United States
Environmental Protection
[illegible]

[illegible]

[illegible]

EPA

RCRA Ground-Water Monitoring Technical Enforcement Guidance Document

RCRA GROUND-WATER MONITORING
TECHNICAL ENFORCEMENT GUIDANCE DOCUMENT
(TEGD)

SEPTEMBER 1986

OVERVIEW

This publication, entitled the RCRA Ground-Water Monitoring Technical Enforcement Guidance Document (TEGD), describes in detail what the United States Environmental Protection Agency deems to be the essential components of a ground-water monitoring system that meets the goals of the Resource Conservation and Recovery Act. This guidance is intended to be used by enforcement officials, permit writers, field inspectors and attorneys at the federal and state levels to assist them in making informed decisions regarding the adequacy of existing or proposed ground-water monitoring systems or modifications thereto. It is not a regulation and should not be used as such. The TEGD is divided into six chapters which contain discussions on the following:

- Characterization of site hydrogeology;
- Location and number of ground-water monitoring wells;
- Design, construction and development of ground-water monitoring wells;
- Content and implementation of the sampling and analysis plan;
- Statistical analysis of ground-water monitoring data; and
- The content and implementation of the assessment plan.

The document is mainly directed towards interim status facilities. Much of the purely technical content, especially regarding site characterization, well design and construction, and assessment of contamination of ground water, is germane to permitted facilities as well as non-RCRA programs. Clearly, the spectrum of hydrogeologic regimes is great, and no single document could provide detailed, step-by-step instructions for monitoring each one. The writers of the TEGD concur and have developed a framework within which a dynamic decision-making process may be applied using a combination of national opinion and site-specific considerations.

In August 1985, the RCRA Ground-Water Monitoring Compliance Order Guide was published. It is the companion document to the TEGD and contains guidance on the use and formulation of compliance orders. It is the hope of U.S. EPA that these guidance documents will further the goal of the regulators and regulated community alike to protect human health and the environment.

The U.S. EPA fully recognizes the dynamic nature of the RCRA program. The TEGD, as it is presented, documents current policy and direction for enforcement and compliance. The TEGD can be used by technical reviewers and the regulated community toward attaining the mandate of protection of human health and the environment.

TABLE OF CONTENTS

TABLE OF CONTENTS
(Continued)

TABLE OF CONTENTS
(Continued)

TABLE OF CONTENTS
(Continued)

APPENDICES

CHAPTER ONE

CHARACTERIZATION OF SITE HYDROGEOLOGY

The adequacy of an owner/operator's ground-water monitoring program hinges, in large part, on the quality and quantity of the hydrogeologic data the owner/operator used in designing the program. Technical reviewers and permit/closure plan reviewers (hereafter permit writers), therefore, should evaluate the adequacy of an owner/operator's hydrogeologic assessment as a first step towards ascertaining the overall adequacy of the detection and/or assessment monitoring network. Clearly, if the design of the well system is based upon poor data, the system cannot fulfill its intended purpose. Because of the complexity of ground-water monitoring systems, owner/operators should discuss the intended approach initially with the State or EPA.

In performing this evaluation, technical reviewers should ask themselves two questions.

- Has the owner/operator collected enough information to: (1) identify and characterize the uppermost aquifer and potential contaminant pathways, and (2) support the placement of wells capable of determining the impact of the facility on the uppermost aquifer?
- Did the owner/operator use appropriate techniques to collect and interpret the information used to support the placement of wells?

The answer to each question will, of course, depend on site-specific factors. For example, sites with more heterogeneous subsurfaces require more hydrogeologic information to determine placement of wells that will intercept contaminant migration. Likewise, investigatory techniques that may be appropriate in one setting, given certain waste characteristics and geologic features, may be inappropriate in another.

This chapter is designed to help technical reviewers answer the above questions. It identifies various investigatory tasks that enable an owner/operator to characterize a site, and explores the factors that technical reviewers should consider when evaluating whether the particular investigatory program an owner/operator used was appropriate in a given case. Technical reviewers should also find this chapter useful when constructing compliance orders that include hydrogeologic investigations.

1.1 Investigatory Tasks for Hydrogeologic Assessments

An owner/operator should accomplish two tasks in conducting a hydrogeologic investigatory program:

1. Define the geology beneath the site area; and
2. Identify ground-water flow paths and rates.

A variety of investigatory techniques are available to achieve these goals, and technical reviewers must evaluate the success of the combination of techniques used by the owner/operator, given the site-specific factors at the facility.

There are certain investigatory techniques that all owner/operators, at a minimum, should have used to characterize their sites. Table 1-1 illustrates a number of techniques that an owner/operator may use to perform hydrogeologic investigations. Those techniques that the owner/operator, at a minimum, should have used to define the geology or identify ground-water flow paths are identified with check marks.

Table 1-1 also presents preferred methods for presentation of the data generated from a hydrogeologic assessment. An owner/operator who has performed the level of site characterization necessary to design a RCRA ground-water monitoring program will be able to supply any of the outputs (cross sections, maps, etc.) listed in the last column of Table 1-1.

The owner/operator should have reviewed the available literature on the hydrogeology of the site area prior to conducting the site-specific

TABLE 1-1

HYDROGEOLOGIC INVESTIGATORY TECHNIQUES

INVESTIGATORY TASKS	INVESTIGATORY TECHNIQUES	DATA PRESENTATION FORMATS/ ASSESSMENT OUTPUTS
Definition of Subsurface Materials [geology]	✓ Survey of existing geologic information	✓ Narrative description of geology
	✓ Soil borings	✓ Geologic cross sections
	• Rock corings	✓ Geologic or soil map (1" = 200')
	✓ Material tests (grain size analyses, standard penetration tests, etc.)	✓ Boring logs or coring logs
	• Geophysical well logs (point and lateral resistivity and/or electromagnetic conductance, gamma ray, gamma density, calipher, etc.)	• Structure contour maps of aquifer and confining layer (plan view)
	• Surface geophysical surveys (D.C. resistivity, E.M., seismic)	• Raw data and interpretive analysis of geophysical studies
	• Hydraulic conductivity measurements of cores (unsaturated zone)	✓ Raw data and interpretive analysis of material tests
	• Aerial photography (fracture trace analysis)	
	• Detailed lithologic/structural mapping of outcrops and trenches	

(Continued)

TABLE 1-1 (Continued)

HYDROGEOLOGIC INVESTIGATORY TECHNIQUES

INVESTIGATORY TASKS	INVESTIGATORY TECHNIQUES	DATA PRESENTATION FORMATS/ ASSESSMENT OUTPUTS
Identification of Ground-Water Flow Paths [hydrology]	✓ Installation of piezometers; water level measurements at different depths and locations	✓ Narrative description of ground water with flow patterns
Ground-water flow directions (including vertical and horizontal components of flow)	✓ Slug tests and/or pump tests • Tracer studies	✓ Water table or potentiometric maps (plan view) with flow lines (1" = 200') ✓ Hydrologic cross sections
Hydraulic conductivities	• Estimates based on sieve analyses	• Raw data and interpretive analysis of slug tests, pump tests, and tracer studies

✓ Minimum techniques and corresponding outputs that should be used to define site hydrogeological conditions.

investigation. Such a review provides a preliminary understanding of the distribution of sediments and rock, general surface water drainage, and ground-water flow that serves to guide the site-specific investigation.

The owner/operator's site-specific investigatory program should have included direct (e.g., borings, piezometers, geochemical analysis of soil samples) methods of determining the site hydrogeology. Indirect methods (e.g., aerial photography, ground penetrating radar, resistivity), especially geophysical studies, may provide valuable sources of information that can be used to interpolate geologic data between points where measurements with direct methods were made. Information gathered by indirect methods alone, however, generally would not have provided the detailed information necessary. The owner/operator should have combined the use of direct and indirect techniques in the investigatory program to produce an efficient and complete characterization of the facility, including an identification of:

- The geology below the owner/operator's hazardous waste facility;
- The vertical and horizontal components of flow in the uppermost aquifer below the owner/operator's site;
- The hydraulic conductivity(ies) of the uppermost aquifer;
- The vertical extent of the uppermost aquifer; and
- The pertinent physical/chemical properties of the confining unit/layer relative to hazardous wastes present.

The following sections outline the basic steps an owner/operator should have followed to implement a site hydrogeologic study, and detail the methods that the owner/operator should have used to collect and present site hydrogeologic data.

1.2 Characterization of Geology Beneath the Site

In order to detail the geology beneath the site and therefore be able to identify potential pathways of contamination, the owner/operator should have collected direct information identifying the lithology and structural characteristics of the subsurface. Indirect methods of geologic investigation such as geophysical studies may be used to augment the evidence gathered by direct field methods, but should not be used as a substitute for them. Surface geophysical studies, such as resistivity, electromagnetic conductivity, seismic reflection, and seismic refraction, and borehole methods like electromagnetic conductivity, resistivity, and gamma ray may yield valuable information on the depth to the confining unit, the types of unconsolidated material(s) present, the presence of fracture zones or structural discontinuities, and the depth to the potentiometric surface. Additionally, geophysical methods may have their greatest utility in correlating the continuity of formations or strata between boreholes. The result is the efficient compilation of extensive site data without drilling an excessive number of boreholes. Geophysical methods, however, should have been used primarily to supplement information obtained from direct sources. In order to characterize the lithology, depositional environment, and geologic characteristics of the area beneath the site, the owner/operator should have used direct means. The limitations of geophysical methods should also be recognized. For instance, electrical borehole logging cannot be performed when the hollow stem auger drilling method is used.

1.2.1 Site Characterization Boring Program

The technical reviewer should determine whether an owner/operator, through the soil/rock boring program, gathered the information necessary to characterize the geology beneath the site and consequently to identify potential contaminant migration pathways. Such a program should have entailed the following:

- Initial boreholes should be installed at a density based on criteria described in Table 1-2 and sufficient to provide initial information upon which to determine the scope of a more detailed evaluation of geology and potential pathways of contaminant migration.

TABLE 1-2

FACTORS INFLUENCING DENSITY OF INITIAL BOREHOLES

FACTORS THAT MAY SUBSTANTIATE REDUCED DENSITY OF BOREHOLES	FACTORS THAT MAY SUBSTANTIATE INCREASED DENSITY OF BOREHOLES
• Simple geology (i.e., horizontal, thick, homogeneous geologic strata that are continuous across site that are unfractured and are substantiated by regional geologic information) • Use of geophysical data to correlate well log data. Preferred methods: DC resistivity, seismic reflection or seismic refraction, geophysical well logging	• Fracture zones encountered during drilling • Suspected pinchout zones (i.e., discontinuous units across the site) • Geologic formations that are tilted or folded • Suspected zones of high permeability that would not be defined by drilling at large intervals • Laterally transitional geologic units with irregular permeability (e.g., sedimentary facies changes)

- Initial boreholes should have been drilled into the first confining layer beneath the uppermost aquifer. The portion of the borehole extending into the confining layer should have been plugged properly after a sample was taken.

- Additional boreholes should be installed in numbers and locations sufficient to characterize the geology beneath the site. The number and locations of additional boreholes should have been based on data from initial borings and indirect investigation.

- Collection of samples of every significant stratigraphic contact and formation, especially the confining layer, should have been taken. Continuous cores should have been taken initially to ascertain the presence and distribution of small- and large-scale permeable layers. Once stratigraphic control was established, samples taken at regular, e.g., five-foot intervals, could have been substituted for continuous cores.

- Boreholes in which permanent wells were not constructed should have been sealed with material at least an order of magnitude less permeable than the surrounding soil/sediment/rock in order to reduce the number of potential contaminant pathways.

- Samples should have been logged in the field by a qualified professional in geology.

- Sufficient laboratory analysis should have been performed to provide information concerning petrologic variation, sorting (for unconsolidated sedimentary units), cementation (for consolidated sedimentary units), moisture content, and hydraulic conductivity of each significant geologic unit or soil zone above the confining layer/unit.

- Sufficient laboratory analysis should have been performed to describe the mineralogy (X-ray diffraction), degree of compaction, moisture content, and other pertinent characteristics of any clays or other fine-grained sediments held to be the confining unit/layer. Coupled with the examination of clay mineralogy and structural characteristics should have been a preliminary analysis of the reactivity of the confining layer in the presence of the wastes present.

At many sites a site characterization has already been done and monitoring wells installed. In evaluating the design of such systems, the technical reviewer should utilize, where appropriate, data already gathered by the owner/operator. Because of the quality of existing data, it is possible that site characterization may be complete or may only need to be supplemented by a few additional boreholes, piezometers, or monitoring wells. Some facilities, including closed facilities, may need to undertake a site characterization from the first phase.

The borehole program to elucidate site hydrogeology generally requires more than one iteration. A benefit to this technique is that data and observations derived from previous boreholes may be used to guide the placement of future ones.

It is imperative that the owner/operator research local hydrogeology before initiating a borehole program. Existing reports, maps, and research papers gathered from a variety of sources can be used to understand, in a broad sense, the hydrogeological regime in which the facility is located. Thus, such information as local stratigraphy, depositional environment, and tectonic history serves to provide an estimate of the distribution and types of geologic materials likely to be encountered. Similarly, knowledge of regional ground-water flow rate, depth, quality, and direction, local pumping, evapotranspiration rates, and surface water hydrology represents an effective first approximation of site-specific ground-water characteristics. The next phase should have been the progressive placement of boreholes based, at first, on research and, subsequently, on previous boreholes and data from research.

The number of initial boreholes should have been sufficient to provide initial information upon which to determine the scope of a more detailed evaluation of geology and potential pathways of contaminant migration. An example of a simple case is illustrated in Figure 1-1. The objective of the initial boreholes is to begin to reconcile the broad, conceptual model derived from research data with the true site-specific hydrogeologic regime. In other words, the borehole program is necessary to establish the small-scale geology of the area beneath the facility and place it in the context of the geology of the region or locale.

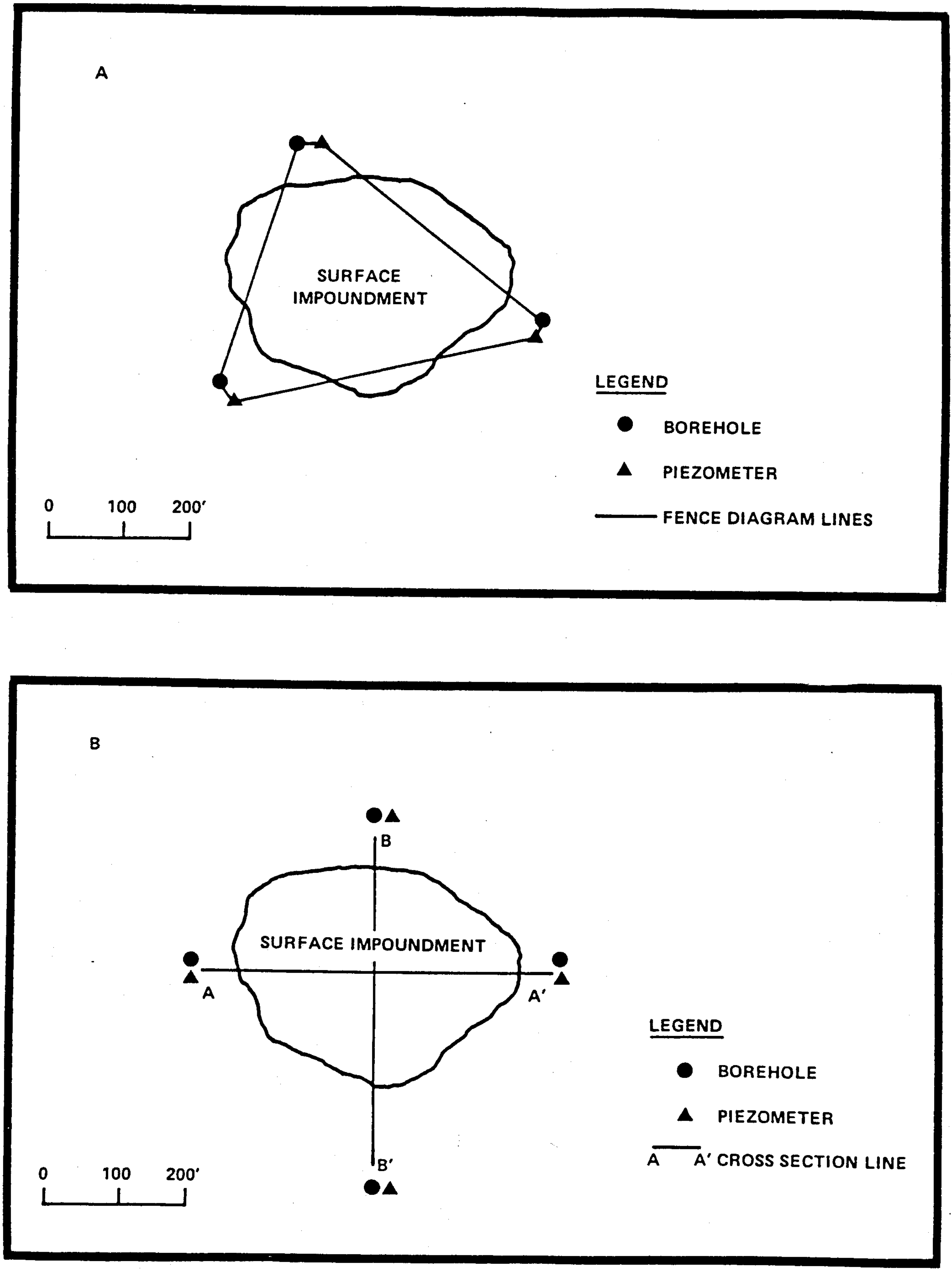


FIGURE 1-1. POSSIBLE BOREHOLE CONFIGURATION FOR A SMALL SURFACE IMPOUNDMENT

The distance between these initial boreholes should be varied based on site-specific criteria, yet should have been close enough so that cross sections would have accurately portrayed stratigraphy with minimal reliance on inference (see Table 1-2). In this way, a suitably restricted configuration of a limited number of initial boreholes, in combination with indirect investigative techniques and research data, will serve to guide efficiently the placement of additional boreholes where needed to characterize potential pathways for contaminant migration. A parallel program using piezometers should also be undertaken. Lithologic data should ultimately correlate with hydraulic parameters (e.g., clean, well sorted, unconsolidated sands should exhibit high hydraulic conductivity). If they do not, further hydraulic testing should be done.

During the completion of the borings, the owner/operator should check drill logs for:

- Correlation of stratigraphic units between soil/rock borings;
- Identification of zones of potentially high hydraulic conductivity;
- Identification of the confining formation/layer;
- Indication of unusual or unpredicted geologic features such as fault zones, fracture traces, facies changes, solution channels, buried stream deposits, cross cutting structures, pinch out zones, etc.; and
- Continuity of petrographic features such as sorting, grain size distribution, cementation, etc., in significant formations.

If the owner/operator is unable to define such structural anomalies, or zones of potentially high conductivity, or to correlate petrographic features and/or stratigraphy between any two adjacent boreholes, then additional intermediate boreholes should be drilled and ancillary investigative techniques employed to describe potential contaminant migration.

On the other hand, if the necessary characterization is largely achieved at the initial placement, fewer additional boreholes and less additional indirect investigation would be necessary to describe pathways.

Figure 1-2 illustrates how subsequent boreholes and indirect supplementary techniques can be added to the initial borehole configuration to characterize potential pathways for contaminant migration. In most cases, additional boreholes will be necessary to complete the characterization because the majority of hydrogeologic settings are complex.

It is vitally important that the owner/operator consider the thickness and potential reactivity of confining clays or other fine-grained sediments in the presence of site-specific waste types. Marl, for instance, is chemically attacked by low pH wastes because of its high carbonate content. Smectites and, to a lesser extent, illitic clays are ineffective impediments to the migration of various organic chemicals (e.g., xylene). In contaminated areas, a chemically degraded confining layer may lead to hydraulic communication unanticipated by literature reviews of stratigraphy. An example is shown in Figure 1-3. In pristine areas, the possible future chemical degradation of a confining layer should be of concern during any assessment monitoring or corrective action necessary at the facility.

All samples should have been logged in the field by a qualified professional in geology (see glossary). These samples should have been collected with a shelby tube, split barrel sampler, or rock corer, and represent the significant formations and stratigraphic contacts. Continuous cores should have been taken initially to obtain stratigraphic control. Samples could have been taken at regular intervals, depending on site-specific conditions once stratigraphic control was established. Drilling logs and field records should have been prepared detailing the following information:

- Gross petrography (e.g., soil classification or rock type) of each geologic unit, including the confining unit;
- Gross structural interpretation of each geologic unit and structural features (e.g., fractures, fault gouge, solution channels, buried streams or valleys), bioturbation zones, petrology, and discontinuities;

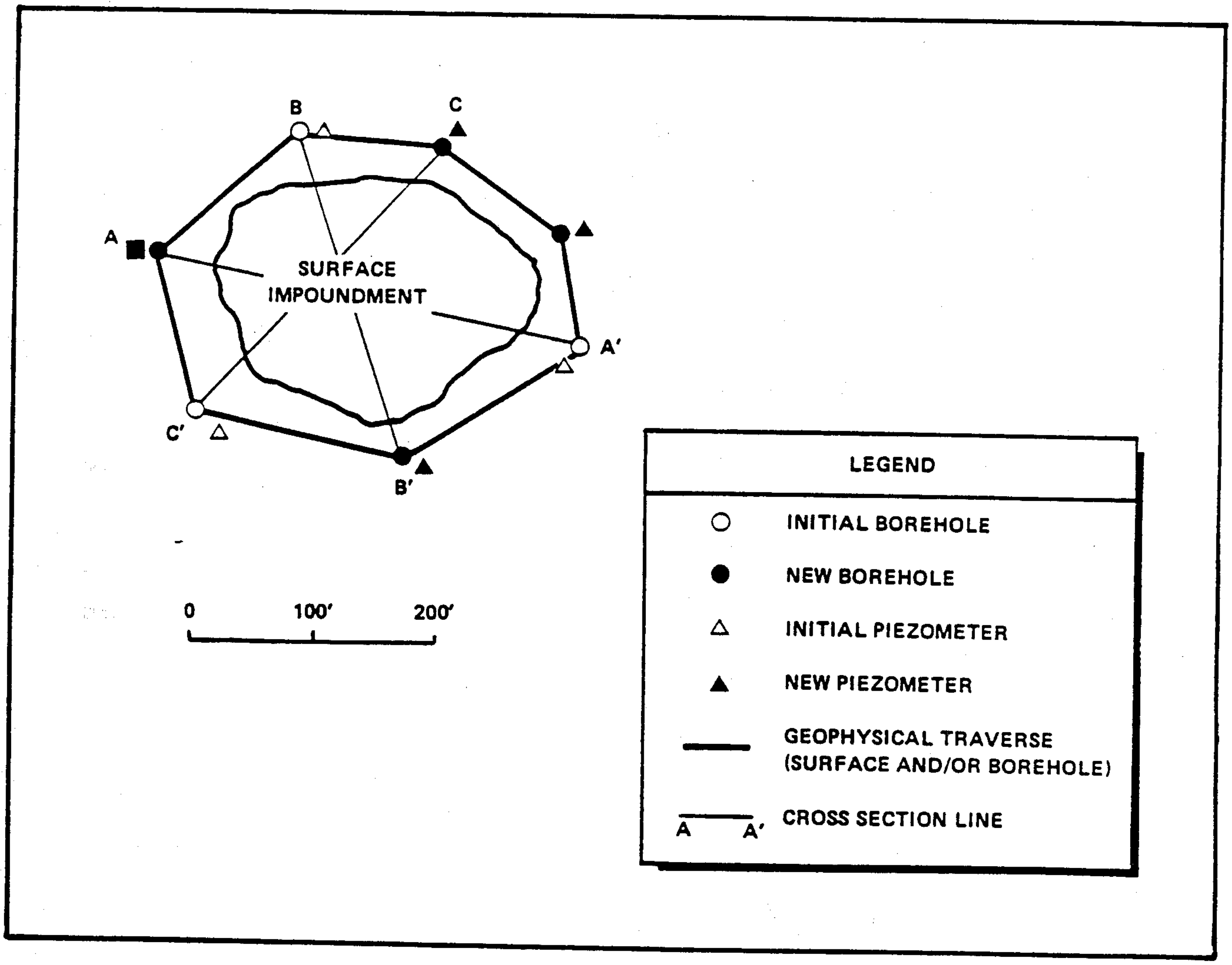
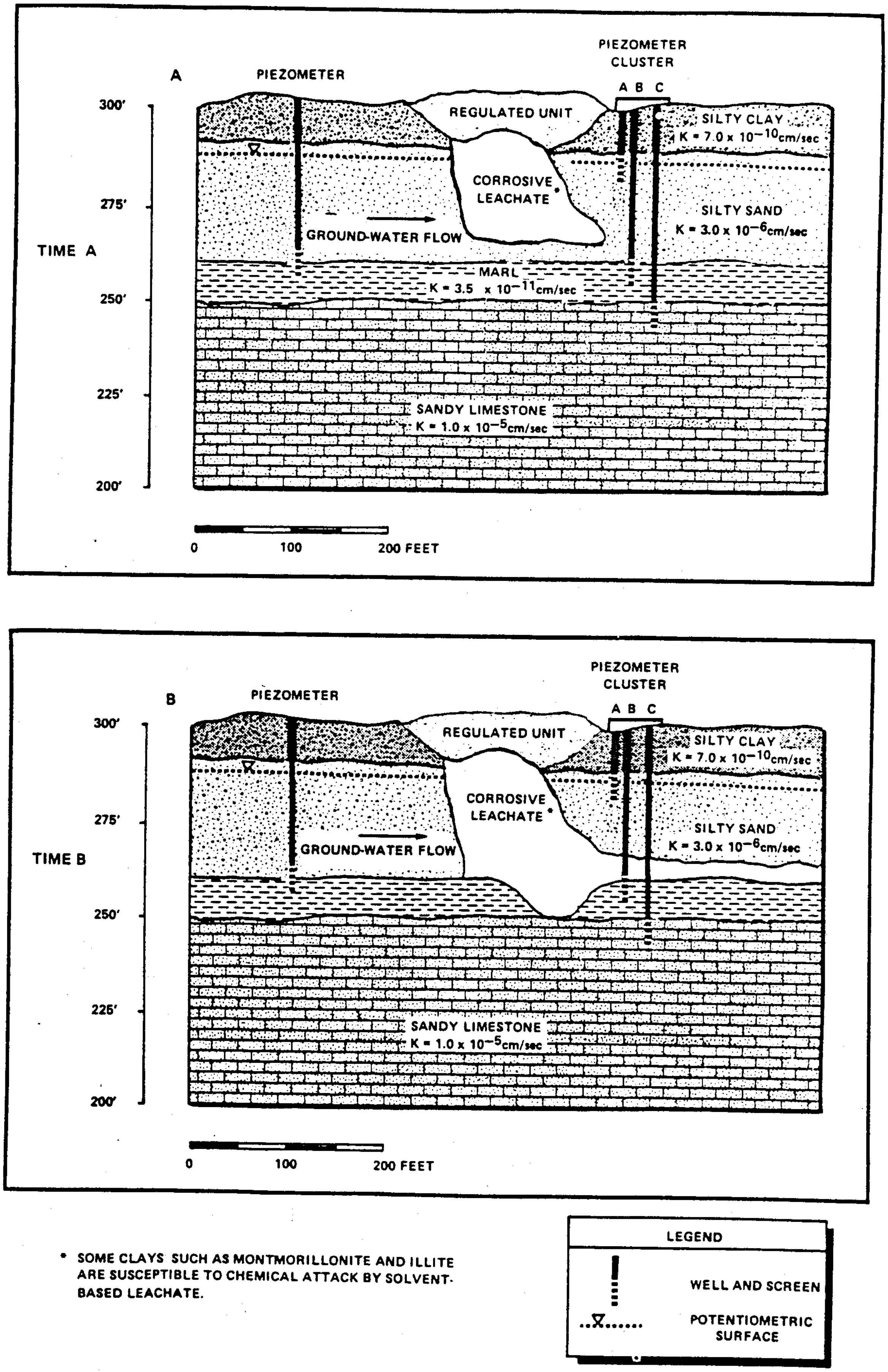


FIGURE 1-2 SUBSEQUENT ITERATION OF BOREHOLE PROGRAM AT A SMALL SURFACE IMPOUNDMENT FROM FIGURE 1-1A.



* SOME CLAYS SUCH AS MONTMORILLONITE AND ILLITE ARE SUSCEPTIBLE TO CHEMICAL ATTACK BY SOLVENT-BASED LEACHATE.

FIGURE 1-3 EXAMPLE OF A CONTAMINANT THAT MAY AFFECT THE QUALITY OF A CONFINING LAYER

- Development of soil zones and vertical extent and field description of soil type (prior to any necessary laboratory analysis);
- Depth of water-bearing unit(s) and vertical extent of each;
- Depth and reason for termination of borehole;
- Depth, location, and identification of any contamination encountered in borehole; and
- Blow counts, colors, and grain-size distributions(s).

Table 1-3 identifies the minimum required information that should have been included in a drilling log. These items are marked with asterisks.

In addition to field descriptions as described above, the owner/ operator should have provided, where necessary, a laboratory analysis of each significant geologic unit and soil zone. These analyses should contain the following information:

- Mineralogy and mineralogic variation of the confining layer and confining units/layers, especially clays (e.g., microscopic analysis and other methods such as X-ray diffraction as necessary);
- Petrology and petrologic variation of the confining layer and each unit above the confining unit/layer (e.g., petrographic analysis, other laboratory methods for unconsolidated materials as deemed necessary) to determine among other things:
    - degree of crystallinity and cementation of matrix
    - degree of sorting, size fraction, and textural variation
    - existence of small-scale structures that may affect fluid flow
- Moisture content and moisture variation of each significant soil zone and geologic unit; and
- Hydraulic conductivity and variation of each significant soil zone and type and geologic unit in the unsaturated zone.

Some laboratory analysis methods available to investigate these laboratory parameters are shown in Table 1-4.

TABLE 1-3
FIELD BORING LOG INFORMATION

General

- Project name
- *Hole name/number
- *Date started and finished
- *Geologist's name
- *Driller's name
- Sheet number
- *Hole location; map and elevation
- *Rig type bit size/auger size
- *Petrologic lithologic classification scheme used (Wentworth, unified soil classification system)

Information Columns

- *Depth
- *Sample location/number
- Blow counts and advance rate
- *Percent sample recovery
- *Narrative description
- *Depth to saturation

Narrative Description

- Geologic Observations:
  - *soil/rock type
  - *color and stain
  - *gross petrology
  - friability
  - *moisture content
  - *degree of weathering
  - *presence of carbonate
  - *fractures
  - *solution cavities
  - *bedding
  - *discontinuities: e.g., foliation
  - *water-bearing zones
  - *formational strike and dip
  - fossils
  - *depositional structures
  - *organic content
  - *odor
  - *suspected contaminant
- Drilling Observations:
  - loss of circulation
  - *advance rates
  - rig chatter
  - *water levels
  - amount of air used, air pressure
  - *drilling difficulties
  - *changes in drilling method or equipment
  - *readings from detective equipment, if any
  - *amount of water yield or loss during drilling at different depths
  - *amounts and types of any liquids used
  - *running sands
  - *caving/hole stability
- Other Remarks:
  - equipment failures
  - *possible contamination
  - *deviations from drilling plan
  - *weather

*Indicates items that the owner/operator should record, at a minimum.

TABLE 1-4

SUGGESTED LABORATORY METHODS FOR SEDIMENT/ROCK SAMPLES

Sample Origin	Parameter	Laboratory Method	Used to Determine
Geologic formation, unconsolidated sediments, consolidated sediments, solum	Hydraulic conductivity	Falling head, static head test	Hydraulic conductivity
	Size fraction	Sieving (ASTM) Settling measurements (ASTM)	Hydraulic conductivity
	Sorting	Petrographic analysis	Hydraulic conductivity
	Specific yield	Column drawings	Porosity
	Specific retention	Centrifuge tests	Porosity
	Petrology/Pedology	Petrographic analysis	Soil type, rock type
	Mineralogy	X-ray diffraction confining clay mineralogy/chemistry	Geochemistry, potential flow paths
-	Bedding	Petrographic analysis	
	Lamination	Petrographic analysis	
	Atterberg Limits	ASTM	Soil cohesiveness
Contaminated samples (e.g., soils producing higher than background organic vapor readings)	Appropriate subset of Appendix VIII parameters (§261)	SW-846	Identity of contaminants

*Owners and operators might also want to consider performing this test while they are obtaining the other types of information listed on this table.

1.2.2 Interpretation of Geology Beneath the Site

The technical reviewer should review the owner/operator's geologic characterization and verify:

- The completeness of the narrative and the accuracy of the owner/operator's interpretation, and
- That the geologic assessment addresses or provides means to resolve any information gaps which may be suggested by the geologic data.

In order to assess the completeness and accuracy of the owner/operator's interpretation, the technical reviewer should:

- Examine and evaluate the raw data;
- Compare his own interpretation, based on the raw data, with that of the owner/operator;
- Compare with other studies and information; and
- Identify any information gaps that relate to incomplete data and/or to narrative presentation.

The technical reviewer should independently conduct the following tasks to support and develop his interpretation of the site geology:

- Review drilling logs to identify major rock or soil types and establish their horizontal and vertical variability;
- Construct representative cross sections from well log data;
- Identify zones of suspected high permeability, or structures likely to influence contaminant migration through the unsaturated and saturated zones;
- Review laboratory data, determine whether laboratory data corroborate field data and that both are sufficient to define petrology; and
- Review mineralogic identification of confining clays and the owner/operator's assessment of general geochemistry and determine corroboration between analytic and field data.

After the technical reviewer has interpreted the geologic data, these results should be compared to the results developed by the owner/operator. The technical reviewer should:

- Identify information gaps between narrative and data.
- Determine whether resolution requires collection of additional data or reassessment of existing data; and
- Identify any information gaps that will affect the owner/operator's ability to have located his/her RCRA monitoring well system.

1.2.3 Presentation of Geologic Data

In addition to the generation and interpretation of site-specific geologic data, the technical reviewer should review the owner/operator's presentation of data in geologic cross sections, topographic maps, and aerial photographs.

An adequate number of cross sections should be presented by an owner/operator to depict significant geologic or structural trends and reflect geologic/structural features in relation to local and regional ground-water flow. Figure 1-4 illustrates an example of a waste disposal unit that is traversed by an adequate number of cross-section lines from which a fence diagram may be created.

On each cross section, the owner/operator should have identified: petrography of significant formations/strata, significant structural features, stratigraphic contacts between significant formations/strata, zones of high permeability or fracture, the location of each borehole, depth of termination, depth to the zone of saturation, and depiction of any geophysical logs. If the owner/operator is unable to supply such details, the site characterization may be inadequate. Figure 1-5 illustrates an example of a geologic cross section. Vertical exaggeration in cross sections should be minimized.

Additionally, surficial features may affect ground-water hydrogeology. An owner/operator should have provided a surface topographic

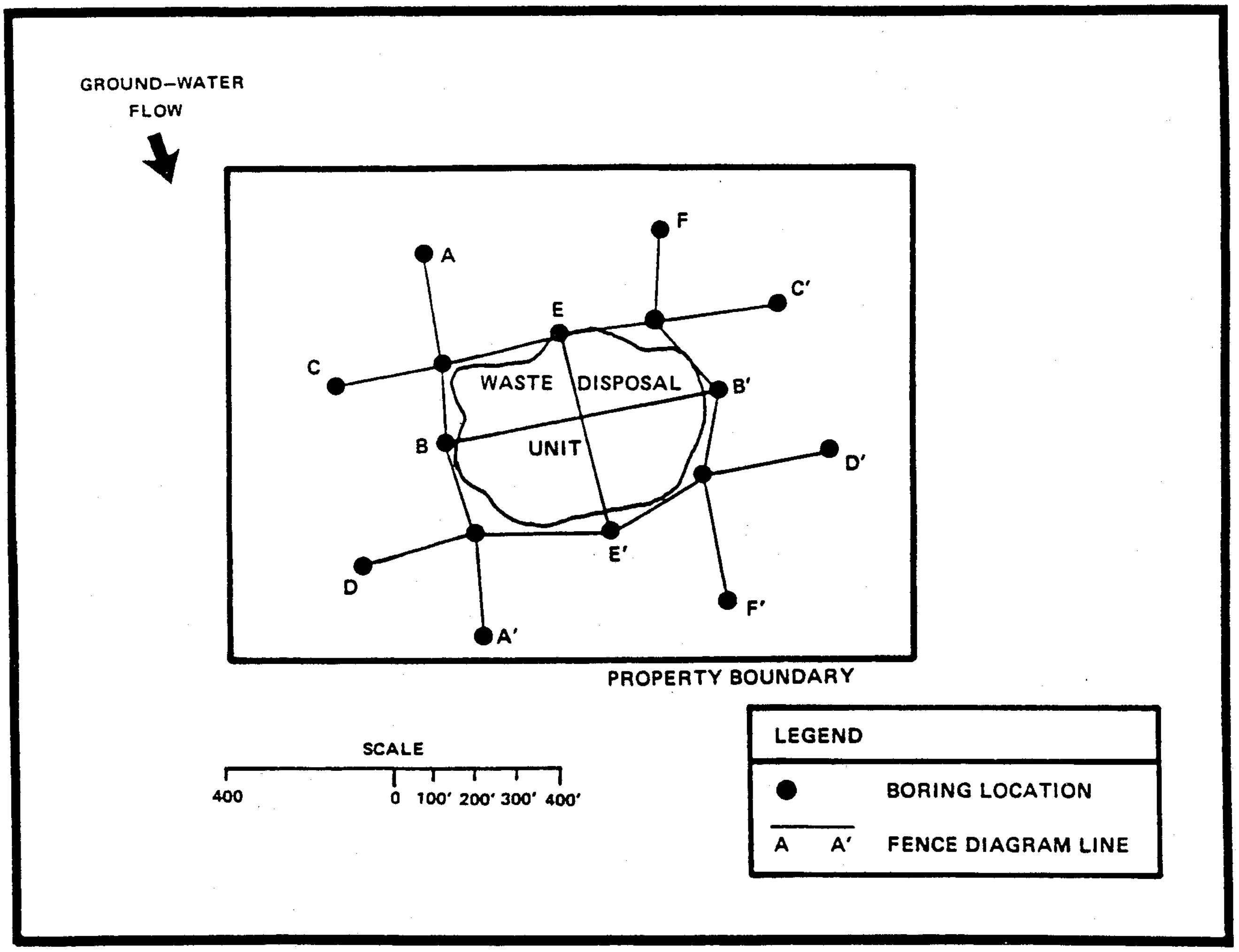


FIGURE 1-4 DATA POINTS USED TO GENERATE A GEOLOGIC FENCE DIAGRAM

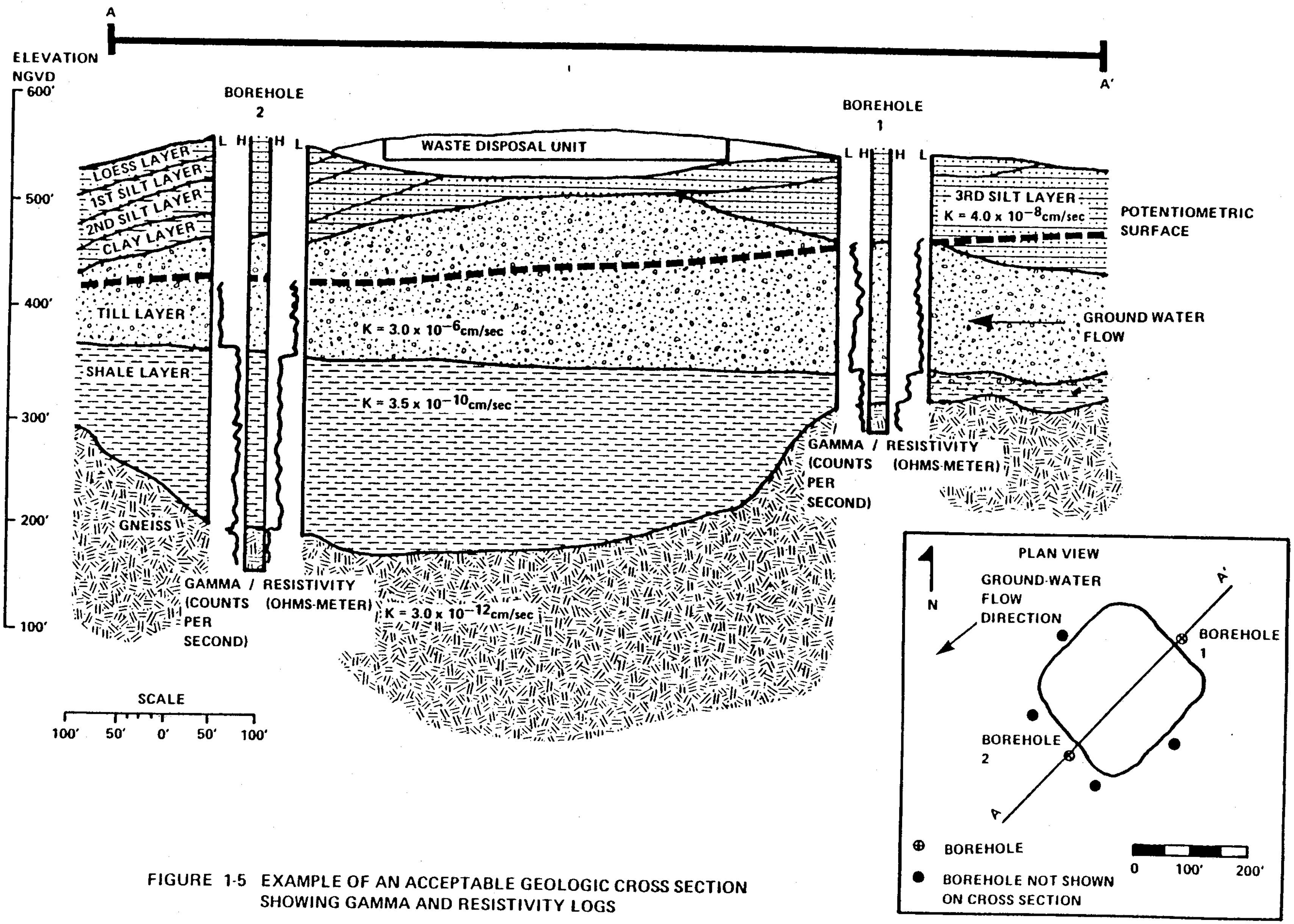


FIGURE 1-5 EXAMPLE OF AN ACCEPTABLE GEOLOGIC CROSS SECTION SHOWING GAMMA AND RESISTIVITY LOGS

map and aerial photograph of the site. The topographic map should have been constructed under the supervision of a licensed surveyor and should provide contours at a two-foot contour interval, locations and illustrations of man-made features (e.g., parking lots, factory buildings, drainage ditches, storm drains, pipelines, etc.), descriptions of nearby water bodies and/or off-site wells, site boundaries, individual RCRA units, delineation of the waste management areas, solid waste management areas, and well and boring locations. An example of a site map is depicted in Figure 1-6. An aerial photograph of the site should depict the site and adjacent off-site features. This photograph should have the site clearly delineated and labeled. In addition, adjacent surface water bodies, municipalities and residences should be labeled.

1.3 Identification of Ground-Water Flow Paths

In addition to evaluating the owner/operator's characterization of geology, technical reviewers must determine whether owner/operators have identified ground-water flow paths. The characterization must have included:

- The direction(s) of ground-water flow (including both horizontal and vertical components of flow);
- The seasonal/temporal, naturally and artificially induced (i.e., off-site production well pumping, agricultural use) variations in ground-water flow; and
- The hydraulic conductivities of the significant hydrogeologic units underlying their site.

In addition, technical reviewers must ensure that owner/operators used appropriate methods for obtaining the above information.

1.3.1 Determining Ground-Water Flow Directions

To locate wells so as to provide upgradient and downgradient well samples, owner/operators should have a thorough understanding of how ground water flows beneath their facility. Of particular importance is

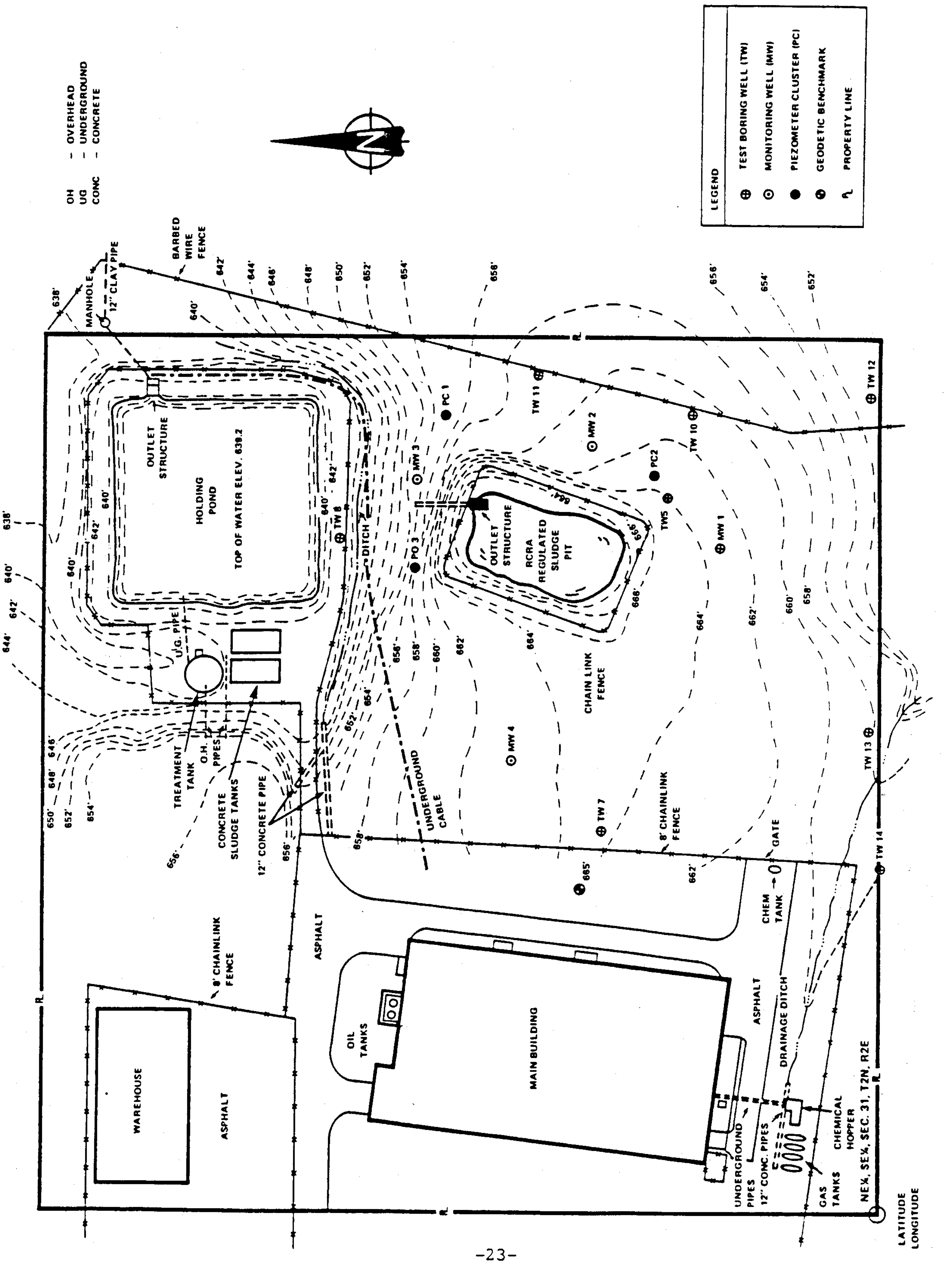


FIGURE 1 6 EXAMPLE OF A TOPOGRAPHIC MAP (2-FOOT CONTOUR INTERVAL) the direction of ground-water flow and the impact that external factors (intermittent well pumping, temporal variations in recharge patterns, etc.) may have on ground-water patterns. In order for an owner/operator to have assessed these factors, a program should have been developed and implemented for precise water level monitoring. This program should have been structured to provide precise water level measurements in a sufficient number of piezometers and at a sufficient frequency to gauge both seasonal average flow directions and to account for seasonal or temporal fluctuation of flow directions.

In addition to considering the components of flow in the horizontal direction, a program should have been undertaken by the owner/operator to accurately and directly assess the vertical components of ground-water flow. Ground-water flow information must be based at least in part on empirical data from borings and piezometers. Technical reviewers should review independently an owner/operator's methodology for obtaining information on ground-water flow and account for factors that may influence that flow at the facility. The following sections provide acceptable methods by which an owner/operator should have assessed the vertical and horizontal components of flow at the site.

1.3.1.1 Ground-water level measurements

In order for the owner/operator to have initially determined the elevation of the potentiometric surface in any monitoring well or piezometer, several criteria should have been considered by the owner/operator.

- The casing height should have been measured by a licensed surveyor to an accuracy of 0.01 feet. This may have required the placement of a topographic benchmark on the facility property.
- Generally, water level measurements from boreholes, piezometers, or monitoring wells used to construct a single potentiometric surface should have been collected within a 24-hour period. This practice is adequate if the magnitude of change is small over

that period of time. There are other situations, however, which necessitate that all measurements be taken within a short time interval:

  - tidally influenced aquifers;
  - aquifers affected by river stage, impoundments, and/or unlined ditches;
  - aquifers stressed by intermittent pumping of production wells; and
  - aquifers being actively recharged due to a precipitation event.

- The method used to measure water levels should have been adequate to attain an accuracy of 0.01 feet.
- A survey mark should be placed on the casing for use as a measuring point. Many times the lip of the riser pipe is not flat. Another measuring reference should be located on the grout apron.
- Piezometers should be re-surveyed periodically to determine the extent of subsidence or rise in ground surface.
- Water levels in piezometers should have been allowed to stabilize for a minimum of 24 hours after well construction and development, prior to measurement. In low yield situations, recovery may take longer.

If an owner/operator cannot produce accurate documentation or provide assurance that these criteria were met during the collection of water level measurements, this may indicate that the generated information may be inadequate.

In cases where immiscible contamination is found during the characterization, water level measurements should be adjusted to reflect its true elevation.

1.3.1.2 Interpretation of ground-water level measurements

After the technical reviewer has assured that the water level data are valid, he should proceed to independently interpret the information. The technical reviewer should:

- Use the owner/operator's raw data to construct a potentiometric surface map (see Figure 1-7). The data used to develop the potentiometric map should be data from piezometers/wells screened at equivalent stratigraphic horizons;

- Compare these data with that of the owner/operator and determine whether the owner/operator has accurately presented the information, and ascertain if the information is sufficient to describe ground-water flow trends; and

- Identify any information gaps.

In reviewing this information, the technical reviewer should now have an approximate idea of the general flow direction; however, in order to have properly located monitoring wells, the owner/operator should have established hydraulic gradient (flow direction) in both the horizontal and vertical directions.

1.3.1.3 Establishing vertical components of ground-water flow

In order for the owner/operator to have determined the direction of flow, vertical components of flow must have been directly determined. This will have required the installation of piezometers in clusters. A piezometer cluster is a closely spaced group of wells screened at different depths to measure vertical variations in hydraulic head. To obtain reliable measurements, the following criteria should be considered in the placement of piezometer clusters:

- Information obtained from multiple piezometer placement in single boreholes may generate erroneous data. Placement of vertically nested piezometers in closely spaced separate boreholes is the preferred method.

- Piezometer measurements should have been collected at least within a 24-hour period, and within shorter intervals under certain conditions, if measurements are to be used in any correlative presentation of data.

- Piezometer measurements should have been determined along a minimum of two vertical profiles across the site. These profiles should be cross sections roughly parallel to the direction of ground-water flow indicated by the potentiometric surface.

PIEZOMETER	WATER - LEVEL ELEVATION	DATE RECORDED
P1	423.10	3/2/85
P2	421.76	3/2/85
P3	427.13	3/2/85
P4	426.96	3/2/85
P5	427.05	3/2/85
P6	422.36	3/2/85
P7	417.55	3/2/85
P8	416.32	3/2/85
P9	417.10	3/2/85
P10	413.26	3/2/85
P11	416.35	3/2/85
P12	419.10	3/2/85
P13	419.01	3/2/85
P14	420.63	3/2/85
P15	426.73	3/2/85
P16	431.48	3/2/85

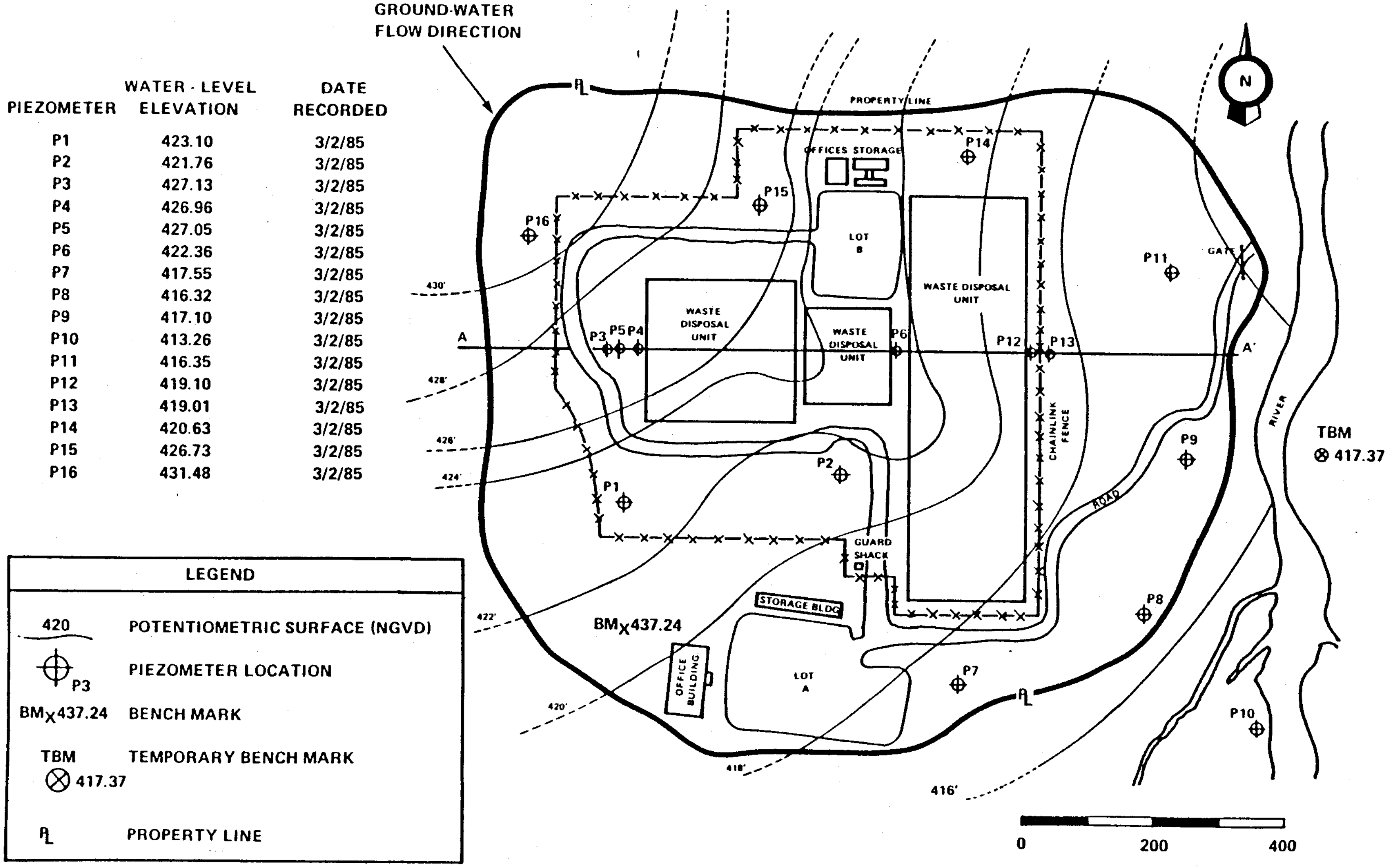


FIGURE 1-7 POTENTIOMETRIC SURFACE MAP

When reviewing piezometer information obtained from multiple placement of piezometers in single boreholes, the technical reviewer should closely scrutinize the construction details for the well. It is extremely difficult to adequately seal several piezometers at discrete depths within a single borehole, and special design considerations should have been considered by the owner/operator. If detailed information for the design is not available, it may indicate that adequate construction considerations have not been used. Placement of piezometers in closely spaced well clusters, where piezometers have been screened at different, discrete depth intervals, is more likely to produce accurate information. Additionally, multiple well clusters sample a greater proportion of the aquifer, and thus may provide a greater degree of accuracy for considerations of vertical potentiometric head in the aquifer as a whole.

The information obtained from the piezometer readings should have been used by the owner/operator to construct flow nets (see Figure 1-8). These flow nets should include information as to piezometer depth and length of screening. The flow net in Figure 1-8 was developed from information obtained from piezometer clusters screened at different, discrete intervals. The technical reviewer should be able to verify the accuracy of the owner/operator's presentation and calculations by either constructing a flow net independently from the owner/operator's data or spot-checking the owner/operator's presentation. It is also important to verify that the screened interval is accurately portrayed and to determine whether the piezometer is actually monitoring the water level of the desired water-bearing unit.

If there is reasonable concurrence between the information presented by the owner/operator and the technical reviewer's interpretation, the technical reviewer should next interpret the flow directions from the waste management area.

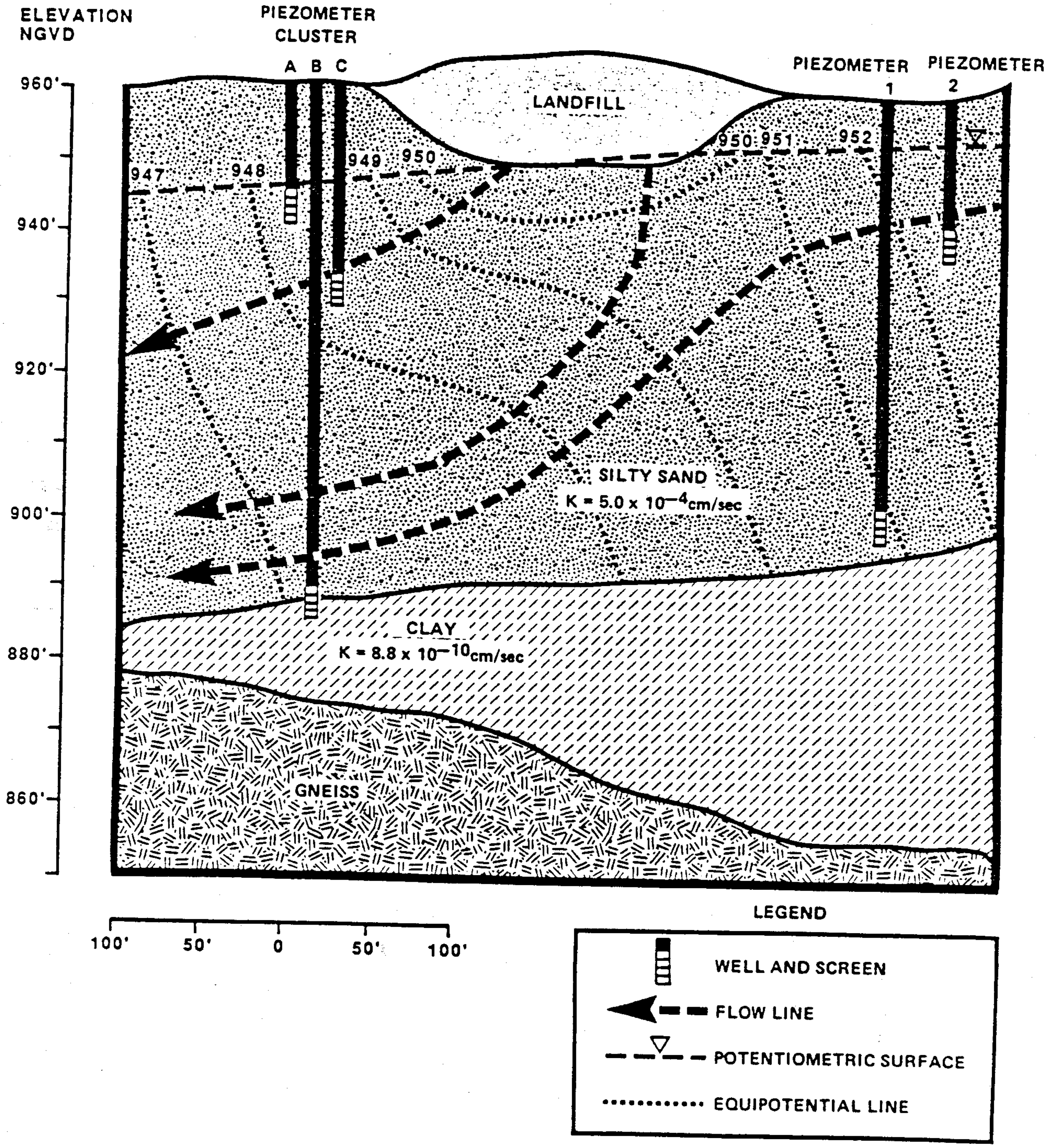


FIGURE 1-8. AN EXAMPLE OF A FLOW NET DERIVED FROM PIEZOMETER DATA

1.3.1.4 Interpretation of flow direction and flow rates

In considering flow directions established by the owner/operator, the technical reviewer should have first established:

- That the potentiometric surface measurements are valid; that is the distributions of hydraulic head and hydraulic conductivity are known, and that the total porosities as approximations of effective porosities (determination of effective porosity can be time consuming) of significant strata are known to permit estimation of flow rate; and

- That the vertical components of flow have been accurately depicted and are based on valid data.

At this point, general direction(s) and rate(s) of ground-water flow may be estimated. The technical reviewer should construct vertical intercepts with the potentiometric contours for both the potentiometric surface map and flow nets. Once the vertical and horizontal directions of flow are established (from points of higher to lower hydraulic head), it is possible to estimate where monitoring wells will most likely intercept contaminant flow in the vertical plane. To consider the placement that will most effectively intercept contaminant flow, hydraulic conductivity(ies) must be calculated.

1.3.2 Seasonal and Temporal Factors: Ground-Water Flow

It is important to note if the owner/operator has identified and assessed factors that may result in short-term or long-term variations in ground-water level and flow patterns. Such factors that may influence ground-water conditions include:

- Off-site well pumping, recharges, and discharges;
- Tidal processes or other intermittent natural variations (e.g., river stage, etc.);
- On-site well pumping;
- Off-site, on-site construction or changing land use patterns;
- Deep well injection; and
- Waste disposal practices.

Off-site or on-site well pumping may affect both the rate and direction of ground-water flow. Municipal, industrial, or agricultural ground-water use may significantly change ground-water flow patterns and levels over time. Pumpage may be seasonal or dependent upon complex water use patterns. The effects of pumpage thus may reflect continuous or discontinuous patterns. Water level measurements in piezometers must have been frequent enough to detect such water use patterns.

Natural processes such as riverine, estuarine, or marine tidal movement may result in variations of well water levels and/or ground-water quality. An owner/operator should have documented the effects of such patterns. Seasonal patterns have a significant effect on hydraulic head and ground-water flow. Short-term recharge patterns may affect ground-water flow patterns that are markedly different from ground-water flow patterns determined by seasonal averages. An owner/operator should have gauged such transitional patterns.

Additionally, an owner/operator should have implemented means for gauging long-term effects on water movement that may result from on-site or off-site construction or changes in land-use patterns. Development may affect ground-water flow by altering recharge or discharge patterns. Examples of such changes might include the paving of recharge areas or damming of waterways.

In reviewing the owner/operator's assessment of ground-water flow patterns, the technical reviewer should consider whether the owner/operator's program was sensitive to such seasonal or temporal variations. An owner/operator should have, in effect, determined not only the location of water resources, but the sources and source patterns that contribute to or affect ground-water patterns below the regulated site.

1.3.3 Determining Hydraulic Conductivities

In addition to defining vertical and horizontal gradients and sources of spatial and temporal variation, the owner/operator must identify the distribution hydraulic conductivity (K) values within each significant formation. Variations in the hydraulic conductivity within or between formations or strata can create irregularities in ground-water flow paths. Strata/formations of high hydraulic conductivity represent areas of greater ground-water flow and therefore zones of potential migration. Further, anisotropy within strata or formations affects the magnitude and direction of ground-water flow. Thus, information on hydraulic conductivities is necessary before owner/operators can make reasoned decisions regarding well placements.

Technical reviewers should review the owner/operator's hydrogeologic assessment to ensure that it contains data on the hydraulic conductivities of the significant formations underlying the site. In addition, technical reviewers should review the method the owner/operator used to derive the conductivity values. It may be beneficial to use analogous or laboratory methods to augment results of field tests; however, field methods provide the best definition of the hydraulic conductivity in most cases.

Hydraulic conductivity can be determined in the field using either single or multiple well tests. Single well tests, more commonly referred to as slug tests, are performed by suddenly adding or removing a slug (known volume) of water from a well and observing the recovery of the water surface to its original level. Similar results can be achieved by pressurizing the well casing, depressing the water level, and suddenly releasing the pressure to simulate removal of water from the well. One recommended method, which will be proposed for inclusion in SW-846 (Test Methods for Evaluating Solid Waste, U.S. EPA, July 1982), is Method 9100, which is also recommended for use in determining aquifer vulnerability.

When reviewing information obtained from single well tests, the technical reviewer should consider several criteria. First, they are run on one well and, as such, the information is limited in scope to the geologic area directly adjacent to the screen. Second, the vertical extent of screening will control the part of the geologic formation that is being tested during the test. That part of the column above or below the screened interval that has not been tested may also have to be tested for hydraulic conductivity. Third, the methods that the owner/operator used to collect the information obtained from single well tests should be adequate to measure accurately parameters such as changing static water (prior to initiation, during, and following completion of the test), the amount of water added to, or removed from, the well, and the elapsed time of recovery. This is especially important in highly permeable formations where pressure transducers and high speed recording equipment may need to be used. The owner/operator's interpretation of the single well test data should be consistent with the existing geologic information (boring log data). The well screen and filter pack adjacent to the interval under examination should have been properly developed to ensure the removal of fines or correct deleterious drilling effects. It is, therefore, important that reviewers examine the owner/operator's program of single well testing to ensure that enough tests were run to provide representative measures of hydraulic conductivity and to document lateral variations of hydraulic conductivity at various depths in the subsurface.

Multiple well tests, more commonly referred to as pumping tests, are performed by pumping water from one well and observing the resulting drawdown in nearby wells. Tests conducted with wells screened in the same water-bearing formation provide hydraulic conductivity data. Tests conducted with wells screened in different water-bearing zones furnish information concerning hydraulic communication. Multiple well tests for hydraulic conductivity are advantageous because they characterize a greater proportion of the subsurface and thus provide a greater amount of detail. Multiple well tests are subject to similar constraints to those listed above for single well tests. Some additional problems that should have been considered by the owner/operator conducting a multiple well test include: (1) storage of potentially contaminated water pumped from the well system and (2) potential effects of ground-water pumping on existing waste plumes. The technical reviewer should consider the geologic constraints that the owner/operator has used to interpret the pumping test results. Incorrect assumptions regarding geology may translate into incorrect estimations of hydraulic conductivity.

In reviewing the owner/operator's hydraulic conductivity measurements, the technical reviewer should use the following criteria to determine the accuracy or completeness of information.

- Values of hydraulic conductivity between wells in similar lithologies should not exceed one order of magnitude difference. If values exceed this difference, the owner/operator may not have provided enough information to sufficiently define a potential flow path, or there is a mistake in the logs.
- Hydraulic conductivity determinations based upon multiple well tests are preferred. Multiple well tests provide more complete information because they characterize a greater portion of the subsurface.
- Use of single well tests will require that more individual tests be conducted at different locations to sufficiently define hydraulic conductivity variation across the site.
- Hydraulic conductivity information generally provides average values for the entire area across a well screen. For more depth discrete information, well screens will have to be shorter. If the average hydraulic conductivity for a formation is required, entire formations may have to be screened, or data taken from overlapping clusters.

It is important that measurements define hydraulic conductivity both vertically and horizontally across an owner/operator's regulated site. Laboratory tests may be necessary to ascertain vertical hydraulic conductivity in saturated formations or strata. In assessing the completeness of an owner/operator's hydraulic conductivity measurements, the technical reviewer should also consider results from the boring program used to characterize the site geology. Zones of high permeability or fractures identified from drilling logs should have been considered in the determination of hydraulic conductivity. Additionally, information from boring logs can be used to refine the data generated by single well or pumping tests.

1.4 Identification of the Uppermost Aquifer

The owner/operator is required under 40 CFR §265 Subpart F to monitor the uppermost aquifer beneath the facility in order to immediately detect a release. Proper identification of the uppermost aquifer is therefore essential to the establishment of a compliant ground-water monitoring system. EPA has defined the uppermost aquifer as the geologic formation, group of formations, or part of a formation that is the aquifer nearest to the ground surface and is capable of yielding a significant amount of ground water to wells or springs (40 CFR §260.10) and may include fill material that is saturated. The identification of the confining layer or lower boundary is an essential facet of the definition of uppermost aquifer. There should be very limited interconnection, based upon pumping tests, between the uppermost aquifer and lower aquifers.* If zones of saturation capable of yielding significant amounts of water are interconnected, they all comprise the uppermost aquifer. Quality and use of ground water are not factors in the definition. Even though a saturated formation may not be presently in use, or may contain water not suitable for human consumption, it may deserve protection because contaminating it may threaten human health or the environment. Identification of formations capable of "significant yield" must be made on a case-by-case basis.

There are saturated zones, such as low permeability clay, that do not yield a significant amount of water, yet act as pathways for contamination that can migrate horizontally for some distance before reaching a zone which yields a significant amount of water. If there is reason to believe that a potential exists for contamination to escape along such pathways, the technical reviewer may invoke enforcement and permitting authorities other than §265.91 to require such zones to be monitored. These authorities include 3008(h) for interim status

---

*Some hydrogeologic settings (e.g., basin and range provinces, alluvial depositional environments) do not offer a clear confining layer. In such cases, the technical reviewer should note the situation and concentrate on the placement of wells in the uppermost aquifer to immediately detect potential releases of contaminants.

corrective action, 3004(u) for corrective action for permitting, the omnibus condition authority under 3005(c) which mandates permit conditions to protect human health and the environment, and 3013 authority which permits broad investigations. Of course, if a release has been detected the plume should be characterized in such saturated zones regardless of yield.

In all cases, the obligation to assess any hydraulic communication and the proper definition of the uppermost aquifer rests with the owner/operator. The owner/operator should be able to prove that the confining unit is of sufficiently low permeability as to minimize the passage of contaminants to saturated, stratigraphically lower units.

The following examples illustrate geologic settings wherein hydraulic communication must be demonstrated before proper identification of the uppermost aquifer can be made. The examples are not intended to be exhaustive in the situations they portray; rather, they are meant to provide a sample of geologic settings that depict hydraulic communication.

Figure 1-9 illustrates a site where preliminary drill logs indicated a confining layer of unfractured, continuous clay beneath the site. (Note: the actual geologic conditions are pictured for purposes of clarity in the figure.) In order to confirm whether the clay layer is continuous or discontinuous, the owner/operator conducted a pumping test. A well at drill point No. 2 was screened at the uppermost part of the potentiometric surface. Another well at drill point No. 3 was located close by and screened below the clay layer. Measurable drawdown was observed in the upper well when the well below the confining layer was pumped. This indicated that the confining unit is not of sufficient impermeability to serve as a significant boundary to contaminant flow. In this case, the water-bearing unit below the clay layer and the formation above the clay layer are both part of the uppermost aquifer.

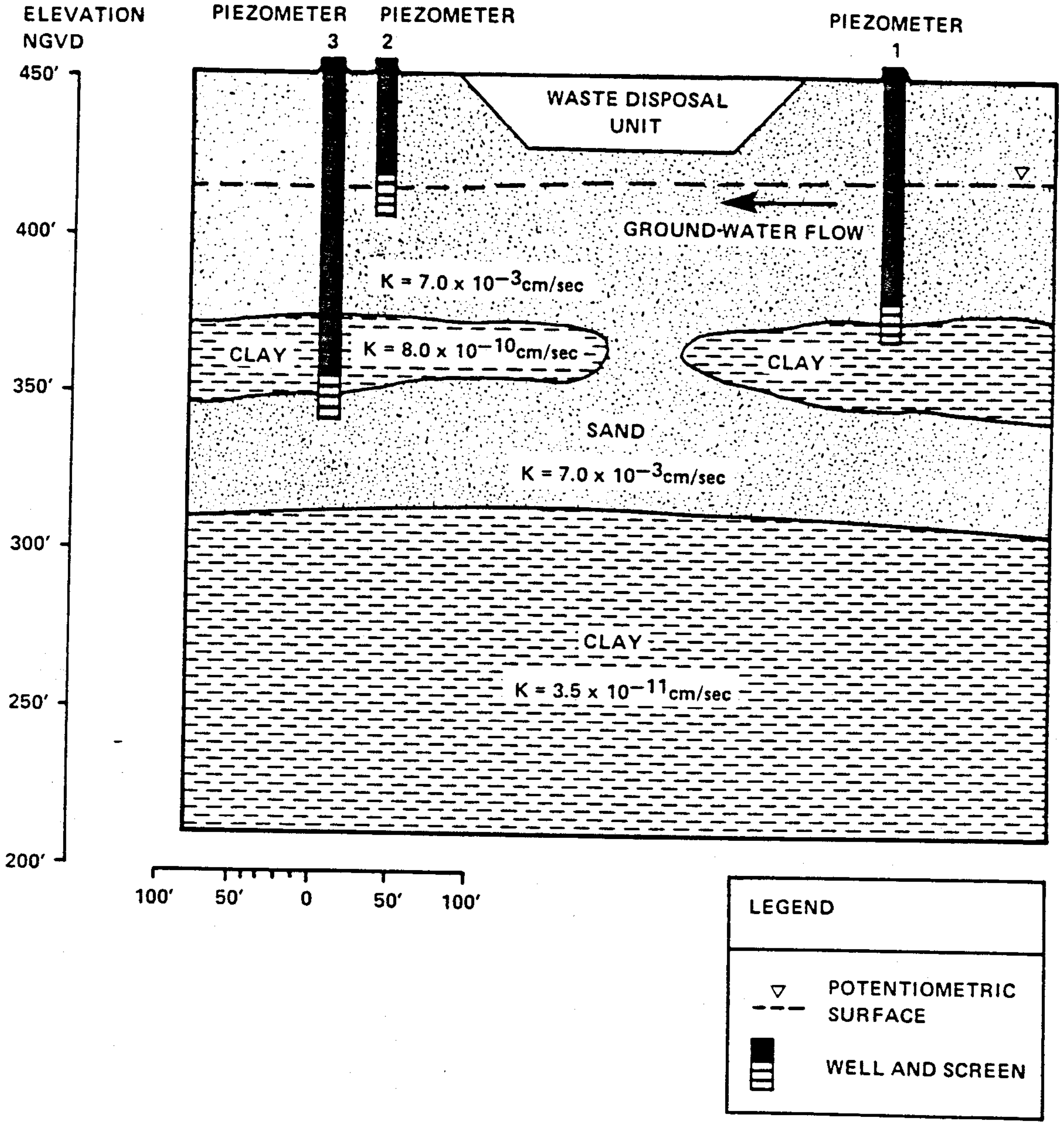


FIGURE 1-9 EXAMPLE OF HYDRAULIC COMMUNICATION BETWEEN WATER - BEARING UNITS

In Figure 1-10, the owner/operator drilled test borings through sand and limestone formations into a sandstone unit. In the initial cores, no indication of fracturing of the limestone unit was observed. The owner/operator initially assumed that the limestone unit dips at a moderate slope due to differing levels of contact. However, as illustrated by the figure, actual conditions involve faulting and post-depositional erosion of the limestone formation (additional corings and geophysical studies detected fracture zones). These fractures represent hydraulic communication between the upper unconsolidated sand layer and the sandstone formation below the limestone unit. The uppermost aquifer, therefore, includes the unconsolidated sand formation, the limestone formation, and the sandstone formation.

Figure 1-11 illustrates a situation where perched water zones lie above the potentiometric surface. The containment pathway includes the perched water zones and that part of the sand formation from the top of the potentiometric surface to the top of the granitic basement.

In Figure 1-12, initial test borings indicated that horizontal sand units are underlain by a consolidated, well-cemented, limestone unit. Initial borings did not indicate the presence of the anticline. The owner/operator incorrectly assumed that the sandstone unit was a confining layer that extended across the subsurface below the site. A dolomite unit, in contact with the unconsolidated sandy silts and directly below the waste unit, is fractured and highly permeable. Additional investigation including pump tests, borings, and/or geophysical analysis better defined the subsurface. The uppermost aquifer, in this case, includes the anticlinal formations.

In Figure 1-13, unconsolidated units are underlain by a consolidated series of variable, near-shore, shallow marine sediments. The owner/operator has installed three borings near the waste management unit to identify the uppermost aquifer. Interpretation of these borings indicates that the unconsolidated units are underlain by a well-cemented limestone

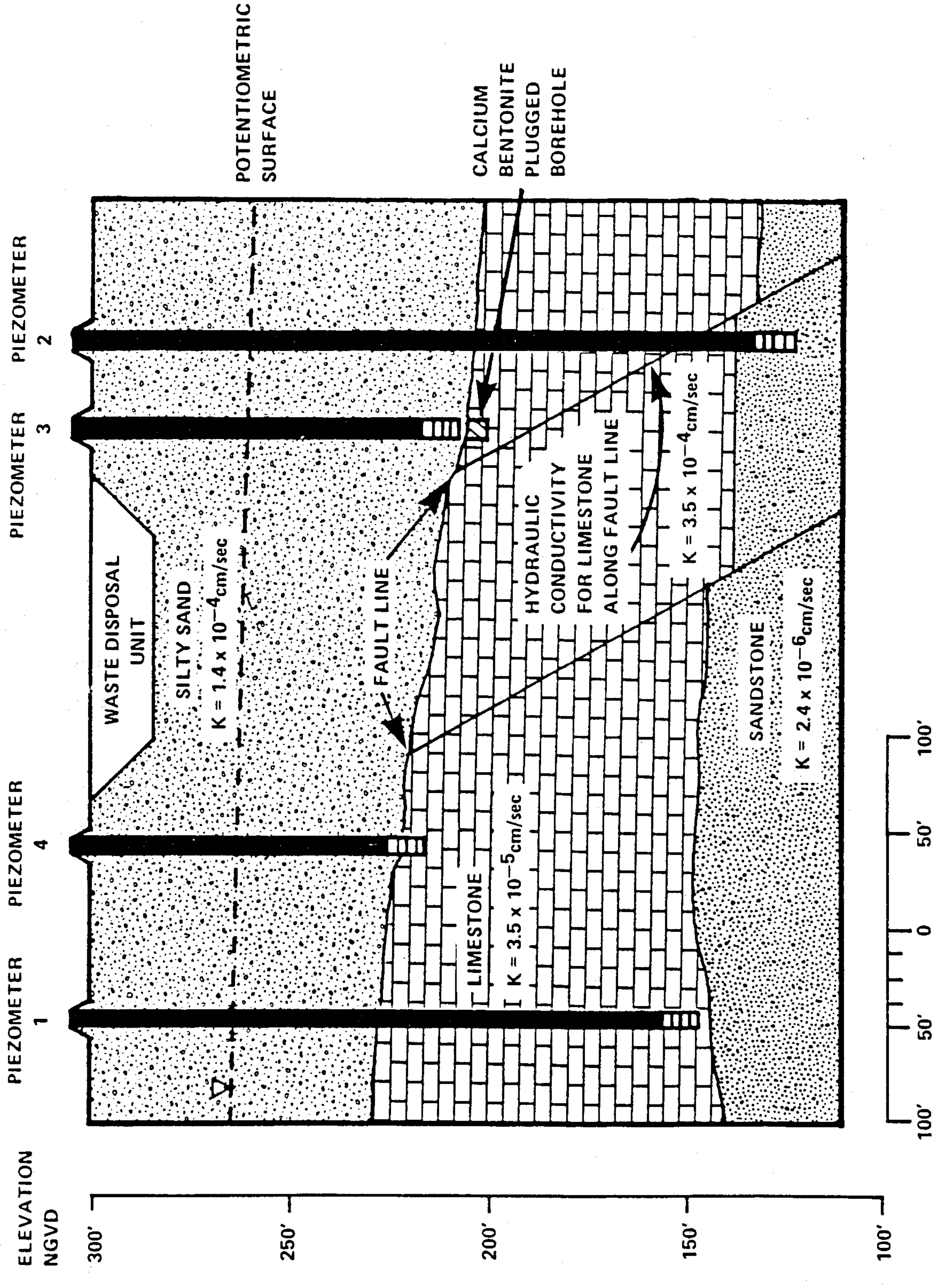


FIGURE 1-10 AN EXAMPLE OF HYDRAULIC COMMUNICATION CAUSED BY FAULTING

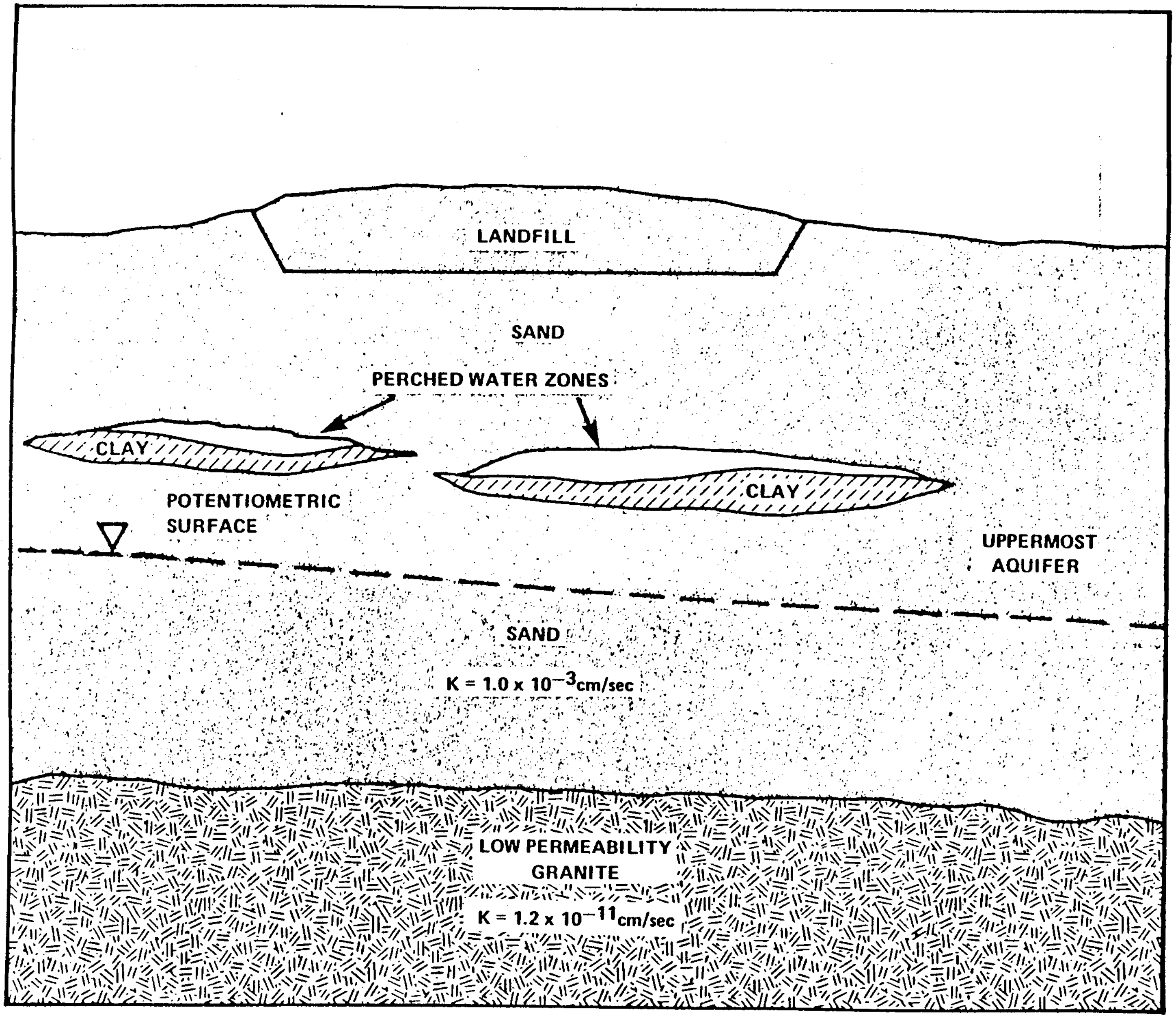


FIGURE 1-11 PERCHED WATER ZONES AS PART OF THE UPPERMOST AQUIFER

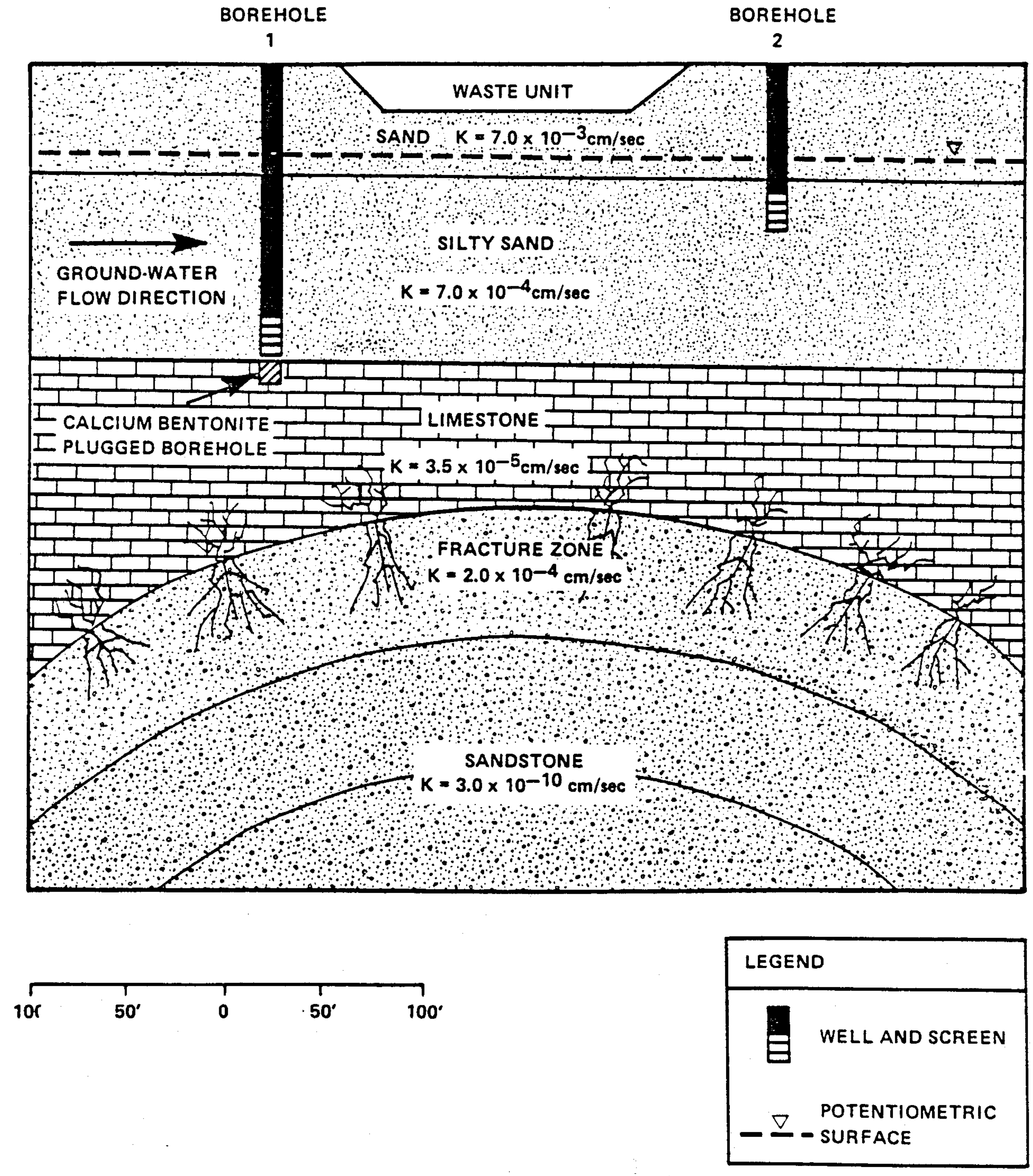


FIGURE 1-12 AN EXAMPLE OF AN UNDETECTED STRUCTURE IN THE UPPERMOST AQUIFER (VERTICAL SCALE IS EXAGGERATED).

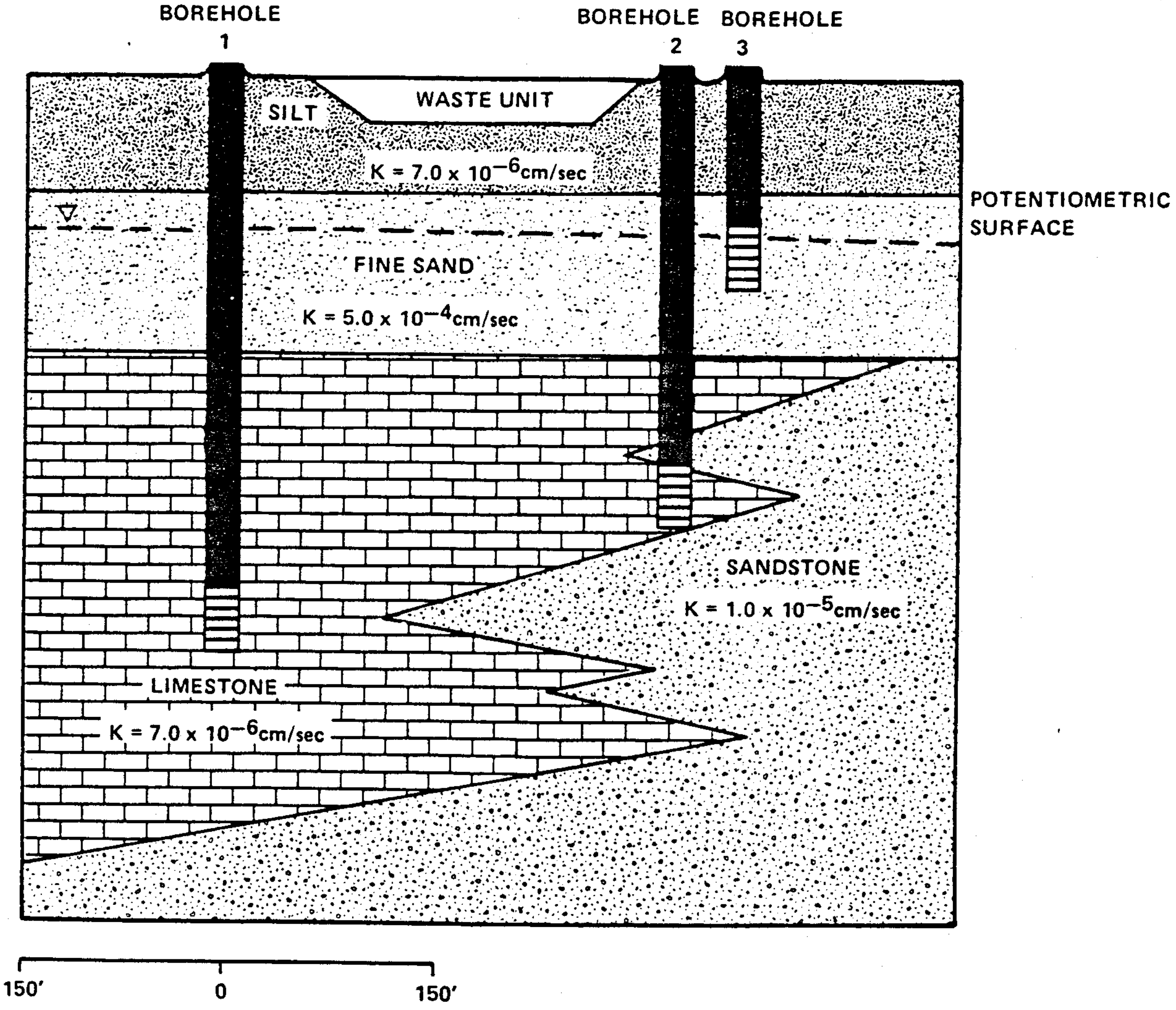


FIGURE 1-13 AN EXAMPLE OF AN UNDETECTED PORTION OF THE UPPERMOST AQUIFER DUE TO AN IMPROPERLY SCREENED BOREHOLE (VERTICAL SCALE IS EXAGGERATED)

of very low permeability. However, an undetected sandstone unit, which is laterally continuous with the limestone unit, is highly permeable and saturated and represents an undetected portion of the uppermost aquifer. Interpretation of the depositional environment of the limestone unit, coupled with a knowledge of the local or regional geology, should have been used in addition to other investigatory techniques to establish the presence of the transitional lateral structural feature and thus properly define the uppermost aquifer.

A special case that should be considered by the technical reviewer is the possibility that existing wells may provide avenues for hydraulic communication between hydrogeologic units. This is of special importance when considering a site where a contaminant plume may have migrated down-gradient to the extent that the plume approaches off-site wells. Such wells may not have been constructed in a manner sensitive to problems of cross-contamination between aquifers (see Chapter Four).

The goal of the site characterization is the identification of potential pathways for contaminant migration in the uppermost aquifer. The next step is to complete the installation of monitoring wells and piezometers in those pathways and upgradient, which will comprise the detection monitoring network.

REFERENCES

Anderson, D.C. and S.G. Jones. 1983. Clay Barrier-Leachate Interaction. Proceedings of the National Conference on Management of Uncontrolled Hazardous Waste Sites, pp. 154-160.

ASTM D2434-68. Reapproved 1974. Standard Test Method for Permeability of Granular Soils (Constant Head). Annual Book of ASTM Standards: Part 19 - Natural Building Stones; Soil and Rock. 7 pp.

Brown, K.W., J.C. Thomas, and J.W. Green. 1984. Permeability of Compacted Soils to Solvent Mixtures and Petroleum Products. Land Disposal of Hazardous Waste. 10th Ann. Res. Symp., pp. 124-137.

Freeze, R.A., and J.A. Cherry. 1979. Groundwater. Prentice-Hall, Inc.

Heath, Ralph C. 1983. Basic Ground-Water Hydrology. United States Geological Survey, Water Supply Paper 2220.

Pollack C.R., G.A. Robbins, and C.C. Mathewson. 1983. Groundwater Monitoring in Clay-Rich Strata--Techniques, Difficulties, and Potential Solutions. 3rd National Symp. of Aquifer and Groundwater Monitoring, pp. 347-354.

U.S. Army Corps of Engineers. 1970. Falling-Head Permeability Test with Permeameter Cylinder. Appendix VII, Section 4, Laboratory Soils Testing, Engineering Manual 1110-2-1906, pp. VII-13 to VII-16.

U.S. Army Corps of Engineers. 1970. Permeability Tests with Consolidometer. Appendix VII, Section 8, Laboratory Soils Testing, Engineering Manual 1110-2-1906, pp. VII-22 to VII-24.

U.S. Environmental Protection Agency. 1983. RCRA Draft Permit Writer's Ground-Water Protection, 40 CFR Part 264, Subpart F. U.S. Environmental Protection Agency Contract No. 68-01-6464.

U.S. Environmental Protection Agency. 1983. Ground-Water Monitoring Guidance for Owners and Operators of Interim Status Facilities. National Technical Information Service. PB83-209445.

U.S. Environmental Protection Agency. September 1985. Protection of Public Water Supplies from Ground-Water Contamination. EPA/625/4-85/016.

U.S. Department of Interior, Bureau of Reclamation. 1974. Designation E-15, One-Dimensional Consolidation of Soils. Earth Manual, 2nd Edition, pp. 509-521.

CHAPTER TWO

PLACEMENT OF DETECTION MONITORING WELLS

The purpose of this chapter is to examine criteria the technical reviewer should use in deciding if the owner/operator has made proper decisions regarding the number and location of detection monitoring wells. In evaluating the design of an owner/operator's detection monitoring system, the technical reviewer should examine the placement of upgradient and downgradient monitoring wells relative to hazardous waste management units, and review the placement and screening of detection monitoring wells for their interception of predicted pathways of migration. The minimum number of monitoring wells an owner/operator may install in a detection monitoring system under the regulations is four--one upgradient well and three downgradient wells. Typically, site hydrogeology is too complex or the hazardous waste unit is too large for the regulatory minimum number of wells to prove adequate in achieving the performance objectives of a detection monitoring system.

A fundamental concept that will be emphasized throughout this chapter is that the placement and screening of wells in the detection monitoring network will be based on the results of a thorough site characterization. The basic goals of the site characterization process as described in Chapter One are the description of the hydrogeological regime and the identification of the uppermost aquifer and potential pathways for contaminant migration. This information is the foundation for the entire ground-water monitoring program and crucial to the placement of detection monitoring wells in particular. It is likely that the technical reviewer may encounter situations where the owner/operator has collected little or no site hydrogeologic information or has relied exclusively on regional data to design a monitoring system. In this situation, the technical reviewer should carefully examine the decisions the owner/operator has made regarding well placement and screen depths, and it may be necessary to require the owner/operator to collect additional site information.

Upgradient monitoring wells are to provide background ground-water quality data in the uppermost aquifer. Upgradient wells must be (1) located beyond the upgradient extent of potential contamination from the hazardous waste management unit to provide samples representative of background water quality, (2) screened at the same stratigraphic horizon(s) as the downgradient wells to ensure comparability of data, and (3) of sufficient number to account for heterogeneity in background ground-water quality.

It is important to recognize that potential pathways for contaminant migration are three dimensional. Consequently, the design of a detection monitoring network that intercepts these potential pathways requires a three-dimensional approach. Downgradient monitoring wells must be located at the edge of hazardous waste management units to satisfy the regulatory requirements for immediate detection. The placement of detection monitoring wells along the downgradient perimeter of hazardous waste management units must be based upon the abundance, extent, and the physical/chemical characteristics of the potential contaminant pathways. The depths at which contaminants may be located and at which downgradient wells must be screened are functions of (1) geologic factors influencing the potential contaminant pathways of migration to the uppermost aquifer, (2) chemical characteristics of the hazardous waste controlling its likely movement and distribution in the aquifer, and (3) hydrologic factors likely to have an impact on contaminant movement (and detection). The consideration of these factors in evaluating the design of detection monitoring systems is described in Section 2.1.3.

A sufficient number of detection monitoring wells screened at the proper depths must be installed by the owner/operator to ensure that the ground-water monitoring system provides prompt detection of contaminant releases. A detection monitoring system should be judged against site-specific conditions; however, there are a number of criteria that technical reviewers can apply to ensure that detection monitoring systems satisfy the RCRA regulatory requirements. This chapter describes those criteria and provides examples on how technical reviewers can evaluate detection monitoring systems in various hydrologic situations. This chapter also examines three common geologic environments: alluvial, karst, and a glacial till. The rationale for well placement and vertical sampling intervals within each geologic environment is discussed.

2.1 Placement of Downgradient Detection Monitoring Wells

The criteria for evaluating the location of downgradient wells relative to waste management areas are described in Section 2.1.1. Section 2.1.2 contains the criteria for evaluating horizontal placement of downgradient detection wells. Section 2.1.3 details the rationale for selection of the vertical placement and sampling intervals of detection monitoring wells. Discussed in Section 2.1.4 are three geologic settings that have been encountered at hazardous waste sites and the rationale for detection well placement at each site.

2.1.1 Location of Wells Relative to Waste Management Areas

In order to immediately detect releases as required by the regulations, the owner/operator must install downgradient detection monitoring wells adjacent to hazardous waste management units. In a practical sense, this means the owner/operator must install detection monitoring wells as close as physically possible to the edge of hazardous waste management unit(s). The two drawings in Figure 2-1 (A and B) illustrate the concept of the placement of wells immediately adjacent to hazardous waste management unit(s). Note: the placement of wells relative to the units shifts as a function of the direction of ground-water flow.

Geologic environments with discrete solution channels such as Karst formations must have detection monitoring wells located in those solution channels likely to serve as conduits for contamination migration.

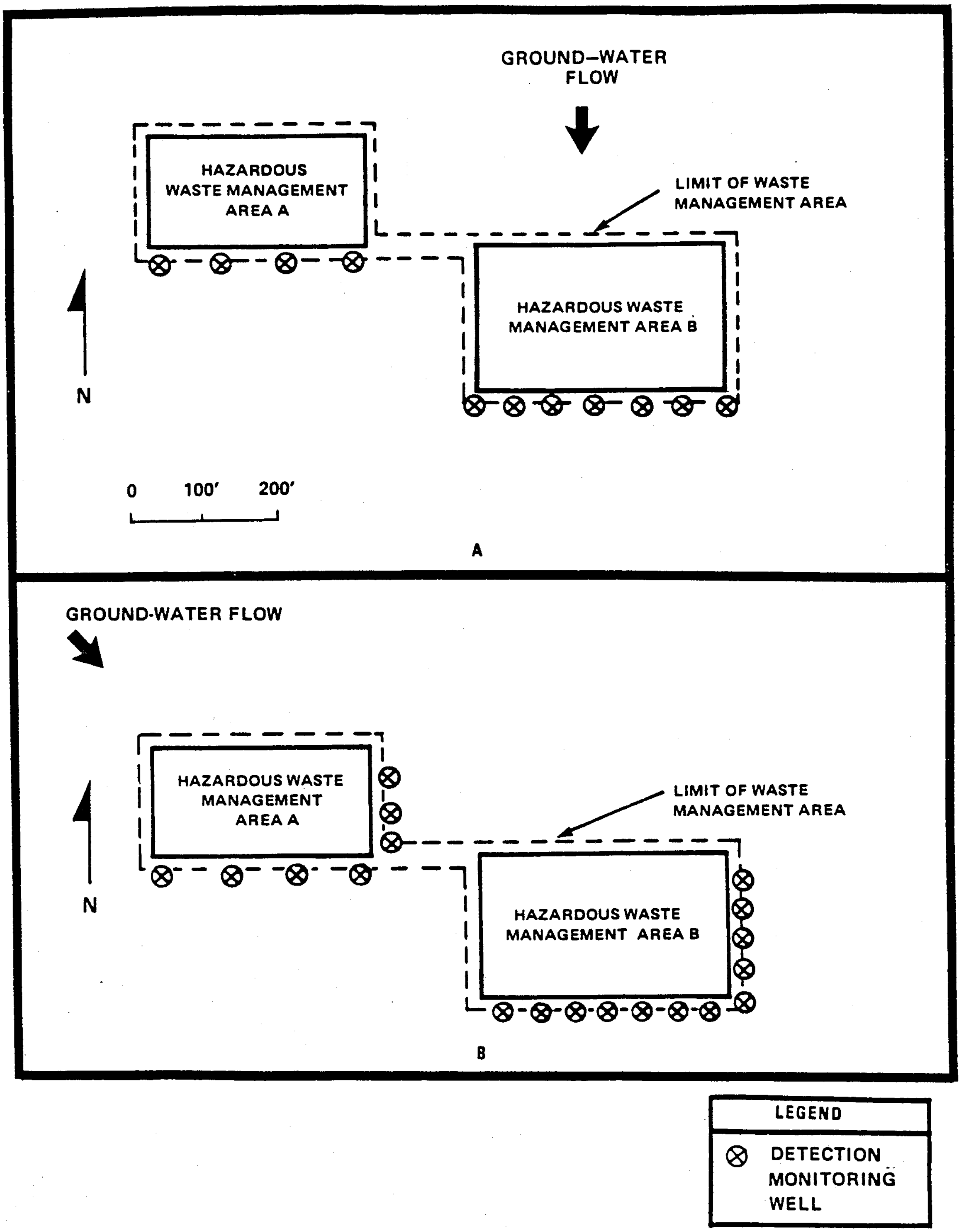


FIGURE 2-1 DOWNGRADIENT WELLS IMMEDIATELY ADJACENT TO HAZARDOUS WASTE MANAGEMENT LIMITS

At sites underlain by interbedded, unconsolidated sands, silts, and clays (e.g., alluvial facies) where the potentiometric surface is deep-seated, the lateral component of contaminant migration may carry contaminants beyond the ground-water monitoring system before they reach ground water, and therefore beyond detection. The owner/operators could institute a program of vadose zone monitoring as a supplement to the ground-water monitoring program in such cases, to provide immediate detection of any release(s) from the hazardous waste management area. Volatile organics that escape to the vadose zone, for instance, may be detected and characterized through soil gas analysis.

2.1.2 Horizontal Placement of Downgradient Monitoring Wells

The horizontal placement of detection monitoring wells along the downgradient perimeter of hazardous waste management units should be predicated on the interception of potential pathways for contaminant migration. The majority of hazardous waste sites will have identifiable pathways for potential contaminant migration. Some potential pathways for contaminant migration are: zones with relatively high intrinsic (matrix) hydraulic conductivities, fractured/faulted zones, solution channels, and zones suspected to be incompatible with the waste(s) present. Sites located in heterogeneous geologic settings can have numerous, discrete zones of potential migration. Each zone of potential migration must be identified and monitored.

Within a potential migration pathway, the horizontal distance between wells should be based upon site-specific factors such as those described in Table 2-1 should be considered by technical reviewers when evaluating the horizontal distance between detection wells. These factors cover a variety of physical and operational aspects relating to the facility, including hydrogeologic setting, dispersivity, seepage velocity, facility design, and waste characteristics.

TABLE 2-1

FACTORS INFLUENCING THE INTERVALS BETWEEN INDIVIDUAL MONITORING WELLS WITHIN A POTENTIAL MIGRATION PATHWAY

<u>WELL INTERVALS MAY BE CLOSER IF THE SITE</u>:	<u>WELL INTERVALS MAY BE WIDER IF THE SITE</u>:
• Manages or has managed liquid waste	
• Is very small	
• Has fill material near the waste management units (where preferential flow might occur)	
• Has buried pipes, utility trenches, etc., where a point-source leak might occur	
• Has complicated geology - closely spaced fractures - faults - tight folds - solution channels - discontinuous structures	• Has simple geology - no fractures - no faults - no folds - no solution channels - continuous structures
• Has heterogeneous conditions - variable hydraulic conductivity - variable lithology	• Has homogeneous conditions - uniform hydraulic conductivity - uniform lithology
• Is located in or near a recharge zone	
• Has a steep or variable hydraulic gradient	• Has a low (flat) and constant hydraulic gradient
• Is characterized by low dispersivity potential	• Is characterized by high dispersivity potential
• Has a high seepage velocity	• Has a low seepage velocity

In the less common homogeneous geologic setting where no preferred pathways are identified, a more regular well placement pattern can be utilized based on formational characteristics (e.g., dispersivity, hydraulic conductivity, and other factors listed in Table 2-1).

2.1.3 Vertical Placement and Screen Lengths

This document addresses separately the horizontal placement and the vertical sampling intervals of detection monitoring wells. These two parameters, however, should be evaluated together in the design of the ground-water detection monitoring system. Proper selection of the vertical sampling interval provides the third dimension to the detection monitoring of potential contaminant pathways to the uppermost aquifer. Site-specific hydrogeologic data obtained by the owner/operator during the site characterization are essential for the determination of the horizontal placement of detection wells, and for the selection of the vertical sampling interval(s). Proper design of a detection monitoring system enables the owner/operator to select the vertical sampling interval capable of immediately detecting a release from the hazardous waste management area. It is essential, therefore, that the owner/operator's decisions regarding vertical sampling intervals are based upon a full site characterization, which defines both the depth and thickness of the stratigraphic horizon(s) that could serve as contaminant pathways. There are several guidelines or criteria that the technical reviewer should follow in evaluating owner/operator decisions. A discussion of these guidelines follows in the examples in Section 2.1.4.

The owner/operator should have determined from the site characterization which stratigraphic horizons represent potential pathways for contaminant migration, and should screen monitoring wells at the appropriate horizon(s) to provide immediate detection of a release. It is extremely important to screen upgradient and downgradient wells in the same stratigraphic horizon(s) to obtain comparable ground-water quality data, as long as the strata are not dipping too strongly. The owner/operator should have ensured and demonstrated that the upgradient and downgradient well screens intercepted the same uppermost aquifer. The determination of the depth to a potential contaminant migration pathway may be made from soil/rock cores, supplemented by geophysical and available regional/local hydrogeological data.

Another factor to be considered in selecting the depth at which wells should be placed (and the selection of well screen lengths) is the physical/chemical characteristics of the hazardous waste or hazardous waste constituents controlling the movement and distribution of contamination in the aquifer. The technical reviewer should consider the mobility of the hazardous waste, its potential reaction products, and the potential for chemical degradation of clays. Different transport processes control contaminant movement depending on whether the contaminant dissolves in water or is immiscible. Immiscible contaminants may vary from extremely light volatiles to dense organic liquids whose migration is governed largely by density and viscosity. Lighter than water phases spread rapidly in the capillary zone just above the potentiometric surface. Alternatively, "the migration of dense organic liquids is largely uncoupled from the hydraulic gradient that drives advective transport and movement may have a dominant vertical component even in horizontally flowing aquifers" (MacKay, et al., 1985).

In addition to the normal flow of ground water (advection), the chemical processes of dispersion and sorption (retardation) greatly influence the potential migration pathways of contaminants within an aquifer. Dispersion is the spread of contaminants resulting from molecular diffusion and mechanical mixing and "may result in the arrival of detectable contaminant concentrations at a given location significantly before the arrival time that is expected solely on the basis of the average ground-water flow rate" (MacKay, et al., 1985). The mobility of different leachate constituents will vary depending upon the extent to which each constituent is adsorbed to solid surfaces (sorption processes). Some nonreactive ionic species (e.g., chloride ion) and low molecular weight organics of relatively high water solubility (e.g., trichloroethylene) can be quite mobile. Heavy metals (e.g., lead) and organics with high molecular weights and relatively low solubilities in water (e.g., chlorinated benzenes) tend to be the least mobile in natural conditions of near neutral pH and Eh.

All of these processes are important in choosing the depth of the screened interval and locating monitoring wells, because contaminants may be confined to and move within narrow zones. For instance, to monitor for heavy metals the screened interval should be just above the confining layer--for light organics, at the potentiometric surface/capillary zone interface. The local lithological variation can influence the rate, quantity, and degree of sorption of particular contaminants and is important in the proper location of monitoring wells.

Studies have shown that certain organic liquids can cause desiccation cracks in clay which can lead to significant increases in permeability. When organic chemicals and strongly acidic wastes are present, the compatibility of these wastes and chemicals with any potentially confining clay layer(s) should be confirmed.

Determination of the appropriate thickness of the vertical sampling interval(s) is a natural extension of the depth selection. The owner/operator should have made the decision on the basis of site characterization data. Sources of information that can be used in determining the thickness of potential contaminant pathways can include isopach maps of highly permeable strata, coring data, sieve analysis, and fracture traces.

The lengths of well screens used in ground-water monitoring wells can be a significant factor in the detection of releases of contaminants. The complexity of the hydrogeology at a site is an important consideration when selecting the lengths of well screens. Most hydrogeologic settings are complex (heterogeneous, anisotropic) and the permeability is variable with depth due to interbedded sediments. Highly variable formations require shorter well screens, which allow sampling of discrete portions of the formation. Longer well screens that span more than a single flow zone can result in excessive dilution of a contaminant present in one zone by uncontaminated ground water in another zone. This dilution can make contaminant detection difficult or impossible, since contaminant concentrations may be reduced to levels below the detection limits for the prescribed analytical methods.

Even in hydrologically simple (homogeneous) formations or within a potential pathway for contaminant migration, the use of shorter well screens may be required to detect contaminants concentrated at a particular depth. A contaminant may be concentrated at a particular depth because of its physical/chemical properties and/or hydrologic factors. In this situation, a longer well screen (length of well screen >> thickness of the contamination zone) can permit excessive amounts of uncontaminated formation water to dilute the contaminated ground water entering the well. This resultant dilution may prevent the detection of statistically significant changes in indicator parameters (pH changes) and, in extreme cases, the diluted concentration of contaminants may be below detection limits of the laboratory method being used.

The use of shorter well screens helps to maintain chemical resolution by reducing excessive dilution and, when placed at depths of predicted preferential flow, such screens can monitor the aquifer or portion of the aquifer of concern. The importance of determining these preferential flow paths in the ground-water monitoring process confirms the need for a complete hydrogeologic site investigation prior to the design and placement of detection wells.

Monitoring wells can be used to confirm or detect changes in ground-water flow directions (determined during the site characterization) by comparisons of potentiometric levels in neighboring wells. In heterogeneous geologic settings, however, longer well screens can intercept stratigraphic horizons with different (contrasting) ground-water flow directions. In this situation, the potentiometric surface will not provide the depth discrete head measurements required for accurate ground-water flow direction determination.

Certain hydrogeologic settings necessitate the use of longer well screens for detection monitoring. Hydrogeologic settings with widely fluctuating potentiometric surfaces are better monitored with longer screens that continuously intercept the water surface and provide monitoring for the presence of contaminants less dense than water. Formations with low hydraulic conductivities can also necessitate the use of longer well screens to allow sufficient amounts of formation water to enter the well for sampling.

Note: The vertical sampling interval is not necessarily synonymous with aquifer thickness. In other words, the owner/operator may select an interval which represents a portion of the thickness of the uppermost aquifer. When a single well cannot adequately intercept and monitor the vertical extent of a potential pathway of contaminant migration at each sampling location, the owner/operator should have installed a well cluster. A well cluster is a number of wells grouped closely together but not in the same borehole and often screened at different stratigraphic horizons. The greater the need for stratified sampling, the more wells the owner/operator should place in a cluster. The use of well clusters is illustrated in the examples in Section 2.1.4.

There are situations where the owner/operator should have multiple wells at a sampling location and others where typically one well is sufficient. They are summarized in Table 2-2. The potential for

TABLE 2-2

FACTORS AFFECTING NUMBER OF WELLS PER LOCATION (CLUSTERS)

One Well Per Sampling Location	More Than One Well Per Sampling
• No "sinkers" or "floaters" (immiscible liquid phases; see glossary for more detail)	• Presence of sinkers or floaters
• Thin flow zone (relative to screen length)	• Heterogeneous uppermost aquifer; complicated geology - multiple, interconnected aquifers - variable lithology - perched water zone - discontinuous structures
• Homogeneous uppermost aquifer; simple geology	• Discrete fracture zones

immiscibles in a thick, complex saturated zone of the uppermost aquifer should prompt the owner/operator to use well clusters. Conversely, in situations where ground water is contaminated by a single contaminant, and geologically there is a thin saturated zone within the uppermost aquifer or homogeneous hydrologic properties are prevalent in the uppermost aquifer, the need for multiple wells at each sampling location is reduced. The number of wells screened at specific depths that should be installed at each sampling location increases with site complexity. Each potential contaminant pathway must be screened to ensure prompt detection of a hazardous waste or hazardous waste constituent release.

2.1.4 Examples of Detection Well Placement in Three Common Geologic Environments

The following examples are based on actual geologic environments encountered during hydrogeologic investigations. The three geologic settings presented--a Karst, an alluvial, and a glacial till--are not intended to be inclusive of all hydrogeologic factors; however, they are illustrative of the technique used in the design of a minimum detection monitoring system. The basic steps in the development of a detection monitoring network include: (1) a review of existing information to determine the regional geologic regime and regional ground-water flow rates and direction; (2) a hydrogeologic investigation of the site to determine the depth to and the extent of the uppermost aquifer; the presence and extent of any confining layers/units; the abundance, location(s), and extent of any potential pathways for contaminant migration; and the direction and flow rates of the ground water; (3) a review of the waste analysis plan to determine the chemical/physical properties that may affect the distribution of a contaminant in the aquifer; (4) the installation of detection wells in order to intercept and completely monitor the potential pathways of contaminant migration; (5) the selection of well screen lengths to provide resolute ground-water samples; and (6) the placement/screening of upgradient monitoring wells to provide representative background samples.

Figures 2-2, 2-3, and 2-4 depict a block diagram, a cross section, and plan views of two lined waste impoundments located in a glacial till environment. This heterogeneous glacial terrain is encountered in many parts of the country, especially northern states. A review of the published regional geologic data aided the subsequent and thorough site-specific hydrogeologic investigation that made it possible to identify three lithologic units in the upper 100 feet of sediments overlying a granite with low hydraulic conductivity. These units were identified by geologic and geophysical analysis. Color, grain size, and texture were also used to characterize each unit. Two sand units are separated by an undulating glacial till varying between 10 and 50 feet thick. Pumping/slug tests were conducted to determine the hydraulic conductivities of each unit. These tests in conjunction with piezometer (not shown in Figure 2-3) readings identified hydraulic intercommunication between the two sand units. This vertical flow from the upper sand unit to the lower sand unit is predominantly a function of the thickness and continuity of the till unit. In locations where the till is thinnest, vertical flow is most prevalent. Borings show that the granite confining unit extends laterally across the entire site. Therefore, the uppermost aquifer includes the two sand units and the till.

Flow in the upper sand unit is southerly, towards a nearby river, and has a moderate hydraulic gradient of 0.01. Flow in the lower sand is representative of regional ground-water flow generally to the southeast. This lower outwash sand has a low hydraulic gradient of .004. Figure 2-4 contains two plan views showing the equipotential lines in the upper and lower sand units. These equipotential lines were drawn using information from the well/piezometric data tabulated on Figure 2-4. The block diagram in Figure 2-2 illustrates the multiple ground-water flow paths present in this glacial terrain. The southern and eastern perimeters of the waste lagoons are downgradient and therefore require monitoring. The cross section in Figure 2-3 depicts the well placement

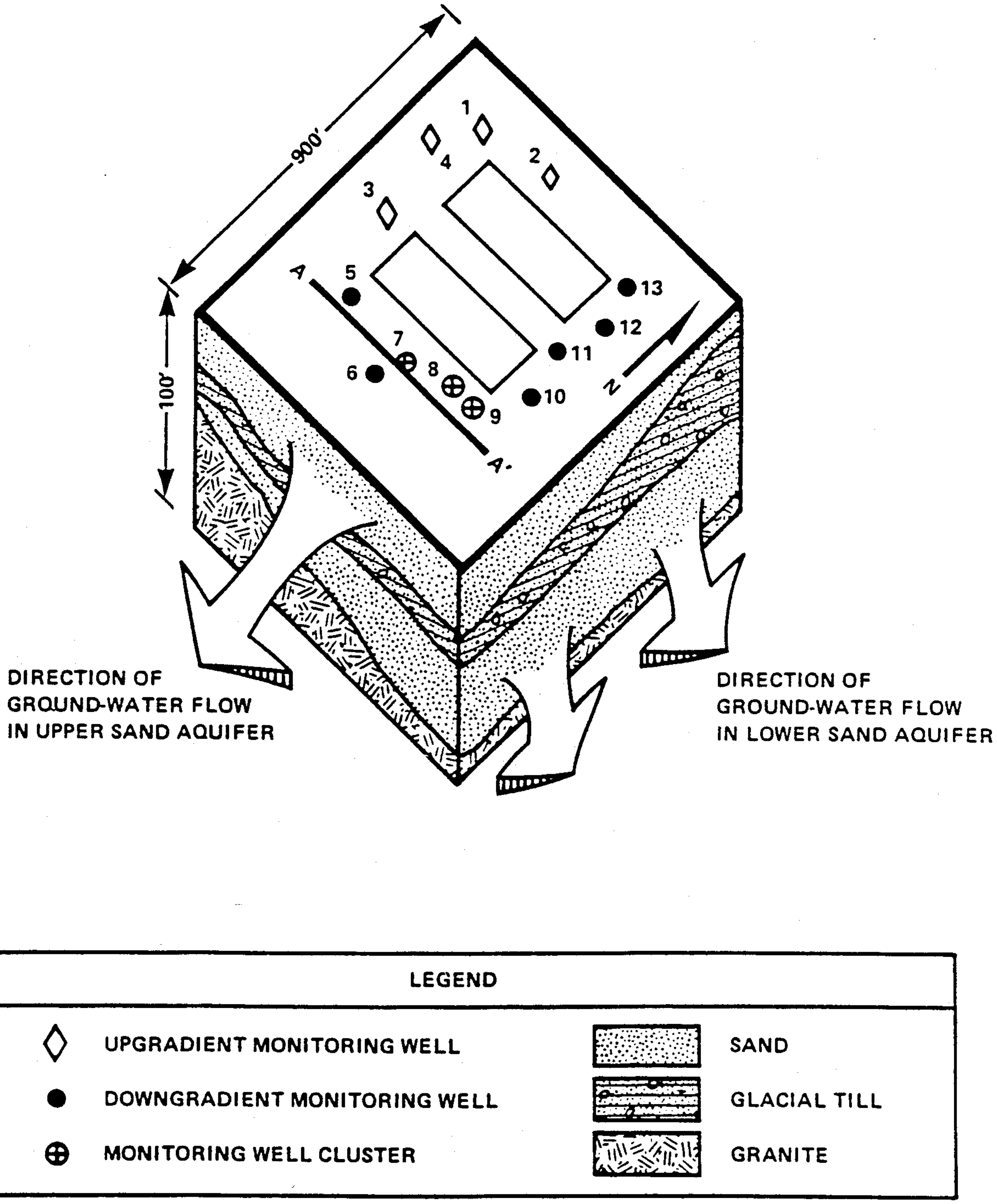


FIGURE 2-2 ILLUSTRATION OF MULTIPLE GROUND-WATER FLOW PATHS IN THE UPPERMOST AQUIFER DUE TO HYDROGEOLOGIC HETEROGENEITY

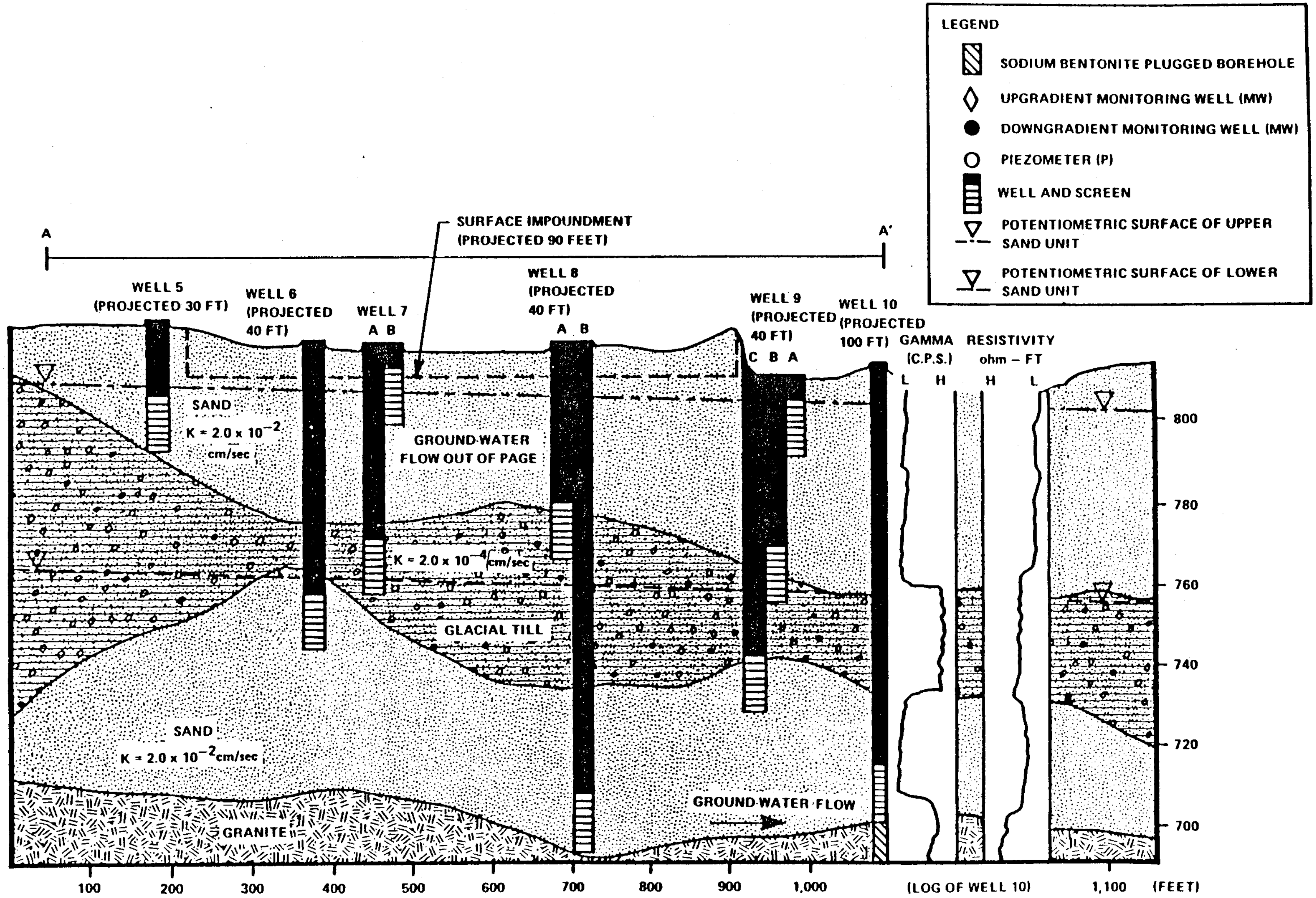
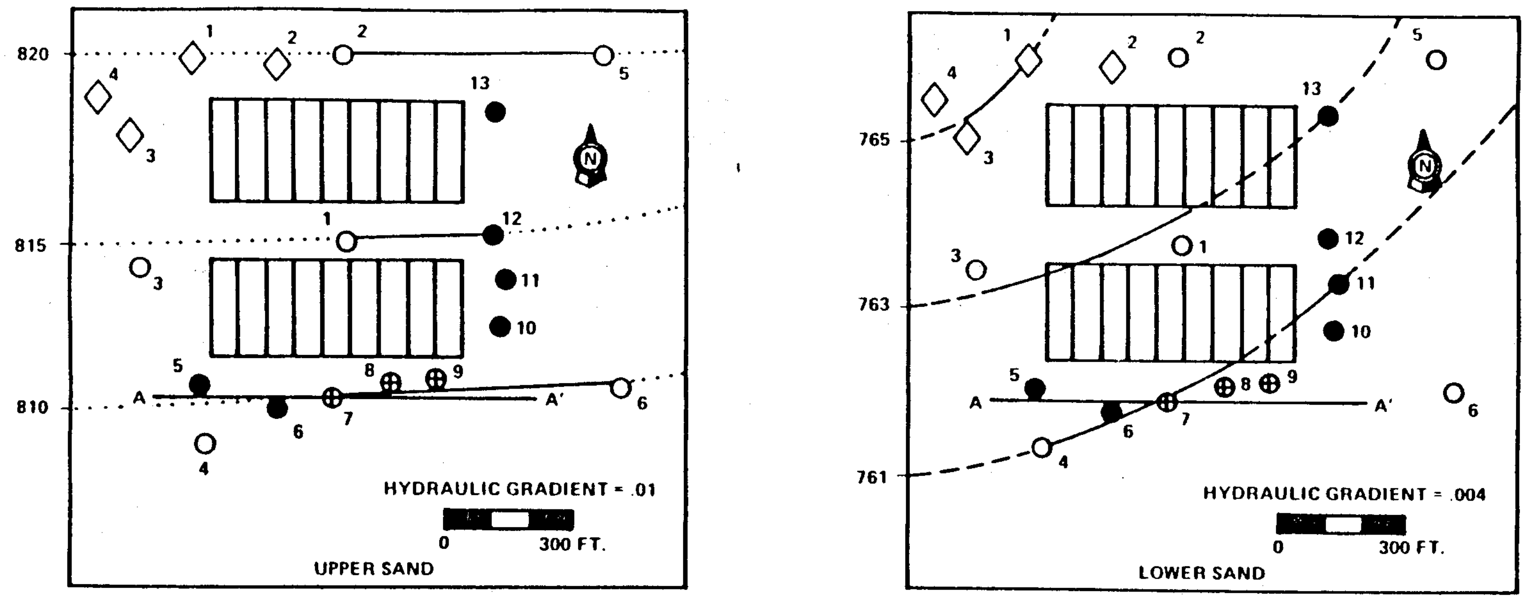


FIGURE 2-3 MONITORING WELL PLACEMENT AND SCREEN LENGTHS IN A GLACIAL TERRAIN



A

B

MONITORING WELL/PIEZOMETER TOP OF CASING ELEVATIONS
(IN FEET RELATIVE TO NATIONAL GEODETIC VERTICAL DATUM)

P1	815.35	(4/1/85)	MW 1	765.04	(4/2/85)
P2	819.81	(4/1/85)	MW 2	765.10	(4/2/85)
P3	763.19	(4/2/85)	MW 6	761.60	(4/2/85)
P4	761.48	(4/2/85)	MW 7A	811.30	(4/1/85)
P5	819.50	(4/1/85)	MW 7B	761.55	(4/1/85)
P6	811.26	(4/1/85)	MW 9A	811.45	(4/1/85)
			MW 11	761.59	(4/2/85)
			MW 12	815.67	(4/1/85)
			MW 13	763.24	(4/2/85)

FIGURE 2-4 A & B. PLAN VIEW OF FIGURE 2-3 SHOWING LINES OF EQUIPOTENTIAL IN THE UPPER (A) AND LOWER (B) SAND UNITS

and screen lengths for the detection monitoring network along the southern perimeter of the impoundment. Along the southern perimeter, the upper sand unit requires more stringent monitoring than the lower sand unit because of the higher ground-water velocity and steeper gradient in the upper zone. Any release must seep through the upper sand before it reaches the till. The hydraulic head resulting from the depth of liquid in the lagoons, and an inventory of wastes and byproducts, indicate the potential for "sinkers and floaters." The decision regarding horizontal well placement was also based upon the likely size of a leak, the distance from a leak source to the downgradient perimeter, dispersion, and seepage velocity. Well placement in the lower sand unit along the southern perimeter reflects the easterly component of ground-water flow in the lower sand, that is, wells screened in the lower sand are located toward the eastern end of the lagoons. It is important to note the care that must be taken to properly grout the boreholes (wells) penetrating the less permeable till to avoid increasing the (or cause a) hydraulic communication between the sand units.

Figure 2-5 illustrates a cross section and plan view of a landfill that may occur in an alluvial setting. A review of the regional and local geology indicated that the area was possibly underlain by interbedded sand and clay units. Split spoon samples collected during the site-specific characterization revealed a massive clay unit extending across the entire area at a depth of approximately 100 feet. Borehole samples and interpretation of geophysical logs suggested that two sand units overlie the massive clay, separated by a clay layer of variable thickness. The upper sand contains several clay lens, each averaging approximately 20 feet thick, beneath the disposal area. Pumping tests within the sand units provided hydraulic conductivity values for the sand units. Laboratory tests were used to determine hydraulic conductivity values for the clay. Further analysis of clay samples identified an illitic clay. Pumping tests across the intervening clay established hydraulic communication between the sand units with downward flow.

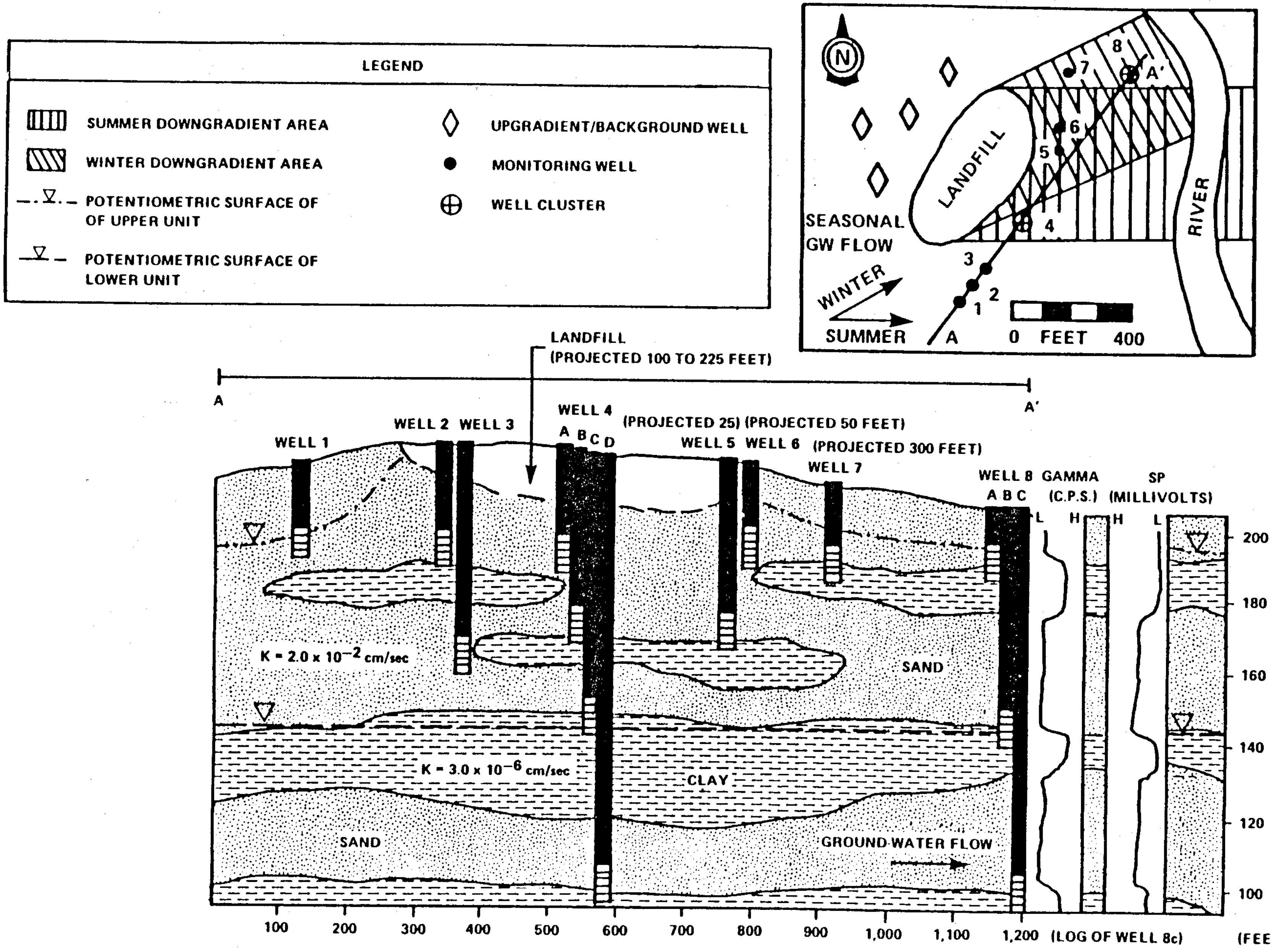


FIGURE 2-5 MONITORING WELL PLACEMENT AND SCREEN LENGTHS IN AN ALLUVIAL SETTING

It is determined through research and substantiated by piezometers that the direction of ground-water flow is predominantly east northeast (out of the page). This direction fluctuates seasonally, however, due to the influence of the river. In the summer, flow is toward the east; in the winter, it shifts to the northeast. The potentiometric surface in the upper sand varies by approximately six feet during the year. Dense phase immiscible wastes are known to be disposed of at the site.

The resultant horizontal and vertical placement of wells (and screen lengths) reflects all of the waste management practices and hydrogeologic factors at the site. The potential pathways for contaminant migration are the two sand units. A greater number of wells are established in the overlapping east-northeast flow zone, because ground-water flow there is continuous and not seasonal. Wells are also placed in the area of intermittent flow. Generally, the lengths of well screens installed at the site reflect the vertical extent of the potential contaminant pathway at the desired sampling location. However, shorter well screens (not fully penetrating the depth of the sand unit) are employed in the thick sand units where dilution effects may impair potential contaminant detection. Several wells are screened at the sand/clay interfaces where high specific gravity (dense) immiscibles may be expected to accumulate. Also, those screens that intercept the potentiometric surface in the upper sand are at least long enough to accommodate seasonal fluctuations in ground-water elevations.

Figure 2-6 illustrates a cross-sectional and plan view of a waste landfill situated in a mature Karst environment. This setting is characteristic of carbonate environments encountered in various parts of the country, but especially in the southeastern states. An assessment of the geologic conditions at the site, through the use of borings, geophysical surveys, aerial photography, tracer studies, and other geological investigatory techniques, made it possible to identify a mature Karst geologic formation characterized by well-defined sinkholes, solution

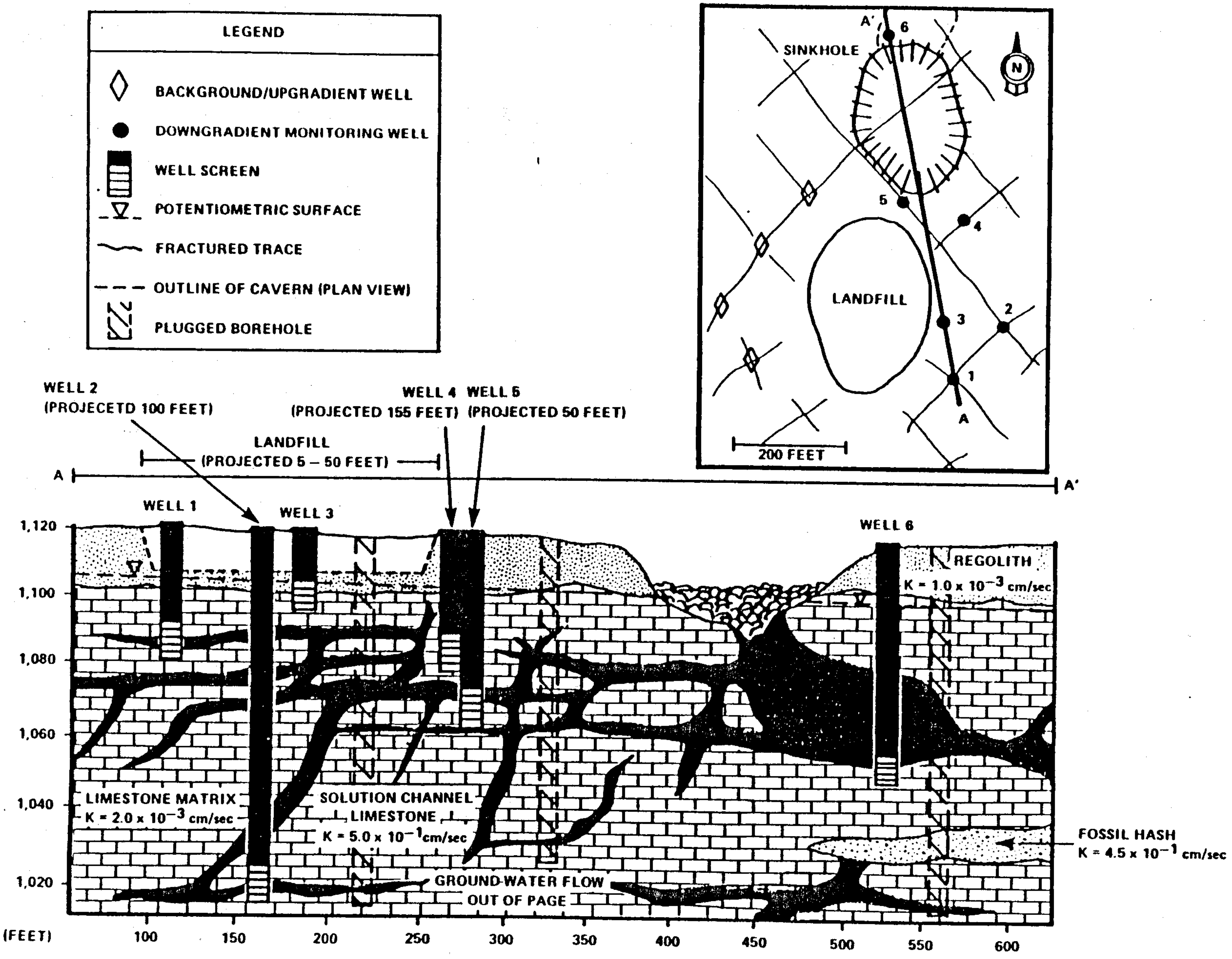


FIGURE 2-6 MONITORING WELL PLACEMENT AND SCREEN LENGTHS IN A MATURE KARST TERRAIN/FRACTURED BEDROCK SETTING

channels, and extensive vertical and horizontal fracturing in an interbedded limestone/dolomite. Using potentiometric data, ground-water flow direction was found to be to the east. Solution channels are formed by the flow of water through the fractures. The chemical reaction between the carbonate rock and the ground water in the fractures produces voids. These voids are referred to as solution channels. Through time, these solution channels are enlarged to the point where the weight of the overlaying rock (overburden) may be too great to provide support, thereby causing a "roof" collapse and the formation of a sinkhole. The location of these solution channels dictates the placement of detection monitoring wells. Note in the plan view the placement of well No. 2 is offset 50 feet from the perimeter of the landfill. The horizontal placement of well No. 2, although not immediately adjacent to the landfill, is necessary in order to monitor all potential contaminant pathways. The discrete nature of these solution channels dictates that each potential pathway be monitored.

The distance between the "floor" and "ceiling" (vertical extent) (height) of the solution channels ranges from three to six feet directly beneath the sinkhole to one foot under the landfill except for the 40-foot deep cavern. This limited vertical distance of the cavities allows for a full screened interval in the solution channels. (Note the change in orientation of solution channels due to the presence of the shell hash layer.)

2.2 Placement of Upgradient (Background) Monitoring Wells

The downgradient wells must be designed and installed to immediately detect releases of hazardous waste or hazardous waste constituents to the uppermost aquifer. The upgradient wells must be located and constructed to provide representative samples of ground water in the same portion of the aquifer monitored by the downgradient wells to permit a comparison of ground-water quality (40 CFR 265, Subpart F, 265.92(a)(1)).

There are at least three main questions that the technical reviewer should ask when reviewing the decisions the owner/operator has made regarding the placement of the background monitoring wells:

- Are the background wells far enough away from waste management areas to prevent contamination from the hazardous waste management units?
- Are enough wells installed and screened at appropriate depths to adequately account for spatial variability in background water quality?
- Are well clusters used at sampling locations to permit comparisons of background ground-water data with downgradient ground-water data obtained from the same hydrologic unit?

By regulation, the owner/operator must install as a minimum one background well. However, a facility that uses only one well for sampling background water quality may not be able to account for spatial variability. It is, in fact, a very unusual circumstance in which only one background well will fully characterize background ground-water quality. The owner/operator who makes comparisons of background and downgradient monitoring well results with data from only one background well increases the risk of a false indication of contaminant release. In most cases, the owner/operator should install multiple background monitoring wells in the uppermost aquifer to account for spatial variability in background water quality data.

The owner/operator should also install enough background monitoring wells to allow for depth-discrete comparisons of water quality. This means simply that for downgradient wells completed in a particular geologic formation, the owner/operator should install upgradient well(s) in the same portion of the aquifer, so that the data can be compared on a depth-discrete basis (Figure 2-7).

Owner/operators should avoid installing background monitoring wells that are screened over the entire thickness of the uppermost aquifer.

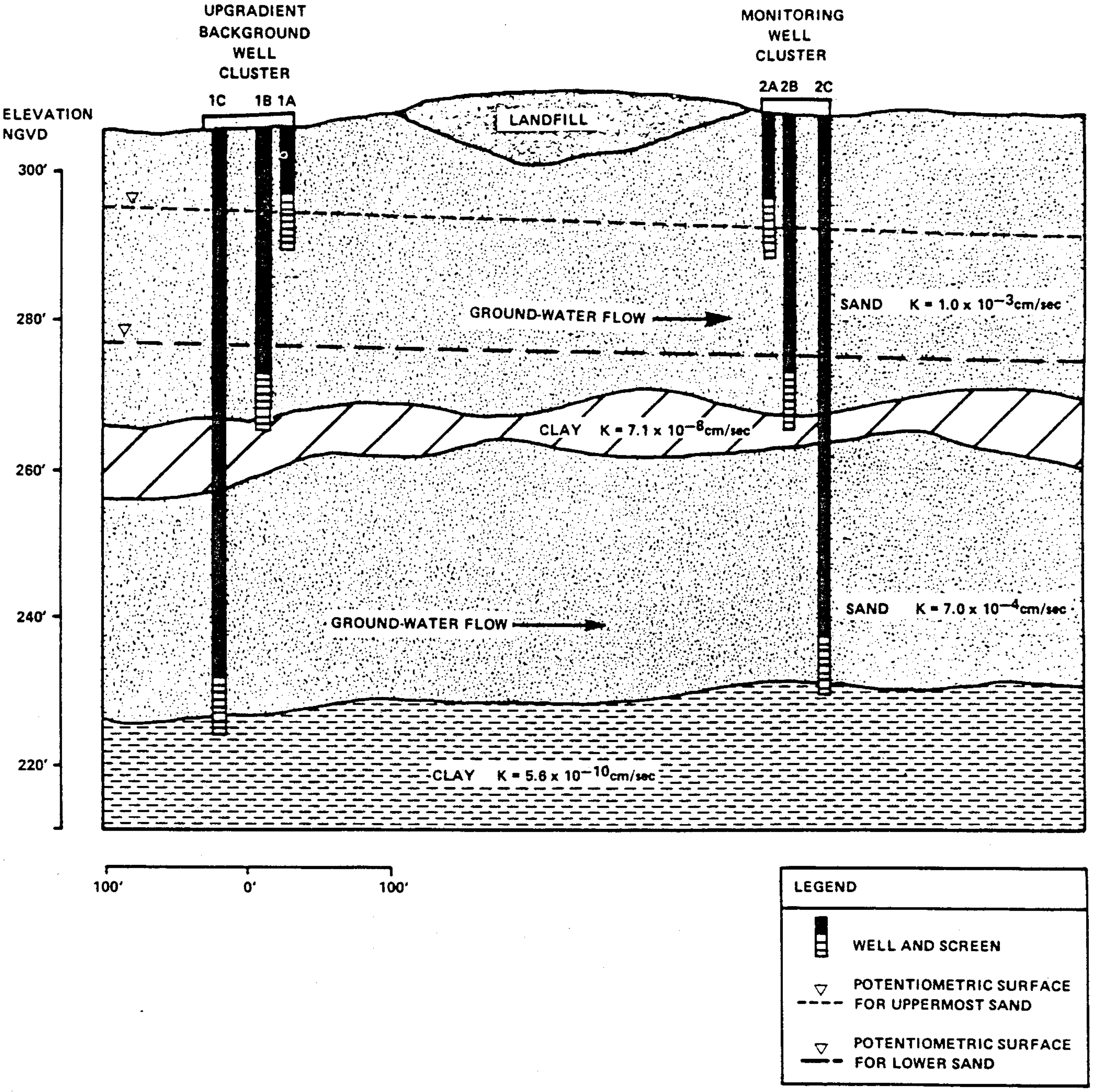


FIGURE 2-7 PLACEMENT OF BACKGROUND WELLS

Screening the entire thickness of the uppermost aquifer will not allow the owner/operator to obtain depth-discrete water quality data. Instead, the owner/operator should use shorter well screens in order to obtain depth-discrete water quality data.

In order to establish background ground-water quality, it is necessary to properly identify the ground-water flow direction and place wells hydraulically upgradient to the waste management area. Usually, this is accomplished by locating the background wells far enough from waste management units to avoid contamination by the hazardous waste management units. There are geologic and hydrologic situations for which determination of the hydraulically upgradient location is often difficult. These cases require further site-specific examination to properly position or place background wells. Examples of such cases include the following:

- Waste management areas above ground-water mounds;
- Waste management areas located above aquifers in which ground-water flow directions change seasonally;
- Waste management areas located close to a property boundary that is in the upgradient direction;
- Waste facilities containing significant amounts of immiscible contaminants with densities greater than or less than water;
- Waste management facilities located in areas where nearby surface water can influence ground-water levels (e.g., river floodplains);
- Waste management facilities located near intermittently or continuously used production wells; and
- Waste management facilities located in Karst areas or faulted areas where fault zones may modify flow.

REFERENCES

Electric Power Research Institute. November 1981. Groundwater Quality Monitoring at Coal-fired Power Plants: Status and Review. Encon Associates, Inc., Research Project 1457, CS-2126.

Geraghty and Miller, Inc. 1980. The Fundamentals of Ground-Water Quality Protection, Seminar Handbook, Geraghty and Miller, Inc. American Ecology Services, Inc.

MacKay, D.M., P.V. Roberts, and J.A. Cherry. 1985. Transport of Organic Contaminants in Groundwater, Engineering Science and Technology, Vol. 19, No. 5, pp. 284-392.

Scalf, M.R., et al. 1981. Manual of Ground-Water Quality Sampling Procedures. National Technical Information Service PB-82-103-045.

Shepard, W.D. 1983. Practical Geohydrological Aspects of Groundwater Contamination. 3rd National Symp. of Aquifer and Groundwater Monitoring, pp. 365-372.

U.S. Environmental Protection Agency. August 1977. Procedures Manual for Ground-Water Monitoring at Solid Waste Disposal Facilities. EPA/530/SW-611.

U.S. Environmental Protection Agency. 1983. RCRA Draft Permit Writer's Ground-Water Protection, 40 CFR Part 264, Subpart F. U.S. Environmental Protection Agency Contract No. 68-01-6464.

U.S. Environmental Protection Agency. 1983. Ground-Water Monitoring Guidance for Owners and Operators of Interim Status Facilities. National Technical Information Service. PB83-209445.

CHAPTER SIX

ASSESSMENT MONITORING

Once contaminant leakage has been detected via detection monitoring efforts, the owner/operator must undertake a more aggressive ground-water program called assessment monitoring. Specifically, the owner/operator must determine the vertical and horizontal concentration profiles of all the hazardous waste constituents in the plume(s) escaping from waste management areas. In addition, the owner/operator must establish the rate and extent of contaminant migration. This information will be used later by the permit writer (in addition to other information collected through the permit application process) to evaluate the need for corrective action at the facility. Alternatively, this information may form the basis for issuing an enforcement order compelling corrective action prior to issuance of a permit.

The Agency has observed a number of problems in the way owner/operators have conducted their assessment monitoring programs. These include:

- Many owner/operators lack satisfactory knowledge of site hydrogeologic conditions. As a result they cannot make informed decisions on how to carry out their assessment programs. The owner/operator should have conducted a thorough site hydrogeologic investigation prior to the installation of the detection monitoring system.

- Some owner/operators fail to implement their assessment programs quickly enough or they implement programs that will take too long to provide information on the extent and migration of a plume.

- Some owner/operators do not support geophysical investigation with a sufficient monitoring well network. Geophysical methods are useful for indicating contamination and for interpolation of contaminant concentrations between wells; however, well sampling is required to provide conclusive data.

- Many owner/operators greatly underestimate the level of effort the regulatory agency expects of them in characterizing plume migration. In most cases, assessment monitoring is an intensive

> effort that will require the owner/operator to install numerous monitoring wells. When full plume characterization is not achieved with the initial round of well installation, additional wells will be required. The owner/operator must track and characterize both the horizontal and vertical components of the plume (i.e., a three-dimensional characterization).

This chapter describes the technical approaches and techniques the Agency feels are minimally necessary for characterizing a plume of contamination as required in Part 265 assessment monitoring.

6.1 Relationship of Assessment Monitoring to Ground-Water Responsibilities Under the Permit Application Regulations (Part 270)

Interim status assessment monitoring is just one in a series of activities that facilities must undertake to prepare adequate permit applications. The Part 270 permit application regulations require interim status facilities to describe in their permit application any plume of contamination (in terms of Appendix VIII sampling) and, based on the levels of contamination found, to develop engineering plans for the appropriate Part 264 ground-water program: detection monitoring, compliance monitoring, or corrective action. Once a facility's permit is called, either operating or post-closure, the owner/operator's ground-water obligations expand from assessment monitoring alone to also include the monitoring and plan development responsibilities imposed by Part 270.

The requirements relevant to facilities subject only to Part 265 assessment monitoring differ from those subject to Part 265 AND Part 270 (by virtue of a permit call-in) in two important ways.

First, the Part 265 assessment program requires monitoring for hazardous waste constituents (primarily Appendix VII), whereas Part 270 [§270.14(c)(4)] requires Appendix VIII monitoring (Note: Appendix VII is a subset of Appendix VIII--see Section 3.3 of the Compliance Order Guidance for a further elaboration of this point). Therefore, assessment plans of facilities subject to permitting should be based on the broader Appendix VIII monitoring requirements embodied in Part 270 (see Section 6.7).

Second, Part 265 assessment monitoring applies only to facilities that detected contamination through a significant increase (or pH decrease) in Part 265 indicator parameters (i.e., those that were formally triggered under the regulations). The requirement to look for and describe any plume of contamination in terms of Appendix VIII constituents (as a condition of the permit application process) applies to facilities that detected contamination through Part 265 detection monitoring, as well as to any facility whose Part 265 detection monitoring system is inadequate to detect a plume, should it occur.

As noted in Chapter 1 of the Compliance Order Guidance (August 1985), facilities with inadequate Part 265 monitoring systems are required to conduct the Appendix VIII sampling and assessment activities required by Part 270 (and necessary to make reasoned decisions about what Part 264 ground-water program to incorporate in the permit) simply because they have avoided compliance with Part 265 detection monitoring in the past. Furthermore, such facilities should not be allowed to start the Part 265 detection sequence over again, thus postponing the time when the facility will be compelled to sample for actual constituents in ground water even if they did not formally "trigger" into Part 265 assessment. The RCRA Ground-Water Monitoring Compliance Order Guidance explains in greater detail the legal and technical bases for advancing facilities with inadequate Part 265 detection systems into the type of assessment activities described in this chapter. While the language of the chapter speaks in terms of Part 265 assessment activities, the techniques discussed herein are equally applicable to facilities conducting plume characterization activities as part of the permit application process.

6.2 Contents of a Part 265 Assessment Monitoring Plan

Owner/operators conducting plume characterization activities as part of Part 265 assessment monitoring are required to have a written assessment monitoring plan. The plan serves as the blueprint for the activities undertaken to characterize the rate and extent of contaminant migration. Plans must contain sufficient detail to determine the nature and extent of the plume. When evaluating facilities in assessment monitoring, technical reviewers should focus both on (1) scrutinizing the adequacy of the written assessment plan, and (2) reviewing the owner/operator's implementation of the plan in the field.

There are a number of elements that owner/operators should include in their assessment monitoring plans. The remaining sections of this chapter are organized around the following elements of an adequate assessment plan:

- Section 6.3 - narrative discussion of the hydrogeologic conditions at the owner/operator's site; identification of potential contaminant pathways;
- Section 6.4 - description of the owner/operator's detection monitoring system;
- Section 6.5 - description of the approach the owner/operator will use to make the first determination (false positives rationale);
- Section 6.6 - description of the investigatory approach the owner/operator will use to fully characterize rate and extent of contaminant migration; identification and discussion of investigatory phases;
- Section 6.7 - discussion of number, location, and depth of wells the owner/operator will initially install, as well as strategy for installing more wells in subsequent investigatory phases;
- Section 6.8 - information on well design and construction;
- Section 6.9 - a description of the sampling and analytical program the owner/operator will use to obtain and analyze ground-water monitoring data;
- Section 6.10 - description of data collection and analysis procedures the owner/operator plans to employ;

- Section 6.11 - a discussion of the procedures the owner/operator will use to determine the rate of constituent migration in ground water; and
- Section 6.12 - a schedule for the implementation of each phase of the assessment program.

6.3 Description of Hydrogeologic Conditions

An owner/operator cannot conduct an adequate assessment monitoring program without a thorough understanding of site hydrogeologic conditions. Such an understanding, garnered through site characterization activities (refer to Chapter One), allows the owner/operator to identify likely contaminant pathways. Identification of these pathways allows the owner/operator to focus efforts on tracking and characterizing plume movement. It is important to note that the initial site characterization carried out by the owner/operator should provide enough hydrogeologic information to allow the owner/operator not only to design a detection monitoring system, but also to plan and carry out an assessment monitoring program.

The owner/operator's assessment plan should describe in detailed narrative form what hydrogeologic conditions exist at the owner/operator's site. The plan should describe the potential pathways of constituent migration at the site, including depth to water in aquifer, aquifer connections to surface water and/or deeper aquifers, flow rate and direction, and any structures such as fractures and faults which could affect migration. The owner/operator's plan should also describe how hydrogeologic conditions have influenced the type of assessment effort that will be used to characterize plume migration. This portion of the owner/operator's assessment plan should recapitulate the hydrogeologic investigatory program the owner/operator undertook prior to installing a detection monitoring system (see Chapter One). It should describe the investigatory approach used by the owner/operator to characterize subsurface geology and hydrology, the nature and extent of field investigatory activities, and the results of the investigation, as well as provide an explicit discussion on how those results have guided decisions the owner/operator has made concerning the planning and implementation of the assessment monitoring program. As part of the plan, the owner/operator should append various supporting documentation such as those described in Table 1-1.

6.4 Description of Detection Monitoring System

The owner/operator's assessment plan should describe the existing detection monitoring system in place at the owner/operator's facility. The primary concern is whether the existing well system is capable of detecting contaminant leakage that may be escaping from the facility. If the owner/operator's detection monitoring system is deficient, either in design or operation, plumes may exist unnoticed. This portion of the owner/operator's assessment plan should describe the physical layout of the owner/operator's detection monitoring well system (e.g., horizontal and vertical orientation of individual wells) and identify assumptions used by the owner/operator in designing the detection monitoring system (particularly how hydrogeologic condition affected the decision making process).

6.5 Description of Approach for Making First Determination - False Positives

Chapter Five described requirements that owner/operators must meet in terms of statistical analysis of detection monitoring data. Once the owner/operator resamples and the statistical test again suggests that an indicator parameter has increased in a downgradient well(s), the owner/operator must implement an assessment monitoring program. Figure 6-1 illustrates the sequence of events that occurs immediately before and after the shift to assessment monitoring. Of particular interest are those situations where the owner/operator believes that contamination may have been falsely indicated and thus describes in the

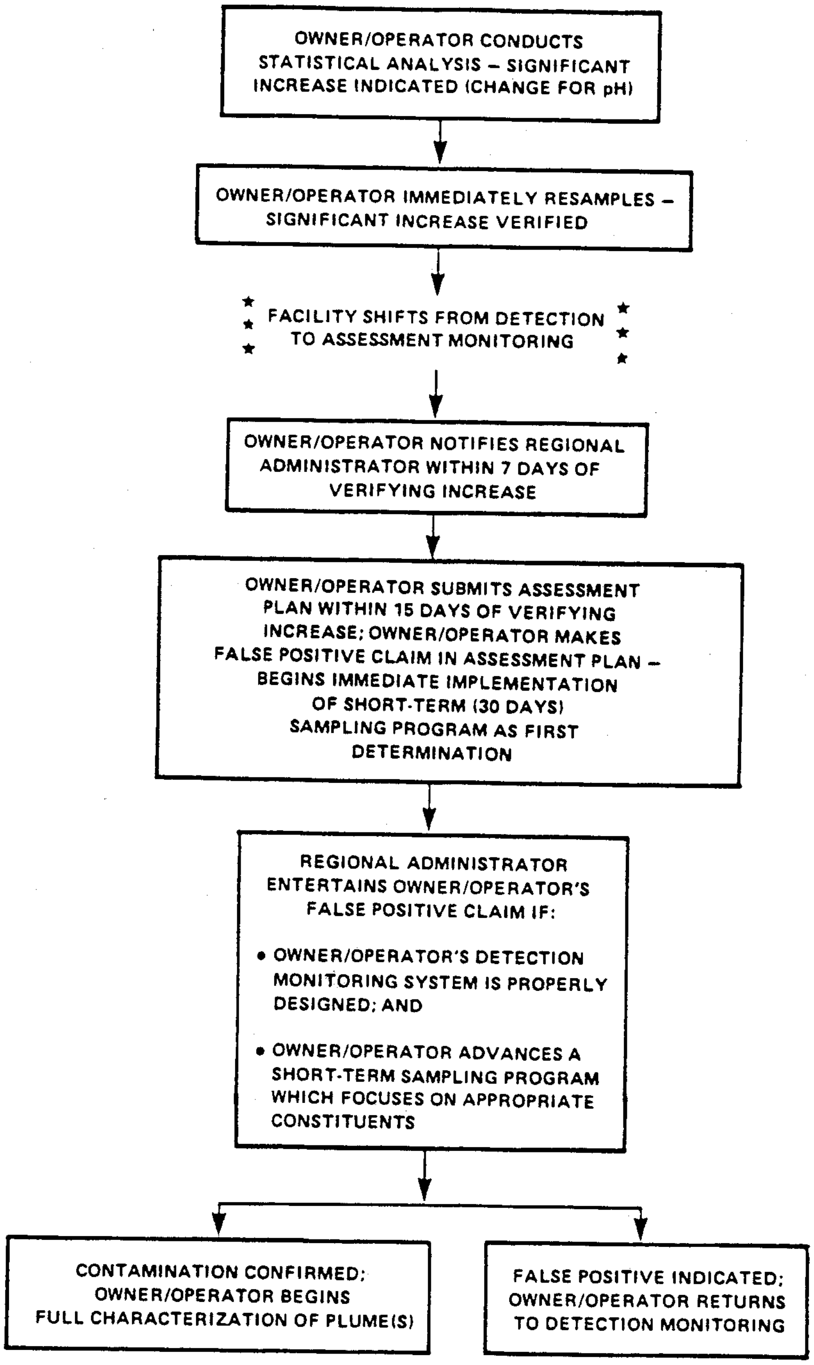


FIGURE 6-1 PROCEDURE FOR EVALUATING FALSE POSITIVE CLAIMS BY OWNER/OPERATORS

assessment plan a short-term program to substantiate or disprove this false positive claim (i.e., false positive investigation is focus of first determination - §265.93(d)(5)). There are a number of facilities for which the first determination is no longer relevant, e.g., facilities under 3008(h) enforcement action. See the RCRA Ground-Water Monitoring Compliance Order Guide for details.

When an owner/operator's detection monitoring system is properly designed, the first determination under assessment monitoring may focus on substantiating a false positive claim. If an owner/operator's detection monitoring system is inadequate, it is difficult to evaluate whether leakage has occurred. Substantiation of a false positive claim would be a lengthy process, potentially involving hydrogeologic work, the installation of a new detection well network, and evaluation of various additional sampling data. In those cases, officials should reject a false positive analysis as the focus of the first determination when the existing system is inadequate, and instead require the owner/operator to (1) correct deficiencies in the detection monitoring system; and (2) initiate a program that will consider specific constituents of concern in the existing wells, and in the new wells as they are installed.

If, however, an owner/operator's detection monitoring system is adequately designed, the owner/operator may propose, as the first determination, a short-term sampling program--generally no longer than 30 days--and an analysis of other related data that will permit investigation of whether the statistical change noted in Part 265 indicator parameters truly represents migration of leachate into the uppermost aquifer. Such short-term sampling programs, however, do not allow for the evaluation of seasonal variation. Data gathered over the short term, therefore, should be analyzed to control for the season in which the data were collected, in order to establish comparability with previous data. For units subject only to the Part 265 standards, the short-term sampling program must, at a minimum, confirm that no hazardous waste constituents (Appendix VII) have migrated into the uppermost aquifer. For units subject to the Part 270 requirements (because they are seeking an operating permit or the Agency has called in their post-closure permit), the owner/operator should include constituents selected from Appendix VIII in the sampling program.

After conducting the short-term sampling program (constituting the first determination), the owner/operator must submit to the Regional Administrator a written report describing the ground-water quality. If the sampling program confirms that leakage has not occurred, the owner/operator may continue the detection monitoring program or enter into a consent agreement with the Agency to follow a revised detection protocol designed to avoid future false triggers. If, however, the short-term sampling confirms that leakage has occurred, the owner/operator must immediately begin implementation of an assessment program.

6.6 Description of Approach for Conducting Assessment

A variety of investigatory techniques are available for use during a ground-water quality assessment. They can be broadly categorized as either direct or indirect methods of investigation.

All assessment programs should be designed around the direct method of actual collection of a sample with subsequent chemical analysis to determine actual water quality (i.e., installation of monitoring wells). Other methods of investigation may be used when appropriate to choose the locations for well installation. For certain aspects of an assessment, such as defining plume location, the use of both direct and indirect methods may be the most efficient approach.

The methods planned for use in an assessment should be clearly specified and evaluated to ensure that the performance standard established for assessments can be met. Evaluating the use of direct and indirect methods is discussed separately below.

6.6.1 Use of Direct Methods

Ground-water monitoring wells, either existing or newly installed, are necessary to provide sampling data to establish the concentration of hazardous constituents released from the hazardous waste management area, and the rate and extent of their migration. The owner/operator should construct assessment monitoring wells and conduct sampling and analysis in a manner that provides reliable data. Chapters Three and Four, respectively, present guidance in these areas.

At facilities where it is known or suspected that volatile organics have been released to the uppermost aquifer, organic vapor analysis of soil gas from shallow holes may provide an initial indication of the areal extent of the plume (Figure 6-2). To this end, the owner/operator may use an organic vapor analyzer (OVA) to measure the volatile organic constituents in shallow hand-augered holes. Alternatively, the owner/operator may extract a sample of soil gas from a shallow hole and have it analyzed in the field, using a portable gas chromatograph. These techniques are limited to situations where volatile organics are present. Further, the presence of intervening, saturated, low permeability sediments strongly interferes with the ability to extract a gas sample. Although it is not necessarily a limitation, optimal gas chromatography results are obtained when the analyte is matched with the highest resolution technique (e.g., electron capture/halogenated species). The owner/operator should attempt to evaluate the effectiveness of this approach by initial OVA sampling in the vicinity of wells known to be contaminated.

Descriptions of the direct methods and their limitations that will be employed during assessment monitoring should be included in the

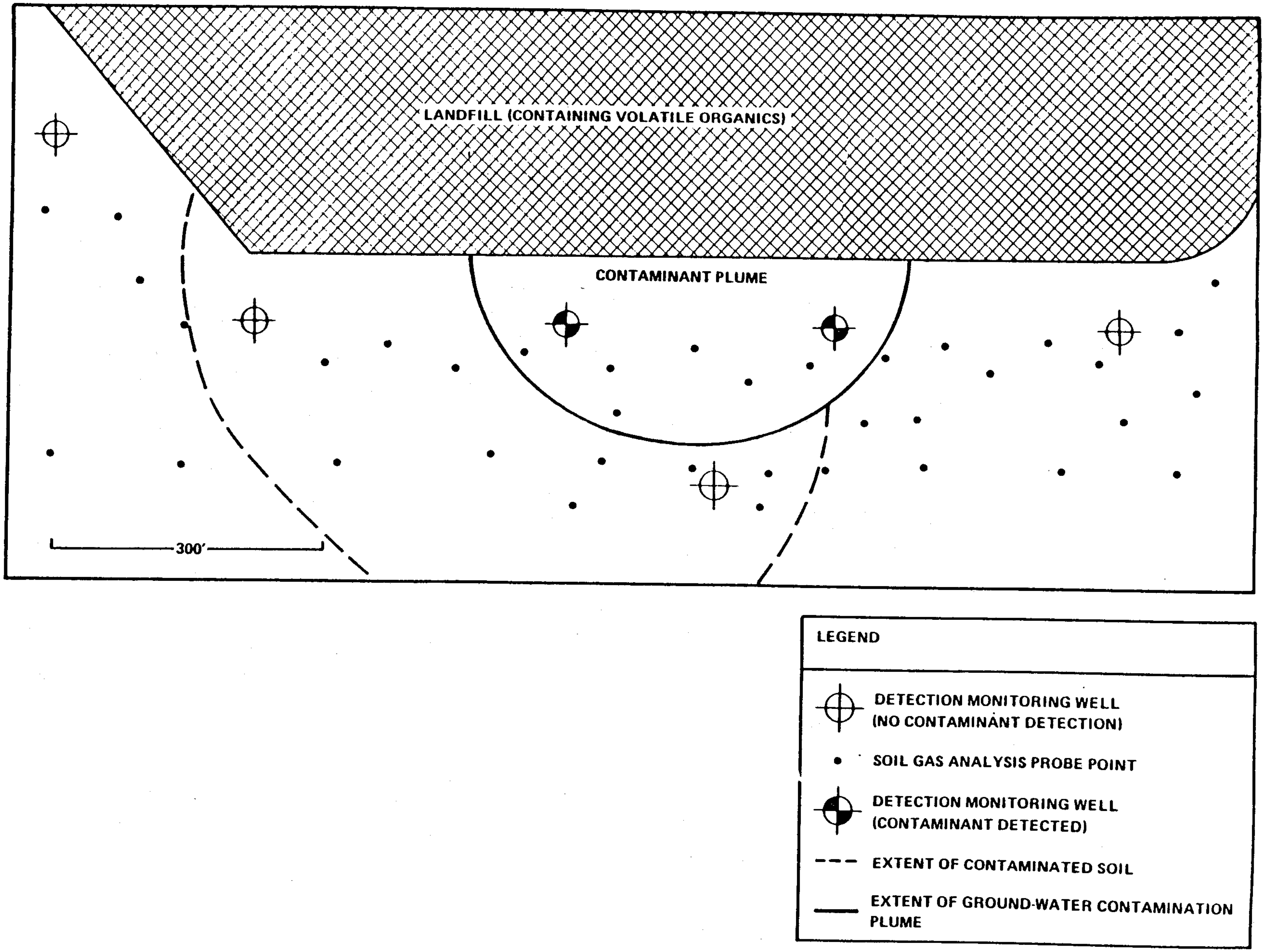


FIGURE 6-2 EXAMPLE OF USING SOIL GAS ANALYSIS TO DEFINE PROBABLE LOCATION OF GROUND-WATER PLUME CONTAINING VOLATILE ORGANICS

assessment plan. These descriptions should be sufficiently detailed to allow the method to be evaluated and to ensure that the method will be properly executed.

Other direct methods that may be used to define the extent of a plume include sampling of seeps and springs. Seeps and springs occur where the local potentiometric surface intersects the land surface and results in ground-water discharge into a stream, rivulet, or other surface water body. Seeps and springs might be observed near marshes, at road cuts, or near streams. Discharges from seeps and springs reflect the height of the potentiometric surface and are likely to be most abundant during a wet season.

6.6.2 Use of Indirect Methods

A variety of methods are currently available for identifying and, to a limited extent, characterizing contamination in the uppermost aquifer. There are several geophysical techniques of potential use to an owner/operator, including electrical resistivity, electromagnetic conductivity, ground penetrating radar, and borehole geophysics. Remote sensing and aerial photography are additional indirect methods an owner/operator may find useful. These techniques, with the exception of aerial photographic methods, operate by measuring selected physical parameters in the subsurface such as electrical conductivity, resistivity, and temperature.

The value of indirect methods is not the provision of detailed, constituent-specific data for which they presently are clearly limited, but rather for delineating the general areal extent of the plume. This is extremely important to the owner/operator for two reasons:

1. Knowing the general outline of the plume before additional wells are constructed reduces the need for speculative wells. The assessment monitoring program, therefore, becomes more efficient, since well placement is guided by analytical data.
2. As the plume migrates and its margins change, the owner/operator may track its movement to help locate new wells.

There are drawbacks to the exclusive use of geophysical techniques in assessment monitoring relating to the high level of detail necessary to characterize the chemical composition of a ground-water plume. For these methods to be successful, contaminant(s) of interest must induce a change in the subsurface parameter measured. This change, in turn, must be distinguishable from ambient conditions. For example, the electrical properties of organic hazardous constituents are generally attenuated or masked by subsurface material properties. Unless these constituents are present in high concentrations, they generally will not register during resistivity or conductivity surveys. Moreover, nonuniform subsurface conditions may obscure low levels of certain contaminants in ground water. Another drawback to the exclusive use of geophysical methods at present is their inability to measure specific concentrations of individual constituents or provide good vertical resolution of constituent concentration. In addition, man-made structures such as powerline towers, buried pipelines, roads, and parking lots may interfere with the performance and reliability of many geophysical methods. The owner/operator should, therefore, only use indirect methods to guide the installation of an assessment monitoring system and to provide an ongoing check of the extent of contaminant migration.

6.6.3 Mathematical Modeling of Contaminant Movement

Mathematical and/or computer modeling may provide information useful to the owner/operator during assessment monitoring and in the design of corrective actions. The information may prove useful in refining conceptualizations of the ground-water regime, defining likely contaminant pathways, and designing hydrologic corrective actions (e.g., pumping and treating, etc.).

Since a model is a mathematical representation of a complex physical system, simplified assumptions must be made about the physical system, so that it may fit into the more simplistic mathematical framework of the model. Such assumptions are especially appropriate, since the model assumes a detailed knowledge of the relevant input parameters (e.g., permeability, porosity, etc.) <u>everywhere</u> in the area being modeled. This is a limitation that must be considered since it would be impossible to obtain all of the input parameters without disturbing and altering the physical system.

Since a model uses assumptions as to both the physical processes involved and the spatial and temporal variations in field data, the results produced by the model at best provide a <u>qualitative</u> assessment of the extent, nature, and migration of a contaminant plume. Because of the assumptions made, a large degree of uncertainty is inherent in most modeling simulations. Therefore, modeling results should not be unduly relied upon in guiding the placement of assessment monitoring wells or in designing corrective actions.

Where a model is to be used, site-specific measurements should be collected and verified. The nature of the parameters required by a model varies from model to model and is a function of the physical processes being simulated (i.e., ground-water flow and/or contaminant transport), as well as the complexity of the model. In simulating ground-water flow, the hydrogeologic parameters that are usually required include: hydraulic conductivity (vertical and horizontal); hydraulic gradient; specific yield (unconfined aquifer) or specific storage (confined aquifer); water levels in both wells and nearby surface water bodies; and estimates of infiltration or recharge. In simulating contaminant transport, the physical and chemical parameters that are usually required include: ground-water velocity; dispersivity of the aquifer; adsorptive characteristics of the aquifer (retardation); degradation characteristics of the contaminants; and the amount of each contaminant entering the aquifer (source).

Dispersivity values of the aquifer should be based on site-specific field test (i.e., tracer test) data or on field dispersivity values obtained from the literature. Caution should be used where laboratory dispersivity values are proposed, since such values are often orders of magnitude lower than field values. Retardation is often expressed as a functional relationship (isotherm) between mass of contaminants in the ground water and mass of contaminants adhering to the soil/rock. These isotherms are based on soil bulk density, effective porosity, and cation exchange capacity. Retardation may also be determined from the octanol-water partition coefficient and fractional portion of organic matter in representative volumes of soil. Degradation of contaminants depends upon the type of constituents and the probability for chemical and biological decay. Dispersion, retardation, and degradation tend to decrease plume concentration and attenuate its travel time. Where these parameters are not well characterized, use of lower values will produce greater conservatism in the results.

Contaminants leaking/leaching from a waste facility may react with the pre-existing ground-water chemistry, resulting in an increase (or decrease) in mobility. Background ground-water quality (e.g., indicator parameters plus Cl^-, Fe, Mn, Na^+, SO_4, Ca^+, Mg^+, NO_3^-, $PO_4^=$, silicate, ammonium, alkalinity, or acidity) is important to determine the reactivity and solubility of hazardous constituents in ground water, and therefore is useful in predicting constituent mobility under actual site conditions. The physical and chemical characteristics of the site-specific leachate (e.g., density, solubility, vapor pressure, viscosity, and octanol-water partition coefficient) and hazardous waste constituents should also be known as they affect constituent movement. To fully assess the effect on contaminant mobility, a water chemistry model may be employed as a component of the overall modeling study. Since this would add a large degree of complexity to the modeling study, conservative assumptions (i.e., maximum mobility of constituents) may be appropriate where time and/or resources are limited.

Mathematical models are comprised of analytical equations by which the hydraulic head or concentration of a contaminant may be calculated for a specified location at a specified time. These models are categorized into two main categories: those which are simple enough that governing equations can be solved by analytic techniques ("analytical models"); and those which are more complex and can only be solved by computer ("numerical models"). The analytical solutions to the first category are often so sufficiently complex that they too can be solved by computer. The numerical models are usually better suited to simulate the complex conditions that describe the actual environment. Both types of models, collectively referred to in this document as computer models, require the recognition of inherent assumptions, the application of appropriate boundary conditions, and the selection of a coherent set of input parameters.

Model input parameters that can be determined directly should be measured with consideration given to selecting representative samples. Since the parameters cannot be measured continuously over the entire region but only at discrete locations, care should be taken when extrapolating over regions where there are no data. These considerations are especially important where the parameters vary significantly in space or time. The sensitivity of the model output both to the measured and assumed input parameters should be determined and incorporated into any discussion of model results. In addition, the ability of the model to be adequately calibrated (i.e., the ability of the model to reproduce current conditions (water levels, contaminant concentrations, etc.)) and to reproduce past conditions should be carefully evaluated in assessing reliability of model predictions. Model calibration with observed physical conditions is critical to any successful ground-water modeling exercise.

A plethora of ground-water computer models exists, many of which would be suitable for a given situation. Since EPA is a public agency and models used by or for EPA may become part of a judicial action, EPA approval of model use should be restricted to those models that are publicly available (i.e., those models that are available to the public for no charge or for a small fee). The subset of ground-water models that are publicly available is quite large and should be sufficient for most ground-water applications. Publicly available models include those models developed by or for government agencies (e.g., EPA, USGS, DOE, NRC, etc.) and national laboratories (e.g., Sandia, Oak Ridge, Lawrence Berkeley, etc.), as well as models made publicly available by private contractors. Any publicly available model chosen should, however, be widely used, well documented, have its theory published in peer-reviewed journals, or have some other characteristics reasonably assuring its credibility. For situations where publicly available computer models are not appropriate, proprietary models (i.e., models not reasonably accessible for use or scrutiny by the public) should only be used where the models have been well documented and have undergone substantial peer review. Where these minimal requirements have not been met, the model should not be considered reliable. A partial list of publicly available computer models includes:

- Modular 3-Dimensional Finite Difference Groundwater Flow Model (USGS), to evaluate complex hydrologic conditions;
- Computer Model of Two-Dimensional Solute Transport and Dispersion in Ground Water (USGS), to predict contaminant transport;
- Illinois State Water Survey Random Walk Solute Transport Model (ISGS), to predict contaminant transport;
- AT123D (Oak Ridge or EPA), to calculate concentrations isopleths for transient contaminant flow through a simplistic aquifer flow field in up to three dimensions;
- FEMWATER/FEMWASTE (Oak Ridge), to predict contaminant transport in both the saturated and unsaturated zones;
- SWIFT (NRC or Sandia), to predict contaminant transport and complex hydrologic flow conditions in up to three dimensions; and
- SWIP (EPA), similar to SWIFT.

If an owner/operator plans to use a model to guide an assessment monitoring program, the owner/operator must be able and willing to describe how the model works, as well as to explain all assumptions used in calibrating and applying the model to the site in question. In addition, the model and all related documentation should be made available to EPA and its contractors for review and scrutiny.

6.7 Description of Sampling Number, Location, and Depth

The regulations require that the assessment plan specify the number, location, and depth of wells to be installed as part of the assessment. As the discussion on assessment methodology provided in Section 6.4 has indicated, the owner/operator may use other sampling techniques (e.g., indirect methods and coring) in addition to the installation of permanent monitoring wells to augment the data generated by wells. The owner/operator's assessment plans should, however, specify the number, location, and depth of wells that will be installed to characterize rate and extent of migration, and constituent concentrations, and present explanations for the decisions.

It may not always be possible for the owner/operator to identify at the outset of an assessment the exact number, location, and depth of all sampling that will be required to meet the goals of an assessment. Many times the investigations undertaken to characterize contamination during an assessment will proceed in phases in which data gained in one round of sampling will guide the next phase of the investigation. For example, surface geophysical techniques can be effectively used in tandem with the installation of monitoring wells as a first phase in the assessment program to obtain a rough outline of the contaminant plume. Based on these findings, a sampling program may subsequently be undertaken to more clearly define the three-dimensional limits of the contaminant plume. In the third phase, a sampling program to determine the concentrations of hazardous waste constituents in the interior of the plume may be undertaken. In this case, a detailed description of the approach that will be used to investigate the site should be included in the assessment plan. This description should clearly identify the number, location, and depth of any sampling planned for the initial phase of the investigation. The outline should also clearly identify what basis will be used to select subsequent sampling locations, including the geologic strata that are likely to be sampled and the anticipated frequency of sampling. At a minimum, several well clusters should be installed concurrently to define the extent of contamination and concentration of contaminants (see Section 6.7.2) and to profile the vertical extent of migration (see Section 6.7.3).

6.7.1 Collection of Additional Site Information

The hydrogeologic site characterization requirements for the detection monitoring program include:

- The subsurface geology below the owner/operator's hazardous waste facility;
- The vertical and horizontal components of flow in the uppermost saturated zone below the owner/operator's site;
- The hydraulic conductivity of the uppermost aquifer; and
- The vertical extent of the uppermost aquifer down to the first confining layer.

If this characterization does not include all the hydrogeologic information necessary to characterize the rate of contaminant movement, the owner/operator should obtain this information for the assessment phase. Examples of the additional information that may be needed to determine the rate of contaminant movement include: mineralogy of the materials in the migration pathway; ion exchange capacity of the material; organic carbon content of the materials; background water quality of the pathway (e.g., major cations and anions); the temperature of ground water in the migration pathway; and the transmissivity and effective porosity of the material in the pathway. This information will help define the transport mechanisms which are most important at the site. All information collected during the investigation of the plume (i.e., boring logs, core analysis, etc.) should be recorded and the hydrogeologic descriptions of the site updated when appropriate.

Prior to adding new wells, a good estimation of plume geometry can be determined from a review of current and past site characterizations. For example, piezometer readings surrounding a contaminated detection well can be taken to ascertain the current hydraulic gradient. When these values are compared to the potentiometric surface map developed during the site investigation, the general direction of plume migration can be approximated. Any seasonal or regional fluctuations should be considered during this comparison. A review of the subsurface geology may also identify preferential pathways of contaminant migration.

To limit drilling speculative wells, geophysical and modeling methods can also be employed to yield a rough outline of the plume. This expedites the assessment monitoring program. Monitoring wells can then be strategically placed to precisely define the plume geometry.

6.7.2 Sampling Density

The program of sampling undertaken during the assessment should clearly identify the full extent of hazardous waste constituent migration and establish the concentration of individual constituents throughout the plume. In the initial phase of the assessment program, the owner/operator's well installation/sampling should concentrate on defining those areas that have been contaminated by the facility. A series of well clusters should be installed in and around the plume to define the extent of contamination and concentration of contaminants in the horizontal plane. This network of monitoring wells, the number of which may vary from site-to-site, must thoroughly define the horizontal boundaries of the plume, and will identify and quantify contaminants. Well placement should be performed expediently, but in accordance with a carefully thought out and documented assessment monitoring plan. To obtain accurate plume definition at a particular moment in time it is necessary to install well clusters concurrently. Surface geophysical techniques should also be used, where appropriate, to help facilitate plume definition. An assessment monitoring program that does not thoroughly characterize the plume may result in higher assessment monitoring costs, higher corrective action costs, and unnecessary delay.

The density of wells or amount of sampling undertaken to completely identify the furthest extent of migration should be determined by the variability in subsurface geology. Formations, such as unconsolidated deposits with numerous interbedded lenses of varying permeability or consolidated rock with numerous fractures, will require a more intensive level of sampling and carefully placed wells to ensure that all contamination is detected.

Assessment monitoring wells should be constructed of inert materials to minimize chemical interaction between well casing material and contaminant constituents. Also, the length of the well screen should be relatively small, since the wells will be used to assess constituent concentrations at discrete locations in the plume.

Sampling is also required to characterize the interior of any plume detected at the site. This is important because the migration of many constituents will be influenced by natural attenuation/transformation processes. Sampling at the periphery of the plume may not identify all the constituents from the facility that are reaching ground water, and the concentration of waste constituents detected at the periphery of the plume may be significantly less than in the plume's interior. Patterns of concentration of individual constituents can be established throughout the plume by sampling along several lines that perpendicularly transect it. The number of transects and spacing between sampling points should be based on the size of the plume and variability in geology observed at the site. When sampling in fractured rock, for example, monitoring wells should be located such that the well screens intersect fracture zones along likely contaminant pathways. Sampling locations should also be selected so as to identify those areas of maximum contamination within the plume. In addition to the expected contaminants, the plume may contain constituent degradation/transformation products, as well as reaction products.

6.7.3 Sampling Depths

The owner/operator should specify in the assessment plan the depth at which samples will be taken at each of the planned sampling locations. These sampling depths should be sufficient to profile the vertical distribution of hazardous waste constituents at the site. Vertical sampling should identify the full extent of vertical constituent migration. Vertical concentration gradients, including maximum concentration of each hazardous waste constituent in the subsurface, should similarly be identified. The amount of vertical sampling required at a specific site will depend on the thickness of the plume and the vertical variability observed in the geology of the site. All potential migration pathways should be sampled. The sampling program should clearly define the vertical extent of migration by identifying those areas on the periphery of the plume that have not been contaminated.

In order to establish vertical concentration gradients of hazardous waste constituents in the plume, the owner/operator must obtain a continuous sample of the plume, which means well clusters should be employed. The owner/operator, however, cannot know the vertical extent of the plume; therefore, the first well in the cluster should be screened at the horizon where contamination was discovered, bearing in mind that screen length should be relatively small. Additional wells in the cluster should be screened, where appropriate, above and below the initial sampling depth, until the margins of the plume are established. Basically, several wells should be placed at the fringes of the plume to define its vertical margins, and several wells should be placed within the plume to identify contaminant constituents and concentrations. Care must be taken in placing contiguously screened wells close together, since the drawdown from one may influence the next, and thus change the horizon from which the samples are drawn. Figure 6-3 shows an example of assessment monitoring well cluster placement in the same setting as depicted in Figure 2-5. These figures illustrate the relationship between detection and assessment monitoring wells and clusters.

The specifications of sampling depths included in assessment plans should clearly identify the interval over which each sample will be taken. It is important that these sampling intervals be sufficiently discrete to permit vertical profiling of constituent concentrations in ground water at each sampling location. Sampling will only provide measurements of the average contaminant concentration over the interval from which that sample is taken. Samples taken from wells screened over a large interval will be subject to dilution effects from uncontaminated ground water lying outside the plume limits. Screened intervals should be kept relatively small, especially where small vertical concentration gradients are expected.

As part of the progressive assessment monitoring program, the owner/operator can use geophysical techniques to help verify the adequacy of the placement of the assessment monitoring network. Adjustments to the assessment monitoring program may be needed to reflect plume migration and changes in direction.

6.8 Description of Monitoring Well Design and Construction

The monitoring well design and construction requirements for assessment monitoring well networks are equivalent to the requirements presented in Chapter Three for detection wells.

6.9 Description of Sampling and Analysis Procedures

The owner/operator's sampling and analysis plan should be updated to reflect the different analytical requirements of assessment monitoring.

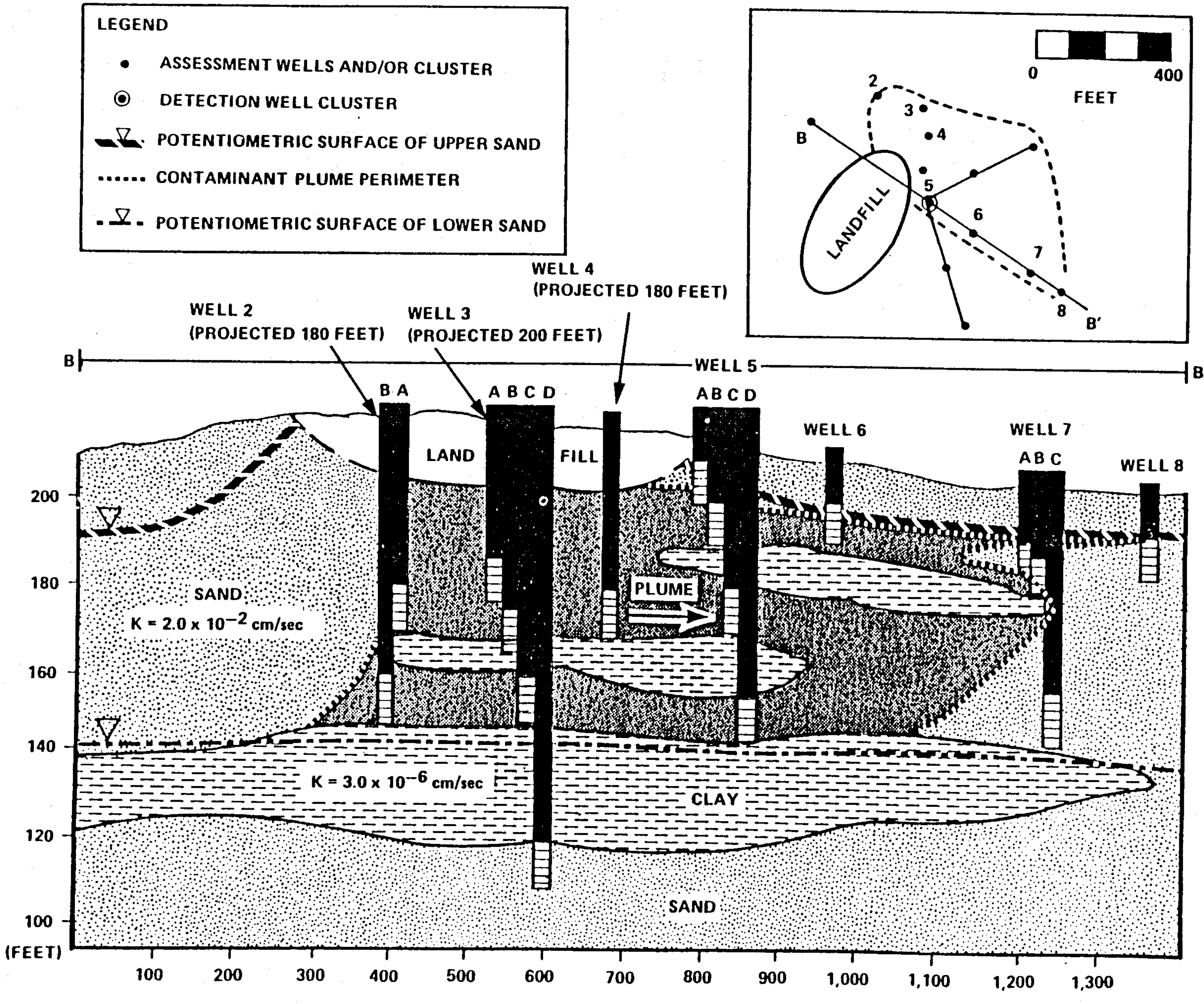


FIGURE 6-3 EXAMPLE OF ASSESSMENT MONITORING WELL PLACEMENT

Otherwise, the sampling and analysis plan used by the owner/operator in the detection monitoring program (see Chapter Four) should suffice for assessment monitoring.

The assessment monitoring plan should identify the parameters to be monitored by the owner/operator, and describe why these parameters are suitable for determining the presence and concentration of contaminants migrating from the facility in the ground water. At a minimum, the owner/operator's assessment monitoring plan should include monitoring for all hazardous waste constituents that are in the facility's waste. Hazardous waste constituents, as defined in §260.10, include all constituents listed in Appendix VII of Part 261, all constituents included in Table 1 of §261.24, and any constituent listed in Section 261.33.

An important consideration in assessment monitoring is the potential for degradation/transformation of hazardous waste constituents; that is, the chemical and/or physical change of a ground-water contaminant resulting in a different intermediate or final product. The physical and chemical properties of all hazardous waste constituents in the facility's waste are an important consideration in evaluating an assessment monitoring system. Assessment monitoring should aim at detecting all contaminants, both initial as well as intermediate or final degraded/transformed products. An example of the degradation/transformation process is the breakdown of trichloroethylene (TCE) and its various isomers into vinyl chloride, a highly toxic substance having different chemical/physical characteristics than TCE. Since vinyl chloride is more water soluble and less affected by sorption than TCE, the detection of vinyl chloride in ground water should lead the owner/operator to suspect the presence of TCE.

Facilities seeking an operating permit also have additional plume characterization responsibilities pursuant to Part 270. Section 270.14(c)(4) requires permit applicants to expand their monitoring from hazardous waste constituents (primarily Appendix VII) to the full complement of Appendix VIII constituents (Note: Appendix VII is a subset of Appendix VIII). Therefore, when a unit is subject to the Part 270 requirements (either because it seeks an operating permit or because the Agency has called in its post-closure permit), the Agency recommends that an owner/operator's assessment plan include parameters that will satisfy the requirements of both Part 265 and Part 270.

Figure 6-4 illustrates in greater detail the sampling protocol recommended by the Agency for units that are subject to both Part 265 and Part 270. First, the owner/operator should perform an Appendix VIII scan of samples from triggering detection monitoring wells. This scan will provide the owner/operator with a list of hazardous constituents in the wells that may be migrating into the uppermost aquifer. The owner/operator should then select a limited number of identified constituents for inclusion in a sampling program to establish geometric dimensions and the rate of migration of the contaminant plume(s). Once the geometric dimensions of the contaminant plume(s) have been established, the owner/opertor should sample for the full subset of identified Appendix VIII constituents to determine vertical and horizontal concentration gradients.

6.10 Procedures for Evaluating Assessment Monitoring Data

The assessment plan must stipulate and document procedures for the evaluation of assessment monitoring data. These procedures vary in a site-specific manner, but must all result in determinations of the rate of migration, extent, and composition of hazardous constituents of the plume. Where the release is obvious and/or chemically simple, it may be possible to characterize it readily from a descriptive presentation of concentrations found in monitoring wells and geophysical measurements. Where contamination is less obvious or the release is chemically complex, however, the owner/operator should employ a statistical inference approach. Owner/operators should plan initially to take a descriptive

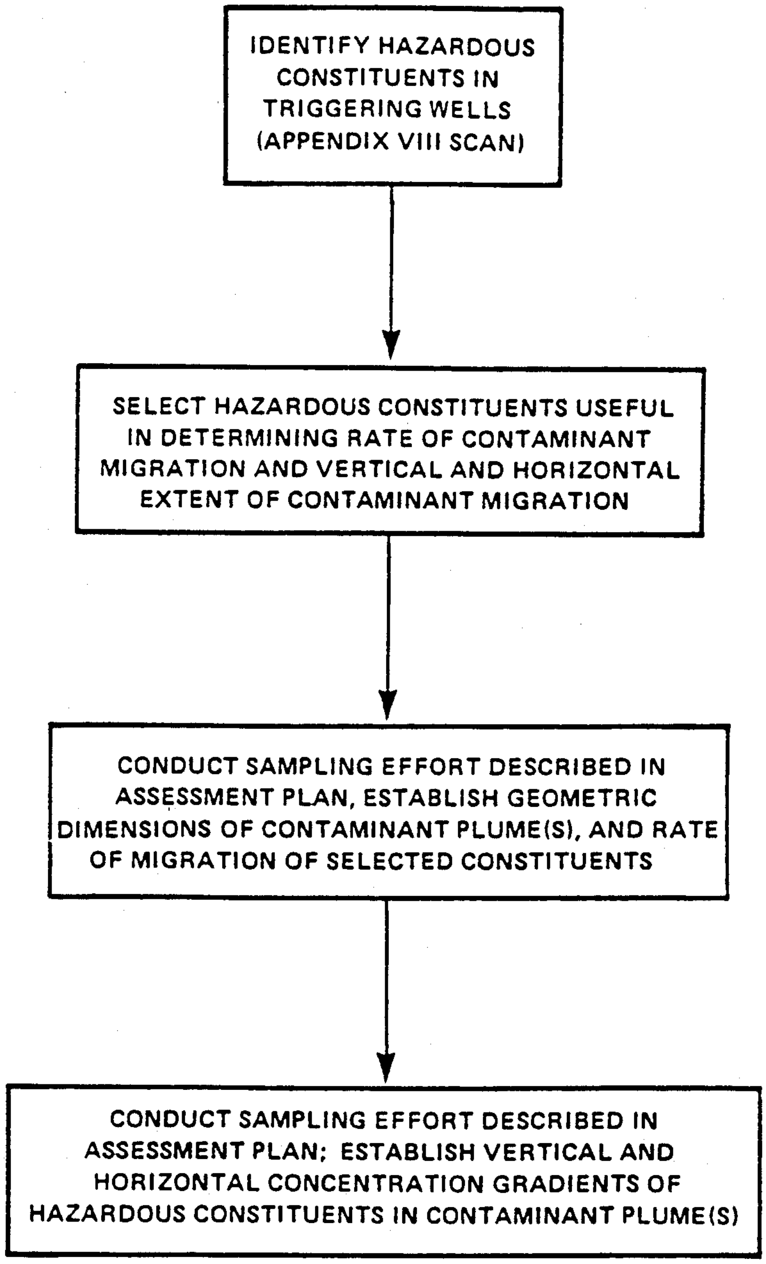


FIGURE 6-4 SELECTION OF PLUME CHARACTERIZATION PARAMETERS FOR UNITS SUBJECT TO PART 265 AND PART 270

approach to data analysis in order to broadly delineate the extent of contamination. Statistical comparisons of assessment monitoring data among wells and/or over time may be necessary, should the descriptive approach provide no clear determination of the rate of migration, extent, and hazardous constituent composition of the release.

The objective of assessment monitoring is to estimate the rate and extent of migration and the concentration of constituents in the plume. Data are therefore collected from a set of assessment monitoring wells that will allow characterization of the dimensions and concentrations of ground-water contaminant constituents (GWCCs) in the plume. In addition, compared to detection monitoring, the number of chemical species analyzed in assessment increases. Because the amount of data collected in assessment is more voluminous than detection monitoring, it is extremely important for the technical reviewer to make sure that the owner/operators specify in their assessment plans the evaluation procedures for the data required by §265.93(d)(3)(iii). The methods used to analyze assessment monitoring data must emphasize organization, data reduction, simplification, and summary.

Technical reviewers may find it useful and necessary to leave GWCC data automated to verify the analyses submitted by owner/operators, to compare recent submissions with historical data submissions, to manipulate and evaluate the information for their specific purposes, or to support permitting activities. EPA's data base system for environmental data is called STORET and is a recommended mechanism for organizing ground-water data acquired from hazardous waste management facilities. Several positive features of STORET are:

- STORET has recently been modified to include data fields that handle well-specific hydrogeological/technical information (e.g., well screen length, general lithology of the screened zone) in conjunction with the GWCC data.

- Most State and EPA regional offices have access to STORET.

- STORET is well supported with capacity for efficient storage, retrieval, and graphical analysis.

Represented below are specific evaluation and reporting procedures that should be followed by the owner/operator when recording and evaluating assessment monitoring data. These procedures are used to structure, analyze, simplify, and present the ground-water monitoring data to help the technical reviewer evaluate the extent and concentration of ground-water contaminants. The four evaluation or reporting procedures that should be described in the assessment plan used to record data in the on-site archives required by §265.94(b) are:

- Listing of Data;
- Summary Statistics Tables;
- Data Simplification; and
- Plotting of Data.

6.10.1 Listing of the Data

A list of all the detection monitoring and the assessment monitoring data (as well as any data from related State or other EPA programs) that have been collected should be available to technical reviewers when they review on-site records. First, data as originally reported and verified by the analytical laboratory for those measures requiring laboratory evaluation, or as recorded in the field for those measures collected at the time of sampling, should be available to the technical reviewer. These reporting forms should include information indicating that quality control samples (e.g., field and filter blanks) were obtained in the field. Also, the laboratory reporting should indicate that the laboratory has performed and reported standard quality control procedures (e.g., recovery analyses, analytical replicates etc.). Finally, the laboratory reporting should include the data that were used to determine the method detection limit or limit of detection (see Chapter 4). Explicit reporting of these quality control data is essential for documenting the precision and accuracy of owner/operator data submissions.

The listing of GWCC concentration data should follow a format similar to Table 6-1. The variables to be included in the listing are codes that identify the GWCC, well, date, unit of measure, whether the value was LT a limit of detection, and the concentration of the GWCC. Also, the listing may include the results of and codes identifying the quality control analyses performed. GWCC concentrations measured as LT a specific method detection limit or limit of detection should be indicated and, if possible, the GWCC concentration that was measured should be reported with the LT designation. Otherwise, the value that accompanies the LT designation should be the accepted detection limit for the method used. Documentation that describes the meaning of the codes used in the listing is required to eliminate ambiguity (e.g., Pb = lead, ppm = parts per million). The listing of GWCC data should include all measurements from all wells since sampling began, including measurements obtained during detection monitoring.

The listing should be organized to allow quick reference to specific data values. One categorization would be to first group by GWCC, then well code, and finally the date, as shown in Table 6-1. For example, all lead measurements are together, followed by all trichloroethylene measurements, etc. The values for each GWCC from one well should be grouped and ordered by date, followed by the data from the next well and so on for all wells in the ground-water monitoring system. Alternate sortings of the data listing may also be useful to the technical reviewer.

The data listing is not intended to function alone as an analytic tool, but the technical reviewer can use the data listing to assist in the review of the GWCC data. First, the ordered list of data will allow the technical reviewer quick reference to every GWCC concentration measurement if, for example, a spurious result was found in a supporting data analysis or report. Also, by requiring a consistent and orderly data listing, the technical reviewer can encourage the owner/operator to

TABLE 6-1
AN EXAMPLE OF HOW ASSESSMENT MONITORING DATA SHOULD BE LISTED

GWCC	WELL	REPLICATE	ALIQUOT	DATE	LT DETECTION	CONCENTRATION	UNITS
LEAD (UG/L)	7A	1	A	12JAN85		29.82	PPB
LEAD (UG/L)	7A	1	A	17FEB85		28.43	PPB
LEAD (UG/L)	7A	1	B	17FEB85		28.29	PPB
LEAD (UG/L)	7A	2	A	17FEB85		28.17	PPB
LEAD (UG/L)	7A	2	B	17FEB85		28.30	PPB
LEAD (UG/L)	9A	1	A	26APR84	<	10.00	PPB
LEAD (UG/L)	9A	1	B	26APR84	<	10.00	PPB
LEAD (UG/L)	9A	2	A	26APR84		20.60	PPB
LEAD (UG/L)	9A	1	A	05MAY84		21.20	PPB
LEAD (UG/L)	9A	2	A	05MAY84		21.80	PPB
LEAD (UG/L)	9B	1	A	26APR84		67.20	PPB
LEAD (UG/L)	9B	1	B	26APR84		67.80	PPB
LEAD (UG/L)	9B	2	A	26APR84		64.10	PPB
LEAD (UG/L)	9B	1	A	05MAY84		38.90	PPB
LEAD (UG/L)	9B	2	A	05MAY84		39.60	PPB
LEAD (UG/L)	9B	1	A	15JUN84		57.22	PPB
LEAD (UG/L)	9B	1	A	15JUL84		20.12	PPB
TRICHLOROETHYLENE (UG/L)	1A	1	A	26APR84	<	10.00	PPB
TRICHLOROETHYLENE (UG/L)	1A	1	A	05MAY84	<	10.00	PPB
TRICHLOROETHYLENE (UG/L)	1A	1	A	15JUN84	<	10.00	PPB
TRICHLOROETHYLENE (UG/L)	1A	1	A	15JUL84		11.10	PPB
TRICHLOROETHYLENE (UG/L)	1A	1	A	15AUG84	<	10.00	PPB
TRICHLOROETHYLENE (UG/L)	1A	1	A	15SEP84		10.10	PPB
TRICHLOROETHYLENE (UG/L)	1A	1	A	16OCT84		10.70	PPB
TRICHLOROETHYLENE (UG/L)	1A	1	A	18NOV84		10.00	PPB
TRICHLOROETHYLENE (UG/L)	1A	1	A	20DEC84	<	10.00	PPB
TRICHLOROETHYLENE (UG/L)	1A	1	A	12JAN85	<	10.00	PPB
TRICHLOROETHYLENE (UG/L)	1A	1	A	17FEB85	<	10.00	PPB
TRICHLOROETHYLENE (UG/L)	10A	1	A	26APR84		17.00	PPB
TRICHLOROETHYLENE (UG/L)	10A	1	B	26APR84		17.30	PPB
TRICHLOROETHYLENE (UG/L)	10A	2	A	26APR84		17.60	PPB
TRICHLOROETHYLENE (UG/L)	10A	1	A	05MAY84		21.00	PPB
TRICHLOROETHYLENE (UG/L)	10A	2	A	05MAY84		21.40	PPB
TRICHLOROETHYLENE (UG/L)	10A	1	A	15JUN84		21.20	PPB
TRICHLOROETHYLENE (UG/L)	10A	1	A	15AUG84		22.90	PPB
TRICHLOROETHYLENE (UG/L)	10A	1	A	15SEP84		19.40	PPB
TRICHLOROETHYLENE (UG/L)	10A	1	A	16OCT84		19.60	PPB
TRICHLOROETHYLENE (UG/L)	10A	1	A	18NOV84		30.10	PPB
TRICHLOROETHYLENE (UG/L)	10A	1	A	20DEC84		31.60	PPB
TRICHLOROETHYLENE (UG/L)	10A	1	A	12JAN85		33.60	PPB
TRICHLOROETHYLENE (UG/L)	10A	1	A	17FEB85		27.80	PPB
TRICHLOROETHYLENE (UG/L)	10A	1	B	17FEB85		27.80	PPB
TRICHLOROETHYLENE (UG/L)	10A	2	A	17FEB85		26.40	PPB
TRICHLOROETHYLENE (UG/L)	10A	2	B	17FEB85		26.50	PPB
TRICHLOROETHYLENE (UG/L)	10B	1	A	26APR84		65.10	PPB
TRICHLOROETHYLENE (UG/L)	10B	1	B	26APR84		65.80	PPB
TRICHLOROETHYLENE (UG/L)	10B	2	A	26APR84		65.40	PPB
TRICHLOROETHYLENE (UG/L)	10B	1	A	05MAY84		84.00	PPB
TRICHLOROETHYLENE (UG/L)	10B	2	A	05MAY84		83.70	PPB
TRICHLOROETHYLENE (UG/L)	10B	1	A	15JUN84		69.00	PPB
TRICHLOROETHYLENE (UG/L)	10B	1	A	15JUL84		68.40	PPB
TRICHLOROETHYLENE (UG/L)	10B	1	A	15AUG84		93.40	PPB
TRICHLOROETHYLENE (UG/L)	10B	1	A	15SEP84		98.90	PPB
TRICHLOROETHYLENE (UG/L)	10B	1	A	16OCT84		88.50	PPB

correct many of the data quality problems, that occur frequently on "raw" laboratory reporting sheets. Finally, data can be placed more easily onto a state or regional computer if the data are organized and reported consistently in a listing, rather than on laboratory reporting sheets having only the sample number identification instead of well codes, dates of sampling, etc. (see the above discussion).

6.10.2 Summary Statistics Tables

The ground-water monitoring data should be summarized and presented in tabular formats. Eight summary statistics should be calculated and used in each of four summary tables. The eight summary statistics are:

- Number of LT detection limit values
- Total number of values
- Mean
- Median
- Standard deviation
- Coefficient of variation
- Minimum value
- Maximum value

The methodology used to estimate these summary statistics can be found in many statistical textbooks.

The four tables of summary statistics should include summaries by:

- GWCC summary (e.g., Table 6-2)
- GWCC summary by well (e.g., Table 6-3)
- GWCC summary by well and date (e.g., Table 6-4)
- Quality control data

The tables should be formatted so that there are from one to three columns on the left side of each table, which provide data identifying, where applicable, the GWCC, well, and date. Eight columns, one for each summary statistic, should be to the right of the identifying columns.

TABLE 6-2

AN EXAMPLE OF HOW DATA SHOULD BE SUMMARIZED BY GWCC

GWCC	SAMPLE SIZE	NUMBER OF LT DETECTION LIMIT VALUES	MEAN	MEDIAN	STANDARD DEVIATION	COEFFICIENT OF VARIATION	MINIMUM	MAXIMUM
CHROMIUM (UG/L)	129	14	50.83	32.10	59.43	117	5.00	345.21
METHYLENE CHLORIDE (UG/L)	137	37	21.45	14.30	23.17	108	5.00	112.70
LEAD (UG/L)	129	15	50.31	20.43	168.22	334	1.00	1879.23
TRICHLOROETHYLENE (UG/L)	139	32	31.21	20.40	27.68	88.7	5.00	98.90

TABLE 6-3
AN EXAMPLE OF HOW DATA SHOULD BE SUMMARIZED BY GWCC/WELL COMBINATION

GWCC	WELL	SAMPLE SIZE	NUMBER OF LT DETECTION LIMIT VALUES	MEAN	MEDIAN	STANDARD DEVIATION	COEFFICIENT OF VARIATION	MINIMUM	MAXIMUM
CHROMIUM (UG/L)	1A	9	3	8.74	10.20	2.83	32.3	5.00	11.24
CHROMIUM (UG/L)	10A	16	0	63.57	49.00	38.99	61.3	30.90	140.00
CHROMIUM (UG/L)	10B	17	0	89.15	48.92	93.16	105	10.10	324.00
CHROMIUM (UG/L)	11A	2	0	13.51	13.51	1.70	12.6	12.31	14.72
CHROMIUM (UG/L)	12A	11	0	135.74	109.32	100.49	74.0	16.23	345.21
CHROMIUM (UG/L)	13A	11	0	27.36	28.09	3.83	14.0	20.86	32.53
CHROMIUM (UG/L)	14A	10	0	45.22	48.06	7.08	15.7	32.63	57.03
CHROMIUM (UG/L)	15A	9	0	27.76	29.69	5.13	18.5	18.62	32.01
CHROMIUM (UG/L)	16A	9	0	54.82	79.47	36.21	66.1	11.89	87.31
CHROMIUM (UG/L)	17A	3	1	10.51	12.31	4.87	46.3	5.00	14.23
CHROMIUM (UG/L)	3A	9	7	6.29	5.00	2.58	41.1	5.00	11.51
CHROMIUM (UG/L)	7A	11	0	59.64	58.71	12.48	20.9	46.91	85.01
CHROMIUM (UG/L)	9A	5	0	21.12	15.00	9.41	44.5	13.80	32.10
CHROMIUM (UG/L)	9B	7	3	11.40	11.10	7.05	61.9	5.00	21.60
METHYLENE CHLORIDE (UG/L)	1A	11	7	7.40	5.00	3.76	50.9	5.00	16.40
METHYLENE CHLORIDE (UG/L)	10A	16	0	13.66	12.95	2.26	16.6	11.00	16.90
METHYLENE CHLORIDE (UG/L)	10B	17	0	22.91	21.50	4.20	18.3	19.70	34.20
METHYLENE CHLORIDE (UG/L)	11A	2	2	5.00	5.00	0.00	0.0	5.00	5.00
METHYLENE CHLORIDE (UG/L)	12A	11	0	39.28	23.60	30.97	78.8	14.30	98.40
METHYLENE CHLORIDE (UG/L)	13A	11	0	20.73	18.90	7.36	35.5	11.00	28.60
METHYLENE CHLORIDE (UG/L)	14A	10	0	86.21	76.95	18.25	21.2	70.10	112.70
METHYLENE CHLORIDE (UG/L)	15A	9	1	11.27	11.90	2.44	21.7	5.00	12.90
METHYLENE CHLORIDE (UG/L)	16A	9	0	30.40	28.70	7.75	25.5	16.70	40.10
METHYLENE CHLORIDE (UG/L)	17A	3	3	5.00	5.00	0.00	0.0	5.00	5.00
METHYLENE CHLORIDE (UG/L)	2A	2	2	5.00	5.00	0.00	0.0	5.00	5.00
METHYLENE CHLORIDE (UG/L)	3A	11	10	5.60	5.00	1.99	35.5	5.00	11.60

TABLE 6-4

AN EXAMPLE OF HOW DATA SHOULD BE SUMMARIZED BY GWCC/WELL/DATE COMBINATION

GWCC	WELL	DATE	TOTAL NUMBER OF VALUES	NUMBER OF LT DETECTION LIMIT VALUES	MEAN	MEDIAN	STANDARD DEVIATION	COEFFICIENT OF VARIATION	MINIMUM	MAXIMUM
CHROMIUM (UG/L)	3A	17FEB85	1	1	5.00	5.00	.	.	5.00	5.00
CHROMIUM (UG/L)	7A	15JUL84	1	0	85.01	85.01	.	.	85.01	85.01
CHROMIUM (UG/L)	7A	15AUG84	1	0	73.52	73.52	.	.	73.52	73.52
CHROMIUM (UG/L)	7A	15SEP84	1	0	67.50	67.50	.	.	67.50	67.50
CHROMIUM (UG/L)	7A	16OCT84	1	0	64.38	64.38	.	.	64.38	64.38
CHROMIUM (UG/L)	7A	16NOV84	1	0	60.01	60.01	.	.	60.01	60.01
CHROMIUM (UG/L)	7A	20DEC84	1	0	58.71	58.71	.	.	58.71	58.71
CHROMIUM (UG/L)	7A	12JAN85	1	0	58.70	58.70	.	.	58.70	58.70
CHROMIUM (UG/L)	7A	17FEB85	4	0	47.05	46.95	0.22	0.5	46.91	47.38
CHROMIUM (UG/L)	9A	26APR84	3	0	14.27	14.00	0.64	4.5	13.80	15.00
CHROMIUM (UG/L)	9A	05MAY84	2	0	31.40	31.40	0.99	3.2	30.70	32.10
CHROMIUM (UG/L)	9B	26APR84	3	1	9.47	11.10	3.91	41.4	5.00	12.30
CHROMIUM (UG/L)	9B	05MAY84	2	0	20.70	20.70	1.27	6.1	19.80	21.60
CHROMIUM (UG/L)	9B	15JUN84	1	1	5.00	5.00	.	.	5.00	5.00
CHROMIUM (UG/L)	9B	15JUL84	1	1	5.00	5.00	.	.	5.00	5.00
METHYLENE CHLORIDE (UG/L)	1A	26APR84	1	1	5.00	5.00	.	.	5.00	5.00
METHYLENE CHLORIDE (UG/L)	1A	05MAY84	1	1	5.00	5.00	.	.	5.00	5.00
METHYLENE CHLORIDE (UG/L)	1A	15JUN84	1	0	10.00	10.00	.	.	10.00	10.00
METHYLENE CHLORIDE (UG/L)	1A	15JUL84	1	0	10.00	10.00	.	.	10.00	10.00
METHYLENE CHLORIDE (UG/L)	1A	15AUG84	1	1	5.00	5.00	.	.	5.00	5.00
METHYLENE CHLORIDE (UG/L)	1A	15SEP84	1	1	5.00	5.00	.	.	5.00	5.00
METHYLENE CHLORIDE (UG/L)	1A	16OCT84	1	0	16.40	16.40	.	.	16.40	16.40
METHYLENE CHLORIDE (UG/L)	1A	18NOV84	1	1	5.00	5.00	.	.	5.00	5.00
METHYLENE CHLORIDE (UG/L)	1A	20DEC84	1	0	10.00	10.00	.	.	10.00	10.00
METHYLENE CHLORIDE (UG/L)	1A	12JAN85	1	1	5.00	5.00	.	.	5.00	5.00
METHYLENE CHLORIDE (UG/L)	1A	17FEB85	1	1	5.00	5.00	.	.	5.00	5.00

There will be one row for each category that is being summarized. A summary statistics table by GWCC, for example, will have a number of rows equal to the number of GWCC that have been sampled. The GWCC-well table will have a number of rows equaling the number of GWCCs measured times the number of wells in the monitoring system (provided that each GWCC was measured at least once in each well). The GWCC-well-date table will be the largest table, and each row should be prefixed with a GWCC, well, and date code. The statistics in the GWCC-well-date table should summarize all replicate sampling that was performed for each GWCC, from each well, during each sampling.

The sample sizes, ranges, minimum, and maximum values will provide a rapid means for checking whether errors appear in the data. It will also facilitate rapid evaluation of GWCC concentrations over the entire ground-water monitoring system. In addition, the summary statistics will allow evaluation of spatial change in GWCC concentrations, which includes identifying the rate and extent of migration of the GWCC plume.

The quality control data should be provided whenever assessment monitoring data are submitted by an owner/operator. The quality control data can be submitted in the format in which they are received from the laboratory, provided that all data are clearly documented. The quality control samples taken in the field (e.g., field and sampling equipment blanks) may not be identified when the samples are supplied to the laboratory, but should be identified in assessment monitoring data submissions. Owner/operators should ensure that the laboratories provide the quality control data that support and validate the data resulting from the analysis of their field samples.

6.10.3 Data Simplification

Ranking procedures, which are described in this section, may be useful for simplifying and interpreting spatial trends in GWCC concentrations by allowing rapid determination of which wells have the overall highest and lowest GWCC concentrations. Table 6-5 presents an example of a data set analyzed by a ranking procedure.

The ranking can be performed using the mean, median, maximum, or minimum concentration values in the summary statistics table describing the values from each GWCC-well combination. For example, the mean concentration from each well is ranked from lowest to highest for each GWCC. The well with the lowest mean concentration of a GWCC will receive a value of 1; the well with the next highest concentration of the same GWCC will receive a value of 2, and so on. If two or more wells have the identical mean concentration, then the ranks for these wells will be averaged and applied to all wells with the same mean concentration. This procedure should be repeated for each GWCC that was detected at least once at every well in the monitoring system. The pH values may be ranked from highest to lowest rather than from lowest to highest, depending on whether the ground-water contamination is likely to result in an increase or decrease in pH. It is also useful to calculate an overall average rank for each well by averaging the ranks across all GWCCs associated with the well. These ranks should be presented in a table using GWCCs as column headings, and well codes as row headings. It may be helpful to group GWCCs with similar chemistry (e.g., volatile organics, metals, salts, etc.) and order the rows based on the wells with spacial proximity (e.g., upgradient, downgradient in plume, downgradient out of plume, shallow screen depth). This will facilitate identification of specific groups of wells where high concentrations of GWCC were detected.

6.10.4 Graphic Displays of Data

Ground-water data should be plotted to allow evaluation of temporal changes in GWCC concentrations over time. Each plot should consist of a X or horizontal axis, which represents time with year and month identified at intervals. The Y or vertical axis should represent the concentrations of GWCCs. The plots may be constructed using the mean values from the GWCC-well-date summary statistics table, and one plot

TABLE 6-5

AN EXAMPLE OF HOW RANKS OF THE MEAN CONCENTRATIONS FOR EACH GWCC/WELL COMBINATION CAN BE USED TO SIMPLIFY AND PRESENT CONCENTRATION DATA COLLECTED FOR A VARIETY OF GWCCs IN A NUMBER OF MONITORING WELLS

WELL	RANK OF MEAN CHROMIUM CONCENTRATION	RANK OF MEAN LEAD CONCENTRATION	RANK OF MEAN TCE CONCENTRATION	RANK OF MEAN MC CONCENTRATION	AVERAGE WELL RANK ACROSS GWCC
17A	3	3	1	3	2.50
2A	3	3	.	.	3.00
4A	3	3	.	.	3.00
11A	5	3	4	3	3.75
3A	1	6	2	6	3.75
9A	6	3	5	3	4.25
1A	2	8	3	7	5.00
9B	4	7	12	8	7.75
15A	8	9	6	11	8.50
13A	7	12	10	9	9.50
10A	12	10	11	10	10.75
14A	9	16	7	12	11.00
7A	11	11	9	15	11.50
12A	14	15	8	14	12.75
16A	10	14	14	13	12.75
10B	13	13	13	16	13.75

could be presented for each GWCC/well combination as in Figure 6-5. Alternatively, it may be more insightful to plot the data from several wells or GWCCs on one graph, as in Figure 6-6, provided the lines do not overlap excessively.

It may also be useful to plot data on facility maps, so that trends in GWCCs both vertically and horizontally can be evaluated. The summary statistics from the GWCC-well table can be used to provide data for plotting. A map of the facility, which identifies well locations, should be used to depict horizontal trends in concentrations. Geological cross sections and/or a facility map may be useful for plotting vertical trends in GWCC concentrations. The mean concentrations can be placed near each well location, similar to the construction of potentiometric maps described earlier. It may also be helpful to plot isopleth contours of concentration on the maps.

6.11 Rate of Migration

An assessment plan should specify the procedures the owner/operator will use to determine the rate of constituent migration in ground water. A rapid approach will generally be required for determining the rate of migration during interim status assessments. Migration rates can be determined by monitoring the concentration of GWCCs over a period of time in monitoring wells aligned in the direction of flow. If these wells are located both at the edge and the interior of the plume, subsequent analysis of the monitoring data can then provide an estimate of the rate of migration, both of the contaminant front as a whole and of individual constituents within the plume. This approach does not necessarily provide a reliable determination of the migration rates that will occur as the contaminant plume continues to move away from the facility in light of potential changes in geohydrologic conditions. More importantly, this approach requires the collection of a time series of data of sufficient duration and frequency to gauge the movement of contaminants. Such a

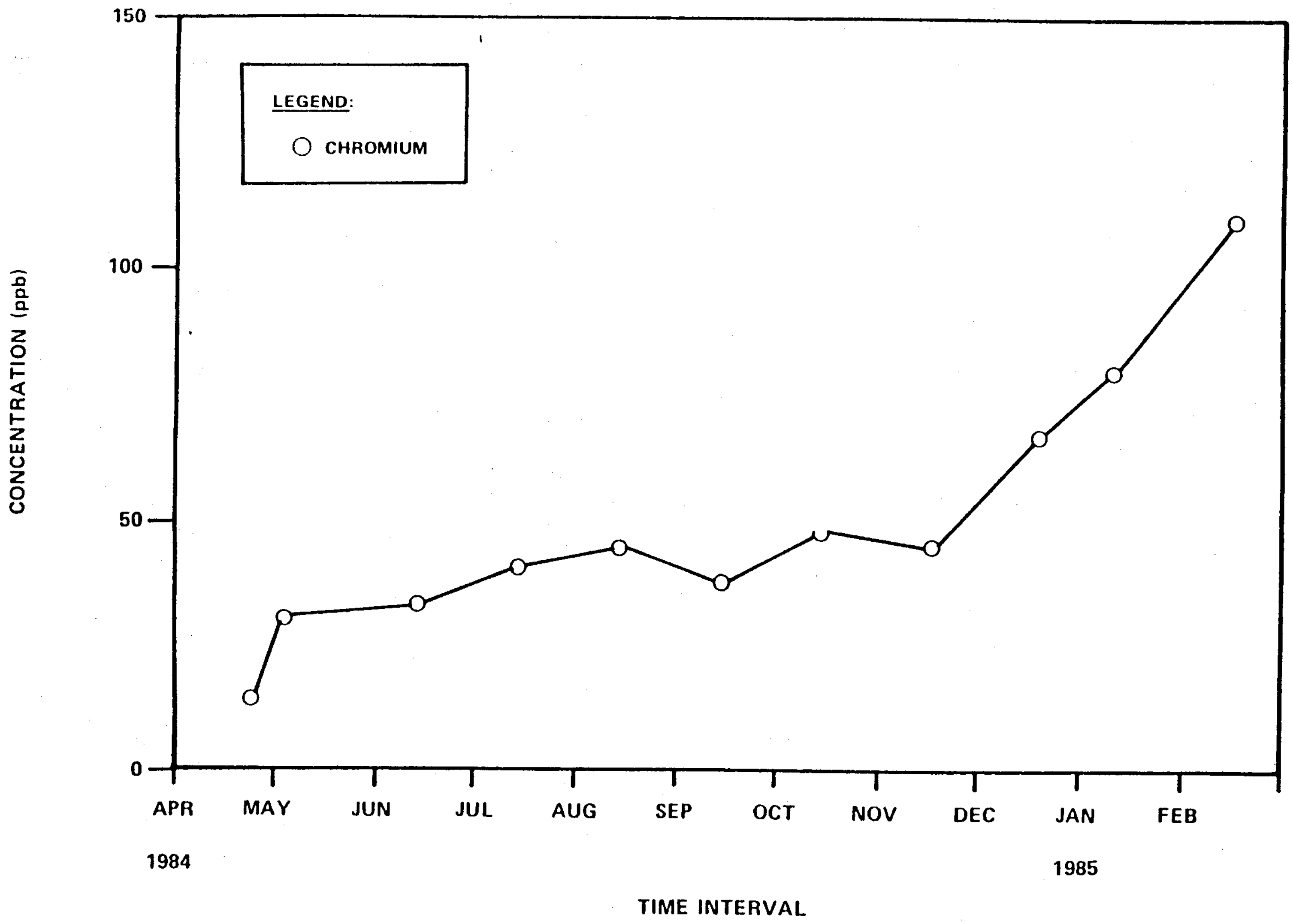


FIGURE 6-5. PLOT OF CHROMIUM CONCENTRATIONS OVER TIME (WELL 9A)

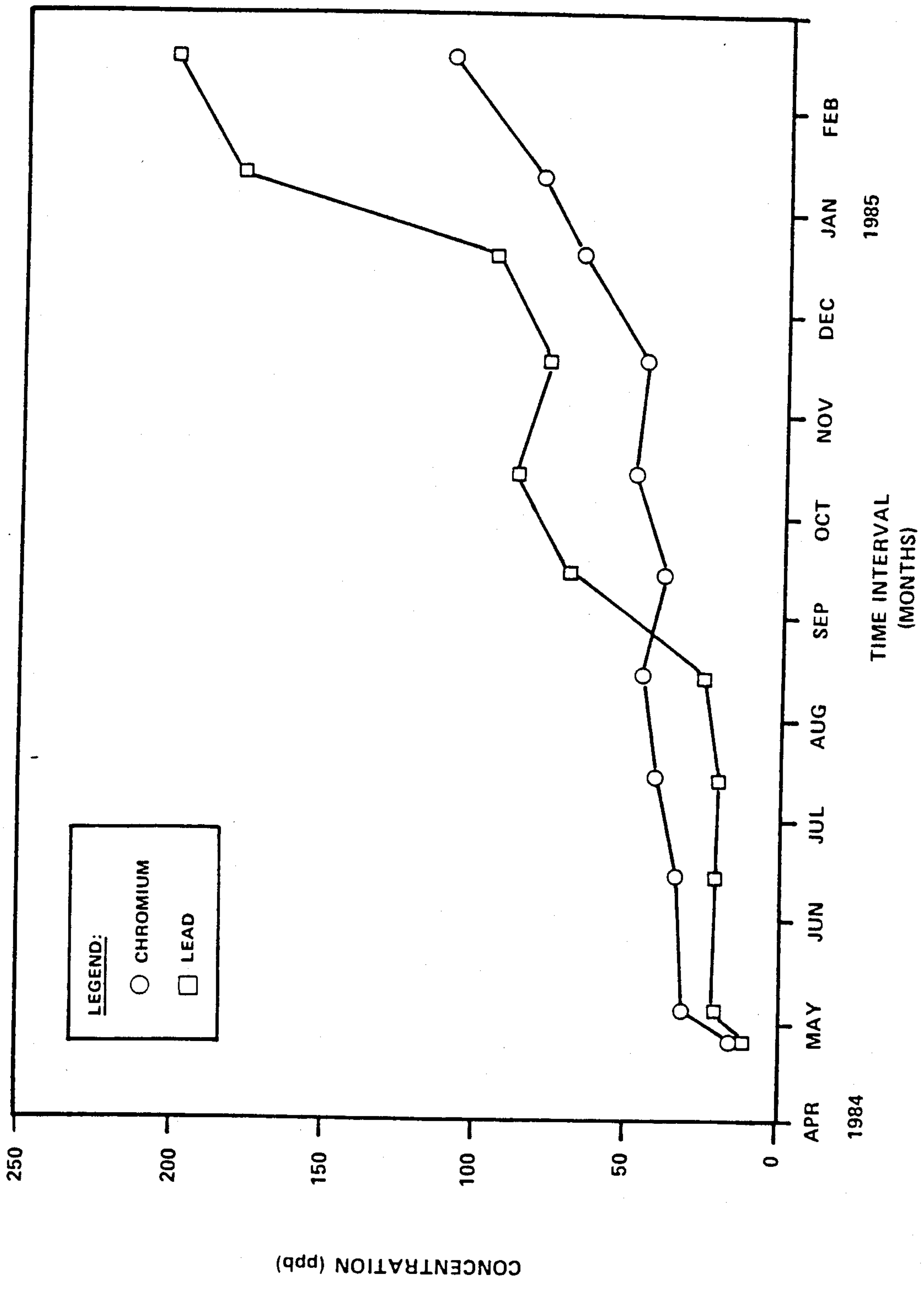


FIGURE 6-6. CHROMIUM AND LEAD CONCENTRATIONS OVER TIME (WELL 9A)

delay is normally inappropriate during initial assessment of ground-water contamination, since a relatively quick determination of at least an estimate of migration rates is required to deduce the impact of ground-water contamination and to formulate an appropriate reaction. Estimates of migration rates can be based on aquifer properties obtained during the site investigation and knowledge of the physico-chemical properties of contaminants known to be present. By recognizing the various factors that can affect transport processes of the GWCCs, the owner/operator can obtain approximate potential rates of migration during an initial assessment phase. Continued monitoring of the plume to verify rates of migration during assessment monitoring should serve as a basis for identifying additional monitoring well locations.

Initial approximations of contaminant migration rates based on ground-water flow rates are not reliable without verification because of potential differential transport rates among various classes of chemical constituents. Differential transport rates are caused by several factors including:

- Dispersion due to diffusion and mechanical mixing;
- Retardation due to adsorption and electrostatic interactions; and
- Transformation due to physical, chemical, and/or biological processes.

Dispersion results in the overall dilution of the contaminant and blurring at plume boundaries. Dispersion can result in a contaminant's arriving at a particular location before the arrival time computed solely on average rates of ground-water flow. Alternatively, retardation processes can delay the arrival of contaminants beyond that calculated by the average rates of ground-water flow. Local geology will also affect constituent migration rates. Relating rates of constituent migration to rates of ground-water flow is appropriate for a quick approximation during the initial assessment phase, but this should be followed by a more comprehensive study of migration rates.

Simple slug tests are not the preferred method for determining the aquifer characteristics. The slug test is limited to the immediate vicinity where it is performed, and its results often cannot be projected across an entire site.

At those facilities where sufficient immiscible contaminants have leaked to form and migrate as a separate immiscible phase (see Figure 6-7), additional analysis will be necessary to evaluate the migration of these contaminants away from the facility. Chapter Five contains a discussion of the ground-water monitoring techniques that can be used to sample multi-phased contamination. The formation of separate phases of immiscible contaminants in the subsurface is largely controlled by the rate of infiltration of the immiscible contaminant and the solubility of that contaminant in ground water. Immiscible contaminants generally have some limited solubility in water. Thus, some amount of immiscible contaminant leaking from the facility will enter into solution in ground water and migrate away from the facility as dissolved constituents. If the amount of immiscible fluid reaching ground water exceeds the solubility constant, however, the ground water in the upper portion of the water table aquifer will become saturated, and the contaminant will form a separate immiscible phase.

At this point, the behavior and migration of the contaminants present in the immiscible phase will be strongly influenced by their density relative to ground water. If the immiscibles are less dense than ground water, the immiscibles will tend to coalesce on the surface of the potentiometric surface and form and migrate as a separate immiscible layer floating on the ground water. If the density of the immiscible contaminants is similar to that of ground water, the immiscible will tend to mix and flow as a separate phase with the ground water, creating a condition of multiphase flow.

If the density of the immiscibles is greater than ground water, the immiscibles will tend to sink in the aquifer (see Figure 6-7). As the immiscibles sink and reach unaffected ground water in a deeper portion of the aquifer, more of the immiscible contaminant will tend to enter into solution in ground water and begin to migrate as dissolved constituents. If enough of the dense immiscible contaminants are present, however, some portion of these contaminants will continue to sink as a separate immiscible phase, until a formation of reduced permeability is reached. At this point, these contaminants will tend to coalesce and migrate as a layer of dense immiscibles resting on the geologic barrier.

In each of these cases, the contaminants present in the separate immiscible phase may migrate away from the facility at rates different from that of ground water. In many cases, they will migrate at rates slower than or equivalent to ground water, but in some instances migration rates can be greater. In addition, migration of the immiscibles may not be in the direction of ground-water flow. However, it is important to reemphasize that some amount of these contaminants will invariably dissolve in ground water and migrate away from the facility as dissolved constituents.

Light immiscible contaminants will migrate downgradient to form a floating layer above the saturated zone (see Figure 6-7). The direction of ground-water flow will dictate the movement of this light immiscible layer. Important factors involved in its migration rate include the intrinsic permeability of the medium and the density and viscosity of the contaminants. With time, an ellipsoidal plume develops, overlying the saturated zone as depicted in Figure 6-7. While it is possible to analyze the behavior of the light immiscible layer using analytical or numerical models, the most practical approach for determining the rate and direction of migration of such a light immiscible layer during an assessment may be to observe its behavior over time with appropriately located monitoring wells.

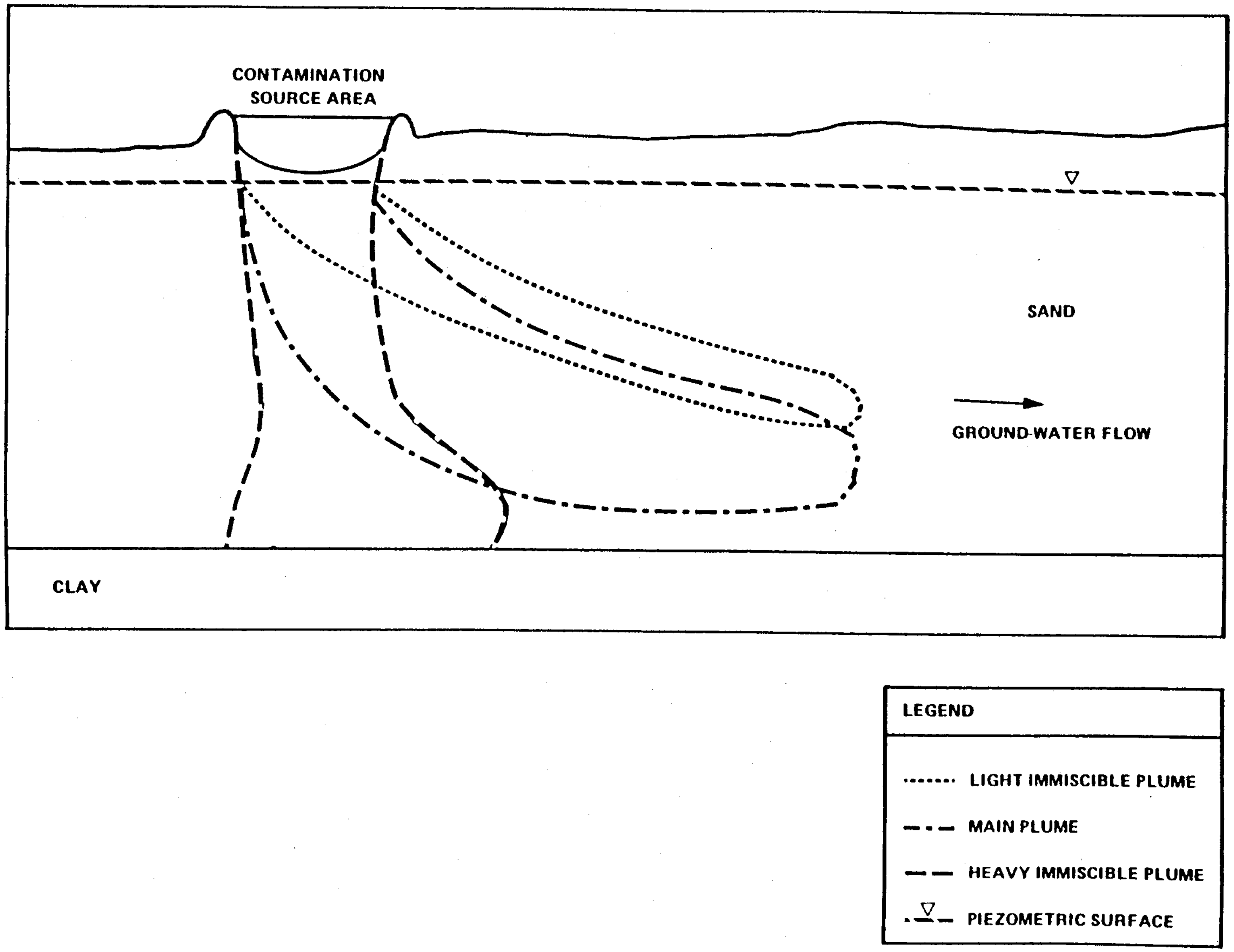


FIGURE 6-7 GENERAL SCHEM C OF MULTIPHASE CONTAMINATION IN SAND

The migration of a layer of dense immiscibles settled on a confining layer may be strongly influenced by gravity. Depending on the slope of the confining layer in the gradients used to calculate flow rates. A program of continued monitoring of the dense immiscible layer should always be included in the assessment plan to verify direction and rate of movement.

6.12 Reviewing Schedule of Implementation

The assessment plan should specify a schedule of implementation. Each assessment program will have to include the amount of work involved in the assessment and other local factors such as weather and availability of equipment and personnel. The schedule should include a sufficient number of milestones, so that the Agency can judge whether sufficient progress is being made toward the completion of the assessment. Any continued monitoring undertaken during the maintenance phase of assessment should be scheduled at least on a quarterly basis.

Activities planned to initially determine whether contamination has actually occurred should not unnecessarily delay the implementation of a comprehensive assessment. When an extensive program to collect additional data to remedy inadequacies in currently available data is to be undertaken, these activities should require only a short period for completion. Additional analysis of water quality data should require no more than 15 days to 30 days. Sampling to determine actual concentrations of hazardous waste constituents should require only time enough for sample collection and analysis, followed by a brief period for subsequent analysis of the data.

A thorough discussion of monitoring well placement, and monitoring well design and construction, can be found in Chapters Two and Three, respectively. A discussion of the ground-water monitoring techniques necessary to effectively characterize a multiphase containment migration is also given in Chapter Four of this document.

REFERENCES

Freeze, R.A. and J.A. Cherry. 1979. Groundwater. Prentice-Hall Inc.

Hoaglin, D.C., F. Mosteller, and Hal Takey. 1985. Exploring Data Tables, Trends, and Shapes. John Wiley and Sons, Inc. 475 pp.

MacKay, D.M., P.V. Roberts and J.A. Cherry. 1985. Transport of Organic Contaminants in Ground-Water, Engineering Science & Technology, Vol. 19, No. 5, pp. 284-392.

U.S. Environmental Protection Agency. 1979. Water-Related Environmental Fate of 129 Priority Pollutants, Volume 1, Introduction, Technical Background, Metals and Inorganics, Pesticides, and PCBs. EPA-440/4-79/029a.

U.S. Environmental Protection Agency. 1979. Water-Related Environmental Fate of 129 Priority Pollutants, Volume 2, Halogenated Aliphatic Hydrocarbons, Halogenated Ethers, Monocyclic Aromatics, Pthalate Esters, Polycyclic Aromatic Hydrocarbons, Nitrosamines, Miscellaneous Compounds. EPA-440/4-79/029b.

U.S. Environmental Protection Agency. 1983. Ground-Water Monitoring Guidance for Owners and Operators of Interim Status Facilities. National Technical Information Service. PB83-209445.

U.S. Environmental Protection Agency. September 1985. Protection of Public Water Supplies from Ground-Water Contamination. EPA-625/4-85/016.