrected for its presence. The thickness of the LNAPL layer, measured with minimal disturbance using an electric interface probe, is multiplied by the specific gravity of the LNAPL (e.g., 0.75 for a typical gasoline). This value is added to the *measured* water level elevation to obtain the *corrected* water level elevation. (Note that the thickness of an LNAPL layer in a well is influenced by a number of factors and typically does not reflect an equivalent accumulation in the adjacent formation).

Upon completion of the survey, water level elevations are plotted on a scaled site map and potentiometric surface contours are drawn, and lateral and vertical flow gradients are determined as described in Section 5.8.

5.7.3 Determination of Hydraulic Conductivity

Slug Tests. Single-well slug tests are a common, cost-effective method for the estimation of hydraulic conductivity in hydrogeologic site assessments. Two major varieties, rising-head tests and falling-head tests can be used. Falling-head tests are more difficult to perform and analyze, and require addition of water to the well. Therefore, rising-head slug tests are more commonly performed.

During a rising-head test, the static water level in the well is first measured and then a "slug," typically a solid cylinder, of known volume is lowered within the well to just below the static level. Following re-equilibration of the water level in the well with that in the aquifer, the slug is removed from the well instantaneously, causing a sudden drop in the water level or head. The return of the water level to static conditions is then monitored. The rising head can be measured by hand in low permeability systems. Higher yield systems may recover too quickly to permit manual collection of the most critical early data, and require the use of pressure transducers placed in the well and monitored with an electronic data logger.

The resultant change in head over time is plotted on semi-log paper, and the curve analyzed according to one of several methods, depending on aquifer and well conditions. The method of analysis will depend on such factors as whether the aquifer is confined or unconfined, and what percentage of the saturated interval is screened in the well. Analytical methods for slug tests are described in Chapter 3.

Slug tests evaluate only the portion of the aquifer immediately surrounding the tested well. Therefore, tests should be performed at a selection of site wells, to best represent the variability in hydraulic conductivity for the aquifer.

Constant-Rate Pump Tests and Well Performance Tests. While slug tests provide reasonable estimates of hydraulic conductivity, they evaluate only the portion of the aquifer immediately adjacent to the well and are generally not adequate for the detailed design of a ground water pumping system. Constant-rate aquifer pumping tests are used to characterize conditions over a larger portion of the aquifer by measuring the response of the aquifer to